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Data-Driven and Model-Based Next-Generation Remedial Action Schemes with Industrial-Grade Hardware-in-the-Loop Validation

to obtain the Ph.D. degree in Electrical
Engineering

Miguel Angel Toro Mendoza

Universidad Autónoma de San Luis Potosí
Facultad de Ingeniería
Centro de Investigación y Estudios de Posgrados

San Luis Potosí, México, July 2026



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19 de marzo de 2026

**M.I. MIGUEL ÁNGEL TORO MENDOZA
P R E S E N T E.**

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Introduction

1. State-of-the-Art of Remedial Action Schemes.
2. Next-Generation Remedial Action Schemes for Modern Power Grids.
3. Model-Based Digital Twin for a Voltage Stability-Oriented Remedial Action Scheme.
4. Data-Driven Digital Twin and Replica for a Frequency Stability-Oriented Remedial Action Scheme.

Conclusions.

Bibliography.

"MODOS ET CUNCTARUM RERUM MENSURAS AUDEBO"

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Área de Investigación y Estudios de Posgrado

D E C L A R A C I Ó N

El presente trabajo que lleva por título:

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y del Dr. Aaron Esparza Gurrola

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Abstract

This thesis proposes a new methodology for the design and operation of adaptive model-based Remedial Action Schemes (RAS) for voltage and frequency stability applications in modern power systems. Increasing system stress, reduced stability margins, and the large-scale integration of power-electronics-based generation have exposed the limitations of conventional load shedding schemes based on static settings and offline studies. To address these challenges, the proposed approach integrates digital twins, replicas, and data-driven techniques to extract system information from real-time measurements, identify critical operating conditions, and determine remedial actions while considering both steady-state and dynamic system behavior in real-time. A voltage-collapse-oriented RAS based on real-time voltage stability margin estimation and a frequency stability RAS based on post-contingency frequency estimation are developed, including adaptive load shedding strategies capable of responding to diverse disturbances. In addition, a data-driven assessment stage is incorporated to evaluate the impact of remedial actions on electromechanical oscillatory behavior. The proposed methodologies are validated through hardware-in-the-loop (HIL) simulations using industrial-grade controllers and communication protocols, demonstrating their feasibility, adaptability, and applicability under realistic operating conditions.

Keywords: Remedial Action Schemes, Digital Twin, Replica, Data-driven assessment, Hardware-in-the-Loop.

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Acronyms

AC-OLS	Alternating Current Optimal Load Shedding.
AGC	Automatic Generation Control.
ANN	Artificial Neural Network.
AVRs	Automatic Voltage Regulators.
CENACE	National Center for Energy Control.
CODESYS	Controller Development System.
COI	Center of Inertia.
COMTRADE	Common Format for Transient Data Exchange.
CPF	Continuation Power Flow.
CSV	Comma-Separated Values.
DAEs	Differential-Algebraic Equations.
DDPG	Deep Deterministic Policy Gradient.
DIGSILENT	Digital Simulation and Electrical Network Calculation Program.
DMD	Dynamic Mode Decomposition.
DNP	Distributed Network Protocol.
DNP3	Distributed Network Protocol version 3.
DQL	Deep Q-Learning.
DRL-D2DQN	Deep Reinforcement Learning based Double-Agent Double Deep Q-Network.
DT	Digital Twin.
DVPS	Dynamic Voltage Performance Sensitivity.
EMS	Energy Management Systems.
EMT	Electromagnetic Transients.
ESS	Energy Storage System.
FACTS	Flexible AC Transmission Systems.
FAT	Factory Acceptance Test.
FERC	Federal Energy Regulatory Commission.
FFR	Fast Frequency Response.
FIDVR	Fault-Induced Delayed Voltage Recovery.
FREPI	Frequency Performance Index.
FVSI	Fast Voltage Stability Index.
GOOSE	Generic Object-Oriented Substation Event.

GTNETx2	RTDS Communication Card.
HIL	Hardware-in-the-Loop.
HVDC	High-Voltage Direct Current.
ICSBEP	Integrated Chaotic Swarm Based Evolutionary Programming.
IEC	International Electrotechnical Commission.
IEC 61131	Programmable Controller Standard.
IEC 61850	Substation Automation Standard.
IED	Intelligent Electronic Device.
IEEE	Institute of Electrical and Electronics Engineers.
LAPACK	Linear Algebra PACKage.
LS-D	Load Shedding Dynamic.
LS-S	Load Shedding Static.
MADDPG	Multi-Agent Deep Deterministic Policy Gradient.
MATLAB	Matrix Laboratory.
MILP	Mixed Integer Linear Programming.
NERC	North American Electric Reliability Corporation.
NGVL	Next Generation Virtual Link.
NN	Neural Network.
OPF	Optimal Power Flow.
OSS	Out of step tripping.
PI	Proportional-Integral.
PID	Proportional-Integral-Derivative.
PMUs	Phasor Measurement Units.
PRC-024-2	Protection and Control standard PRC-024-2.
Pseudo-Arc-CPF	Pseudo Arc-Length Continuation Power Flow.
PSO	Particle Swarm Optimization.
PSO-Fuzzy	Particle Swarm Optimization-Fuzzy.
PSS/E	Power System Simulator for Engineering.
PV	Power-Voltage.
PVECU	Photovoltaic Energy Conversion Unit.
QR	QR decomposition.
QVSI	Q-based Voltage Stability Index.
RAS	Remedial Action Schemes.
RL	Reinforcement Learning.
RMS	Root Mean Square.
ROCOF	Rate of Change of Frequency.
ROCOF-FVSI	Rate of Change of Frequency and Fast Voltage Stability Index.
ROCOV	Rate of Change of Voltage.

ROPEC	IEEE International Autumn Meeting on Power, Electronics and Computing.
RTAC	Real-Time Automation Controller.
RTDS	Real-Time Digital Simulator.
RTS	Real-Time Simulator.
SAT	Site Acceptance Test.
SCADA	Supervisory Control and Data Acquisition.
SEL	Schweitzer Engineering Laboratories.
SEL-3555	SEL-3555 Real-Time Automation Controller.
SFR	System Frequency Response.
SGP	Sparse Gaussian Process.
SM	Synchronous Machine.
SNR	Signal-to-Noise Ratio.
SPS	Special Protection Schemes.
SVD	Singular Value Decomposition.
TEF	Transient Energy Function.
TVRC	Transient Voltage Recovery Criterion.
TVSI	Transient Voltage Stability Index.
UFLS	Under-Frequency Load Shedding.
UPF	Unified Power Flow.
UVLS	Under-Voltage Load Shedding.
VCPI	Voltage Collapse Proximity Indicator.
VQS	Voltage Quality Sensitivity.
VSI	Voltage Stability Index.
VSM	Voltage Stability Margin.
VSM-MF-TSGA	Voltage Stability Margin Multi-Feature Two-Stage Genetic Algorithm.
WAMS	Wide Area Monitoring System.
WECC	Western Electricity Coordinating Council.
WKELM	Weighted Kernel Extreme Learning Machine.
WLS	Weighted Least Squares.
ZIP	Constant Impedance, Current, and Power.

Symbols

$\mathbf{A}$	Best-fit linear operator.
$\tilde{\mathbf{A}}_H^{(\ell)}$	Hessenberg matrix at QR iteration ℓ .
$\mathbf{a}_i$	Subcolumn used to construct the Householder vector.
$\tilde{a}_{ij}$	Element of the active Hessenberg block.
$\tilde{\mathbf{A}}$	Reduced best-fit linear operator.
$\tilde{\mathbf{A}}_H$	Hessenberg representation of the reduced best-fit linear operator.
c	Number of measurements.
$\dagger$	Moore–Penrose pseudo-inverse operator.
$\boldsymbol{\delta}$	Vector of voltage phase angles.
δ_i	Voltage phase angle at bus i .
$\ \Delta \mathbf{y}\ _2$	Euclidean norm of measurement vector.
Δf_{pu}	Frequency correction in per unit.
$\Delta \lambda$	Corrector-step update of the loading parameter.
$d\lambda$	Differential increment of the loading parameter.
$\Delta P_{\text{Droop},\gamma}$	Active power variation of the γ -th generation unit operating under droop control.
$\Delta \mathbf{P}^{\text{Ref}}$	Active power residual vector associated with the UPF equations.
$\Delta P_{\text{shed},i}$	Load-shedding amount at bus i .
$\Delta P_{\text{shed}}^{\text{max}}$	Maximum load-shedding amount allowed.
ΔP_{total}	Total load-shedding amount.
$\Delta \mathbf{Q}^{\text{Ref}}$	Reactive power residual vector associated with the UPF equations.
$d\mathbf{u}$	Differential increment of the state vector.
$\Delta V_{av,i}$	Average voltage deviation at bus i .
ΔV_i	Voltage deviation at bus i .
ΔV_{th}	Voltage-deviation threshold.
$\Delta \mathbf{x}$	State correction vector.
Δy_i	i -th element of the measurement-vector variation.
ℓ	Iteration of the QR-based algorithm.
$\mathbf{e}_1$	First canonical vector.
ϵ	Convergence tolerance of the iterative state estimation process.
$\mathbf{F}_\delta$	Partial derivative of the power-flow equations with respect to voltage angles.
f_j	Oscillation frequency of mode j .

$\mathbf{F}_\lambda$	Partial derivative of the power-flow equations with respect to the loading parameter.
f_{pu}	System frequency in per unit.
f_{ss}^{post}	Post-contingency steady-state frequency.
$f_{ss}^{post,ref}$	Post-contingency steady-state reference frequency.
$\mathbf{F}_u$	Partial derivative of the power-flow equations with respect to the state vector.
$\mathbf{F}_V$	Partial derivative of the power-flow equations with respect to voltage magnitudes.
$\mathbf{\Gamma}$	Sub-matrix of the Hessenberg block.
γ	Generation-unit index.
$\mathbf{G}_\lambda$	Partial derivative of the pseudo-arc-length constraint with respect to the loading parameter.
$\mathbf{G}_{SE}$	Gain matrix of the WLS-based state estimator.
$\mathbf{G}_u$	Partial derivative of the pseudo-arc-length constraint with respect to the state vector.
$\mathbf{h}(\mathbf{x})$	Vector of nonlinear measurement functions.
$\mathbf{H}_i$	i-th Householder reflection.
h_{ij}	Element of the Hessenberg matrix.
$\mathbf{H}_{SE}$	Measurement Jacobian matrix of the state estimator.
$ \mathbf{I} $	Vector of current magnitudes.
$\mathbf{I}$	Identity matrix.
j	Deflation index.
K_c	Calibration gain or coefficient used in the FIDVR stage.
K_i	Load-shedding gain at bus i.
k	Discrete-time index.
Λ	Discrete-time DMD eigenvalues.
λ	Loading parameter.
λ_j	j-th discrete-time DMD eigenvalue.
λ_k	Corrected loading parameter at continuation step k.
λ_{max}	Maximum loading parameter.
λ_p	Predicted loading parameter.
$LS\text{-}D_i$	Dynamic load-shedding amount at bus i.
$LS\text{-}S_i$	Static load-shedding amount at bus i.
m	Number of synchronized PMU channels.
m_i	Number of generation units connected to bus i.
μ_j	j-th continuous-time eigenvalue.
$\mu(t)$	Voltage ride-through admissibility function or dynamic recovery criterion.
N	Number of buses in the power system.
n	Initial snapshot index.
N_m	Number of monitored buses.

p	Number of measurement snapshots.
$P_{\text{Const},\gamma}$	Active power output of the γ -th constant-power generation unit.
$p_{\text{Const},\gamma}^{\text{Ref}}$	Scheduled active power setpoint of the γ -th constant-power generation unit.
$P_{\text{Droop},\gamma}$	Active power output of the γ -th droop-controlled generation unit.
$p_{\text{Droop},i}^{\text{Ref}}$	Aggregate active power reference of droop-controlled generation units connected to bus i .
$p_{\text{Droop},\gamma}^{\text{Ref}}$	Active power reference setpoint of the γ -th droop-controlled generation unit.
P_{e_i}	Electrical output power of generator i .
$\mathbf{P}_{\text{flow}}$	Vector of active power flow measurement.
$p_{\Gamma}(\rho)$	Characteristic polynomial of Γ .
P_{gi}	Active power generation at generator i .
Φ	Mode shape.
P_i	Active power injection at bus i .
P_{ij}	Active power flow from bus i to bus j .
$\mathbf{P}_{\text{inj}}$	Vector of active power injection measurement.
P_{li}	Active power load at bus i .
$P_{\text{Load},i}$	Active power load at bus i .
$P_{\text{LS-S},i}$	Static load-shedding amount at bus i .
P_{m_i}	Mechanical input power of generator i .
p_i^{Ref}	Specified active power reference at bus i .
$\mathbf{Q}_{\text{flow}}$	Vector of reactive power flow measurement.
Q_i	Reactive power injection at bus i .
Q_{ij}	Reactive power flow from bus i to bus j .
$\mathbf{Q}_{\text{inj}}$	Vector of reactive power injection measurement.
Q_{li}	Reactive power load at bus i .
$\mathbf{Q}_{qr}^{(\ell)}$	Orthogonal factor in the shifted QR iteration.
Q_i^{Ref}	Specified reactive power reference at bus i .
r	Rank of $\mathbf{S}_1$.
R_{γ}	Droop coefficient of generation unit γ .
ρ	Wilkinson shift.
$\mathbf{R}_{\text{meas}}$	Measurement covariance matrix.
$\mathbf{R}_{qr}^{(\ell)}$	Upper triangular factor in the shifted QR iteration.
s	Arc-length continuation parameter.
$\mathbf{S}_1^{\dagger}$	Moore–Penrose pseudo-inverse of $\mathbf{S}_1$.
$S_{\text{Droop},\gamma}$	Base power of the γ -th droop-controlled generation unit.
Σ	Full singular-value matrix.
σ	Continuation step size.
Σ_r	Diagonal matrix of singular values.
s_k	Measurement snapshots from PMUs over a discrete-time observation window.
$\mathbf{S}_1$	First snapshot data matrix.
$\mathbf{S}_2$	Second snapshot data matrix.
$\mathbf{t}$	Tangent vector.

τ	Integration interval or time delay.
T	Final time of the ride-through evaluation interval.
θ_{in}	Phase angle of the bus admittance matrix element Y_{in} .
$\mathbf{T}_{\text{system}}$	Participation vector of the load or generation in the CPF.
t_0	Initial time for the voltage-deviation assessment window.
$\mathbf{u}$	State vector.
$\mathbf{u}_k$	Corrected state vector at continuation step k.
$\mathbf{u}_p$	Predicted state vector.
$\mathbf{U}_r$	Left singular vector.
$\mathbf{U}_r^\perp$	Orthogonal complement of $\mathbf{U}_r$.
$\mathbf{V}$	Vector of voltage magnitudes.
V_i	Voltage magnitude at bus i.
$\mathbf{v}_i$	Householder vector.
V_n	Voltage magnitude at bus n.
$\mathbf{V}_r$	Right singular vector.
$\mathbf{V}_r^\perp$	Orthogonal complement of $\mathbf{V}_r$.
$\mathbf{V}_r^T$	Transpose of the right singular-vector matrix.
$V_{th,i}$	Reference voltage threshold at bus i.
$\mathbf{W}$	Matrix of eigenvectors of $\tilde{\mathbf{A}}$.
ξ	Auxiliary vector used to compute the CPF tangent direction.
$\mathbf{y}$	Measurement vector.
Y_{in}	Element of the bus admittance matrix between buses i and n.
$\mathbf{z}$	Measurement vector used in the state estimator.
ζ	Damping ratio.
ζ_j	Damping ratio of mode j.

Contributions

Journal Citation Reports publications

- Toro-Mendoza, M. A., Segundo-Ramírez, J., Rosas, E., Rodriguez-Soto, R. D., Esparza-Gurrola, A., & Barocio-Espejo, E. (2026). **Industrial-grade hardware-in-the-loop validation of wide-area monitoring system based on dynamic mode decomposition for electromechanical oscillation in power systems.** *Journal of Modern Power Systems and Clean Energy*, 14(3), 845–857.
- Toro-Mendoza, M. A., Segundo-Ramírez, J., Gurrola, A. E., Visairo-Cruz, N., Núñez-Gutiérrez, C. A., Torres, U., & Barocio-Espejo, E. (2025). **Digital twin adaptive remedial action scheme for preventing voltage collapse.** *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, 6(2), 523–535.
- Toro-Mendoza, M. A., Segundo-Ramírez, J., Esparza-Gurrola, A., Visairo-Cruz, N., Núñez-Gutiérrez, C. A., & Pérez-Negrón, C. (2023). **Toward adaptive load shedding remedial action schemes in modern electrical power systems.** *IEEE Access*, 11, 111011–111033.

Chapters from peer-reviewed publications

- Segundo-Ramírez, J., Toro-Mendoza, M. A., Rosas, E., Esparza-Gurrola, A., Hernandez-Ramírez, J., & Torres, U. (2026). **Impact of remedial action schemes on the reliability and integrity of power electrical systems.** In *Design Reliability and Maintainability of Energy Systems* (pp. 293-319). Elsevier.
- Segundo-Ramírez, J., Esparza-Gurrola, A., Hernandez-Ramírez, J., Rosas, E., Toro-Mendoza, M. A., & Torres, U. (2026). **Hardware-in-the-loop-based assessment of special protection schemes for reliability enhancement.** In *Design Reliability and Maintainability of Energy Systems* (pp. 127-147). Elsevier.

Peer-reviewed conference proceeding

- Toro-Mendoza, M. A., Segundo-Ramírez, J., Visairo-Cruz, N., Núñez-Gutiérrez, C. A., Esparza-Gurrola, A., & Torres, U. (2023). Pseudo arc-length continuation power flow method in a real-time controller. *2023 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*, 7, 1–6.

Introduction

Power systems constitute the largest and most complex infrastructure ever developed; consequently, ensuring their continuous and secure operation represents a critical challenge. In recent decades, these systems have evolved toward significantly more demanding operating conditions, characterized by high loading levels, congestion in critical transmission corridors, reduced inertia due to the large-scale integration of power-electronics-based generation, and a sustained reduction in stability margins. As a result, modern power systems have become more vulnerable to severe disturbances and more susceptible to instability phenomena, particularly voltage collapse and frequency instability. In this context, **Remedial Action Schemes (RAS)** are not merely relevant tools, but indispensable elements for preserving operational security and preventing large-scale blackouts.

Among the different types of RAS, load shedding schemes have been widely used to mitigate voltage and frequency stability problems. However, their operation is based on static approaches, relying on predefined parameters and offline studies. These characteristics make them poorly suited to adapt to the dynamics and complexity of modern power systems. Consequently, these schemes exhibit limitations that may lead to inefficient responses, where load shedding actions are either insufficient or excessive. Therefore, the development of truly adaptive remedial action schemes, capable of integrating real-time system information and accurately representing system dynamics, is not optional but a fundamental necessity.

Despite these advances, fully adaptive RAS have rarely been reported in practical power system applications. This indicates that the principal challenge is no longer the development of increasingly sophisticated adaptive algorithms, but rather demonstrating that such methodologies can satisfy the security, reliability, and robustness requirements imposed by critical infrastructures. Furthermore, many of the methodologies reported in the literature assume levels of system observability, controllability, and computational resources that are seldom available in practical substations, while their validation is commonly limited to offline simulations that do not capture the constraints associated with industrial protection and control platforms. Consequently, a significant gap remains between the research development of adaptive RAS and their practical deployment in real power systems.

To bridge this gap, this thesis establishes a methodological framework for the design, implementation, and validation of a new generation of adaptive model-based remedial action schemes supported by Digital Twins, Replicas, and data-driven techniques. The proposed framework enables the automatic adjustment of corrective actions according to the current operating conditions by extracting the physical properties of the power system from real-time measurements, identifying critical operating conditions, and adaptively determining the required remedial actions. Furthermore, it incorporates a dynamic assessment stage to evaluate the impact of such actions, consistently integrating steady-state analysis with the dynamic response of the system. In contrast to conventional schemes, the proposed methodology provides a systematic framework for adaptive RAS operation capable of responding effectively to a wide range of disturbances.

The main contributions of this thesis are as follows. First, a methodology for the operation of a voltage-collapse-oriented RAS is developed, based on digital twins and supported by a steady-state model capable of estimating the system voltage stability margin in real time. This margin is used as an index to determine and adjust the required amount of load shedding. In addition, a two-stage load-shedding strategy is proposed to address the dynamic voltage response by monitoring the voltage deviation during disturbances.

Second, the methodology is extended to frequency stability problems through a digital twin based on a model that estimates post-contingency frequency. This approach enables the calculation and adjustment of the load shedding amount required to maintain frequency within acceptable limits, using a single-stage strategy, in direct contrast to conventional multi-stage schemes. Furthermore, the concept of a replica is incorporated to capture the physical characteristics of industrial-grade controllers, enabling realistic validation through real-time simulation.

Third, a data-driven evaluation stage is integrated within the replica framework to analyze the dynamic impact of the single-stage load shedding strategy on critical system variables, particularly electromechanical oscillation modes, ensuring that no poorly damped or unstable oscillatory conditions are introduced.

Although the proposed methodology can be evaluated using specialized simulation software, such an approach is insufficient to capture the limitations and phenomena associated with the industrial controllers in which RAS are implemented in practice, such as processing delays, internal architecture, and communication protocols. These constraints directly affect system performance and cannot be neglected.

For this reason, the methodology is validated in a **Hardware-in-the-Loop (HIL)** environment, in which the RAS, together with their models and operational logic, are implemented on industrial-grade controllers similar to those used in electrical substations. This approach enables performance evaluation under realistic conditions, incorporating physical implementation constraints and demonstrating the feasibility and applicability of the proposed methodology in real-world operational environments.

Thesis objectives

General objective

The objective of this thesis is to propose, develop, and validate an adaptive operating methodology for remedial action schemes based on digital twins, replicas, and data-driven techniques, capable of operating in real time to determine, adjust, and dynamically assess load-shedding actions for voltage and frequency stability applications, while addressing key limitations of conventional static schemes.

The contributions of this thesis are of a dual nature: on one hand, they are methodological and analytical, involving the formulation of an integrated mathematical framework for digital twins of voltage and frequency stability, the development of operational logics for adaptive load shedding, and the application of dynamic mode decomposition to assess electromechanical oscillations induced by remedial actions; on the other hand, they are experimental, involving the implementation and verification of these methodological contributions on industrial-grade hardware through hardware-in-the-loop testing. The experimental component is not a substitute for scientific rigor but a means of validating the proposed methodology under conditions that cannot be reproduced in pure offline simulation, while also contributing to technological development by demonstrating its practical applicability and potential for real-world deployment.

Specific objectives

- Develop a model-based methodology for voltage stability-oriented RAS, supported by digital twins, capable of estimating the system voltage stability margin in real time and using it as a control index to determine and adjust load shedding actions.
- Design and implement a two-stage load shedding strategy that incorporates both steady-state and dynamic voltage response, enabling effective mitigation of voltage collapse under a wide range of operating conditions.
- To extend the proposed methodology to frequency stability problems, by developing a digital twin capable of estimating post-contingency frequency and determining the required load shedding through a single-stage adaptive strategy.
- Incorporate the concept of replica for industrial-grade controllers, enabling the representation of physical and operational constraints associated with real RAS implementations.
- Integration of a data-driven evaluation stage within the replica framework, aimed at assessing the dynamic impact of load shedding actions on critical system variables, particularly electromechanical oscillation modes.
- Validate the proposed methodology under realistic operating conditions through hardware-in-the-loop simulations using industrial-grade controllers and communication protocols.

Hypothesis

This thesis hypothesizes that conventional load-shedding schemes, due to their reliance on fixed parameters and offline studies, tend to produce insufficient or excessive remedial actions under modern operating conditions. An adaptive model-based RAS supported by digital twins, replicas, and a data-driven dynamic assessment can address these limitations by adjusting load-shedding actions according to real-time operating conditions and by validating their dynamic impact prior to execution, resulting in improved post-contingency performance in voltage and frequency stability problems, in terms of steady-state values, frequency nadir, and load-shedding amount, while remaining implementable on industrial-grade controllers.

General structure of the thesis

Chapter 1: State-of-the-Art of Remedial Action Schemes

This chapter provides a conceptual description of remedial action schemes, along with a comprehensive review of the different RAS approaches reported in the literature. A comparative analysis is conducted, focusing on the operational parameters targeted for enhanced adaptability.

Chapter 2: Next-Generation Remedial Action Schemes for Modern Power Grids

This chapter describes the main challenges in the design of remedial action schemes for modern power systems. It also defines the concepts of digital twin and replica, highlighting their importance in the development of next-generation RAS. Furthermore, the role of hardware-in-the-loop testing is emphasized as a critical step for evaluating remedial action schemes prior to field deployment.

Chapter 3: Model-Based Digital Twin for a Voltage Stability–Oriented Remedial Action Scheme

This chapter addresses the voltage stability problem and presents the proposed two-stage operational methodology, along with the theoretical foundations of the remedial action scheme, explicitly detailing both its steady-state in the digital twin and dynamic stages. It also describes the hardware-in-the-loop validation platform used for implementation. Finally, the results of the proposed methodology are presented, including the validation of each stage and a comparative performance assessment against a conventional RAS.

Chapter 4: Data-Driven Digital Twin and Replica for a Frequency Stability-Oriented Remedial Action Scheme

This chapter addresses the frequency stability problem and presents the proposed single-stage operational methodology, together with the theoretical foundations of the remedial action scheme. It describes the model used within the digital twin, the data-driven stage for dynamic performance evaluation, and the stage based on the replica concept. The hardware-in-the-loop simulation platform used to validate the proposed methodology is also detailed. Finally, multiple case studies are presented, including direct comparisons with a conventional RAS and a comprehensive evaluation of the proposed scheme under parametric variations.

1

State-of-the-Art of Remedial Action Schemes

Power systems are extensive, complex, and geographically widespread infrastructures that transfer large amounts of energy from diverse generation technologies to residential, industrial, commercial, and service consumers. Traditionally, control centers have sought to ensure a reliable, secure, efficient, and continuous electricity supply under both normal operating conditions and power system disturbances.

Security standards guide the planning and operation of power systems to preserve stability even after component outages. This requirement, commonly known as the $N - 1$ criterion, has historically been a fundamental pillar of secure power system planning and operation [1]. In recent years, several factors have significantly increased the complexity of satisfying these operational objectives, including sustained demand growth, limited transmission expansion, and the increasing penetration of renewable energy sources with dynamic characteristics that differ from those of conventional synchronous generation. In many power systems, electricity demand has exceeded initial projections, placing considerable stress on existing infrastructure without a proportional expansion of the transmission grid.

The limited deployment of new transmission corridors has led to persistent congestion and bottlenecks in critical network links, reducing operational margins and complicating compliance with the $N - 1$ criterion. As a result, control centers often adopt conservative operational strategies by avoiding highly stressed operating points that, although potentially sustainable under normal conditions, could become unacceptable after a predefined contingency.

Although this practice is necessary for security reasons, it may lead to underutilization of the transmission capacity of the power system. Moreover, under high-demand conditions, particularly during peak hours, severe grid congestion can impose significant constraints on dispatch and operational alternatives. In some cases, this can place the system near its security limits, increasing the complexity of control-center tasks and raising the risk of incidents that could disrupt power system stability and lead to service interruptions or blackouts.

To address these challenges and prevent the propagation of large-scale disturbances, power systems employ remedial action schemes, which automatically and rapidly identify and respond to predefined critical conditions. RAS play an essential role in preserving power system stability during critical periods by implementing targeted corrective measures. These actions may include network

reconfiguration, load shedding, or generation tripping.

1.1 Remedial Action Schemes

For several decades, remedial action schemes have been widely used to preserve security and enhance the resilience of power grids under highly stressed operating conditions. In the literature, these schemes are also commonly referred to as **Special Protection Schemes (SPS)**. The **North American Electric Reliability Corporation (NERC)**, the **Western Electricity Coordinating Council (WECC)**, and the **Federal Energy Regulatory Commission (FERC)** have adopted the term RAS as a unified term. According to the WECC, a RAS is “a scheme designed to detect predetermined system conditions and automatically take corrective actions that may include, but are not limited to, adjusting or tripping generation (MW and Mvar), tripping load, or reconfiguring the system(s)” [2].

It is essential to distinguish between the operational and protection objectives of conventional protection schemes and RAS. Traditional protection schemes mainly focus on safeguarding power system equipment against faults by selectively and coordinately disconnecting faulted components from the rest of the system. These components may include transmission lines, transformers, generators, feeders, and buses. To achieve this, conventional protection schemes incorporate a variety of protection functions that detect and clear different electrical faults. The fundamental principles underlying these schemes and their operation are rooted in the classical theories of power system protection.

Conversely, RAS are focused on an operational goal. Their purpose is to maintain critical power system variables within acceptable thresholds during contingency conditions, preventing the uncontrolled disconnection of power system elements that could lead to large-scale blackouts. Therefore, RAS act on elements already connected to the system by applying predefined corrective actions with the objective of preserving overall power system stability. Since contingencies can produce different dynamic behaviors, remedial actions must be selected accordingly. In this context, RAS incorporate a range of corrective actions designed to address specific operational conditions. The following subsection describes the most common remedial actions used in RAS.

Remedial action schemes can implement a wide range of remedial actions, depending on the operating conditions of the power grid. The most common actions include [3]:

- Automatic generation shedding.
- Automatic load shedding.
- Changes in the power system topology.
- **Out of step tripping (OSS)**.
- Controlled separation of power grid areas.
- Automatic switching of capacitor banks.
- Automatic switching of reactor banks.
- Setpoint changes in **Flexible AC Transmission Systems (FACTS)** devices.
- Setpoint changes in **High-Voltage Direct Current (HVDC)** systems.
- **Automatic Generation Control (AGC)** actions.
- Fast control of photovoltaic plants.
- Fast control of wind turbine plants.
- Fast control of energy storage systems.

The selection of the remedial action is directly related to the phenomenon affecting the power grid and the condition requiring mitigation. A contingency can lead to different types of power

system instability, including voltage instability, frequency instability, transient instability, and poorly damped oscillations.

The presence of multiple remedial actions and highly stressed operating scenarios does not, by itself, justify the implementation of a remedial action scheme. While the need for a RAS may be apparent, this does not guarantee that a given set of remedial actions will be effective under all operating conditions. Therefore, it is essential to first establish the need for a RAS, then define the set of actions to be implemented, and finally determine the criteria for RAS activation. This process requires careful and structured design, aligned with the specific phenomenon to be mitigated.

In this context, it is essential to systematically analyze how the need for a RAS is identified in a power grid, as well as how its structure, design criteria, and operational methodology are defined. These aspects are addressed in the following section.

1.2 Identification and Design of RAS

Control centers perform power system planning studies to analyze the future evolution of the grid. These studies consider load demand trends, new generation integration, and their impact on power system security and stability, using static and dynamic frameworks as needed. These evaluations reveal potential future operational and security challenges for the system. Many of these challenges can be alleviated through infrastructure expansion, for example by constructing new transmission lines to enhance network robustness or by installing reactive power compensation devices, including FACTS, to increase power transfer capability. However, such measures generally entail long implementation lead times and substantial capital expenditures. By contrast, RAS constitute a flexible solution with comparatively short deployment horizons, as they can be authorized, engineered, and commissioned within significantly reduced time frames. In this scenario, RAS act as a provisional support system, preserving requisite power system security and performance while enduring the development and integration of planned infrastructural upgrades.

In weak power systems with frequent stability problems, the integration of large synchronous generating units may require the implementation of remedial action schemes as a condition for interconnection to the transmission network [4]. This requirement is driven by the need to mitigate the significant impact that the sudden or uncoordinated disconnection of such units may have on system security and stability. In such systems, the loss of a large generating unit can lead to severe frequency or voltage deviations, potentially triggering cascading events. This highlights that RAS design must consider both system-level and asset-level requirements.

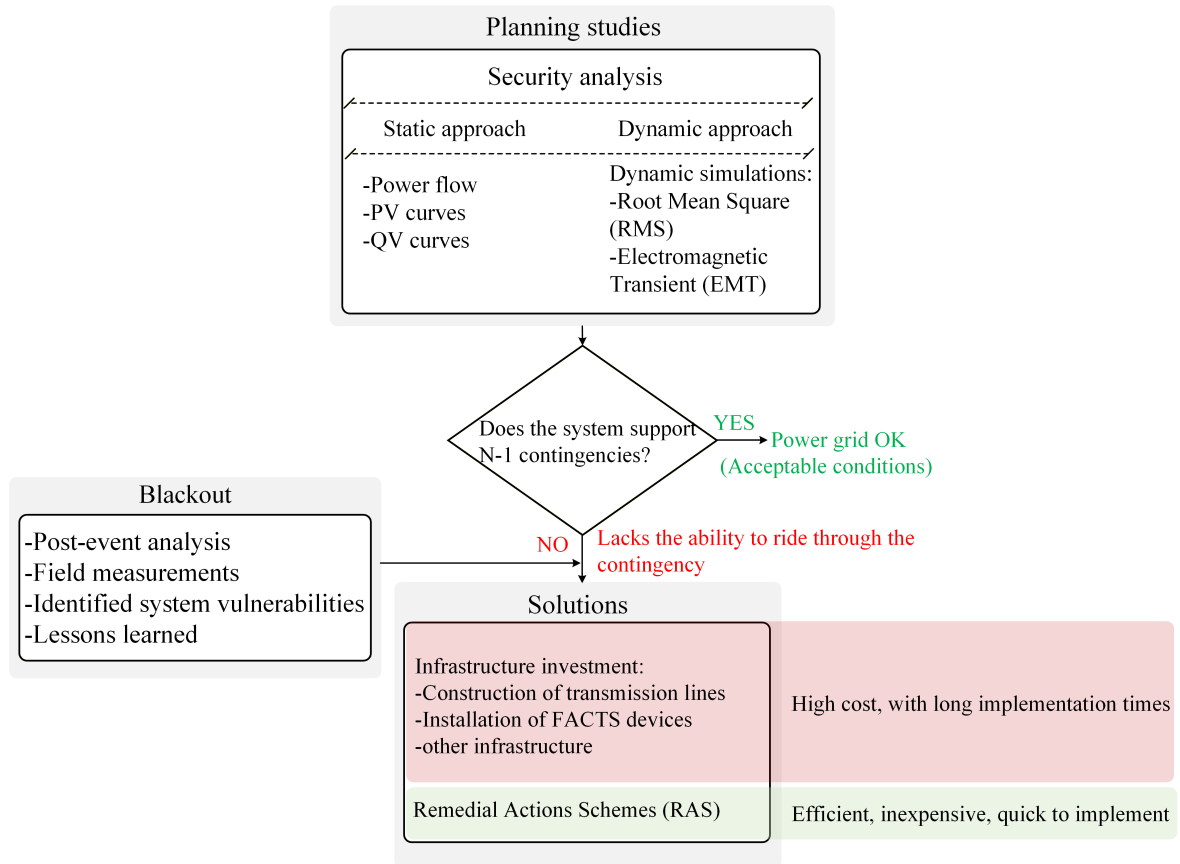
Conceptually, the need for a remedial action scheme should be identified a priori. However, in practice, the dynamic behavior of a power grid is inherently difficult to predict due to its highly complex and nonlinear nature, and the number of possible operating conditions and contingency combinations is considerably large, which makes it infeasible to evaluate all scenarios beforehand. Consequently, a significant proportion of RAS currently employed in real-world power systems have been implemented reactively, following severe grid disturbances, including large-scale blackouts associated with pronounced economic losses and adverse social consequences [5]. After such events, post-event analyses based on field measurements are conducted to identify system vulnerabilities and extract lessons learned. In many cases, these analyses reveal the need to implement RAS as corrective measure. Table 1.1 presents examples of RAS developed after major disturbances. Additionally, Figure 1.1 illustrates the key aspects considered when identifying the need for a RAS.

After a RAS is approved, design begins, defining its operating parameters. Conventionally, RAS are designed through a set of offline studies, where a wide range of credible contingencies is evaluated under different operating conditions of the power system. These studies rely on detailed models

Table 1.1: Representative Remedial Action Schemes implemented after major power system disturbances

Ref	Country/Event	Power system problems	Implemented RAS
[4]	Panamá Blackout	Voltage collapse	Load shedding
[6]	Georgia Blackout	Overloads	Load shedding
[7]	México-Centro América Isolate	Undamped Oscillations	Controlled separation
[8]	México Blackout	Transient stability	Generation shedding
[9]	Uruguay-Blackout	Voltage collapse	Load shedding
[10]	Peru Blackout	Transient stability	Load shedding
[11]	Colombia-Ecuador Blackout	Undamped Oscillations	Controlled separation
[12]	Turkey-losing interconnection	Overloads	Load shedding
[13]	Belgian-losing interconnection	Overloads	Shut down offshore and HVDC

that represent system behavior with high fidelity.

**Figure 1.1:** Process for identifying the need for Remedial Action Schemes based on planning studies and post-event analysis.

Steady-state analyses are commonly employed to assess operating conditions related to transmission line congestion, voltage profiles, reactive power margins, system transfer capability, and compliance with generator operating limits. However, since these studies only capture the static behavior of the system, they must be complemented with dynamic studies. To this end, different dynamic models are available, and their selection depends on the phenomena and system dynamics of interest. **Root Mean Square (RMS)** models are typically used to analyze low-frequency dynamics associated with the electromechanical behavior of synchronous machines [14].

In contrast, **Electromagnetic Transients (EMT)** models provide a higher level of detail and a wider bandwidth, enabling the capture of fast dynamics and complex phenomena arising from the

interaction among the network, power-electronics-based resources, and other elements of the power system. As a result, EMT models allow for a more detailed representation of phenomena such as voltage oscillations, harmonic stability, and sub-synchronous oscillations [15].

This modeling framework, which integrates steady-state, RMS, and EMT analyses, provides the foundation for the systematic design of RAS, supporting the definition of appropriate control actions and the establishment of activation criteria consistent with the underlying system dynamics and operating conditions.

Based on offline studies, the information required to identify and define the key operating parameters of the RAS is obtained. These parameters determine the logic of operation and its response to specific contingencies. Among the most commonly defined parameters are the following [16]:

1. **Arming parameters:** Define the operating conditions of the power grid under which the RAS is enabled and prepared for possible activation. These parameters are established based on measured variables that allow the identification of operating points, or ranges of operating conditions, associated with increased system risk. Arming parameters are commonly implemented through predefined thresholds on variables representative of the power grid state, most often power flows on critical grid elements.
2. **Start parameter:** Refers to the parameter or measured variable that indicates the occurrence of a predefined critical contingency. When this condition is detected and the RAS is already armed, the start parameter initializes the corresponding remedial action.
3. **Control action:** Represents the remedial action associated with a critical contingency. The control action comprises a set of operational parameters, which depend on the type of remedial action implemented. The parameters can include, but are not limited to, the level of load or generation shedding, activation thresholds determined by electrical variables, where the action is implemented, and setpoint adjustments for various system devices.
4. **Required response time:** Refers to the time required for the remedial action to be executed in order to produce an effect on the power grid. This time interval spans from the detection of the contingency to the actuation of the breakers associated with the remedial action.

Based on the operating parameters defined through offline studies, the operating methodology of the RAS can be established. In this context, the following methodologies can be identified [17]:

- **Event-based:** This approach represents the conventional operating methodology, which relies on a predefined contingency table derived from prior offline analyzes. Within this framework, each anticipated event is mapped to a corresponding remedial action. Upon detection of a contingency, the RAS is triggered and executed immediately. Event-based schemes are thus characterized by their rapid response capabilities and their predominant reliance on pre-contingency system measurements for decision-making.
- **Response-based:** This methodology also relies on predefined remedial actions for anticipated events. However, certain operating parameters are adjusted based on the severity of the dynamic response of the power grid following the contingency. This approach requires additional dynamic measurements, such as the **Rate of Change of Frequency (ROCOF)**, **Rate of Change of Voltage (ROCOV)**, or other response indicators. Response-based schemes are generally characterized by slower response times, as they require observing and evaluating the system behavior during the contingency before executing the remedial action.

The selection of the RAS operating methodology is directly related to the type of phenomenon to be mitigated in the power system. Slow-dynamic phenomena, such as overloads, typically evolve over time frames on the order of seconds, which allows the use of response-based methodologies

[18]. In contrast, phenomena characterized by fast dynamics, such as voltage collapse, may evolve over much shorter time scales, requiring the execution of immediate remedial actions and, therefore, the implementation of event-based schemes [19]. Figure 1.2 illustrate a general framework for remedial action scheme design and operation.

Although these methodologies have been widely used for many years, their design parameters are only valid within the range of operating conditions for which they were evaluated. Consequently, if system conditions change significantly, or if a considerable time has elapsed since the last design process, the scheme must be redesigned. In such cases, offline studies must be repeated, and the operating parameters must be updated [20].

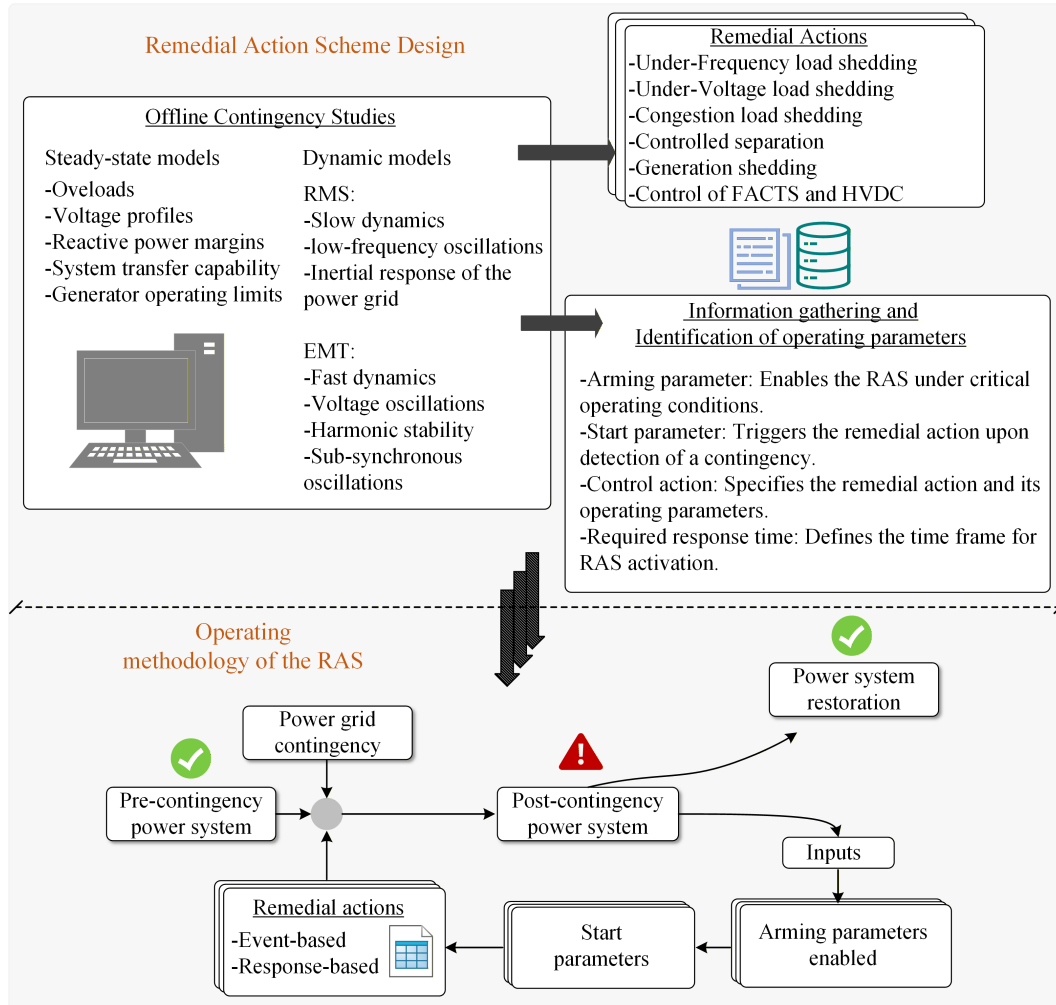


Figure 1.2: General framework for Remedial Action Scheme design and operation.

These limitations highlight the need for more adaptive and robust RAS design methodologies. In particular, there is a need for approaches capable of accounting for changing operating conditions and evolving system dynamics. This motivates the development of advanced frameworks that enable a more systematic and flexible design of RAS, ensuring adequate system performance across a wide range of scenarios.

Additionally, the design of a RAS must account for its interaction with other protection and control schemes operating in the power system. The defined remedial actions should be evaluated to ensure they do not trigger unintended activations of other schemes or introduce adverse effects on overall system stability and operation. In this regard, the RAS should be designed to coexist and

coordinate effectively with existing schemes, ensuring selective and coherent operation.

Among the RAS widely implemented in power systems are **Under-Voltage Load Shedding (UVLS)** and **Under-Frequency Load Shedding (UFLS)** schemes, which play a fundamental role under critical operating conditions [21]. The following section describes their conventional implementation structures and the main approaches reported in the literature.

1.3 UVLS and UFLS Schemes

UVLS and UFLS schemes are among the most widely deployed remedial actions in power grids, particularly for mitigating severe voltage and frequency stability problems [22]. This section first describes the conventional operating methodology of UVLS and UFLS schemes, including their typical operating parameters. Subsequently, a review of adaptive UVLS and UFLS approaches reported in the literature is presented.

Conventional Operating Methodology

The implementation of UVLS and UFLS schemes mitigates severe voltage and frequency instability by enabling the controlled shedding of predefined load sections within the power system. Although both schemes address different phenomena, they share similar operational methodologies and a common structure based on predefined operating parameters.

In UVLS schemes, when a severe contingency leads to voltage levels dropping below predefined thresholds, a predetermined amount of load is automatically shed to restore voltages to acceptable levels. In the literature, this type of scheme is commonly classified as rule-based, where the operating methodology is defined through rules of the form [23]:

$$V \leq V^{\text{th}} \text{ for } \tau \Rightarrow \Delta P_{\text{Load}}$$

In this type of methodology, the most relevant operating parameters include:

1. Number of rules
2. Voltage thresholds (V^{th})
3. Load shedding delay (τ) [s]
4. Amount of load to be shed (ΔP_{Load}) [MW]
5. Location of load shedding

In UFLS schemes, a generation-load imbalance resulting from the loss of large generating units can lead to a rapid frequency fall [24]. In response, predefined load blocks are disconnected to counteract the frequency drop. These schemes are typically structured in multiple stages, each associated with predefined frequency thresholds and load-shedding amounts. When the system frequency crosses an initial threshold, a corresponding portion of load assigned to that stage is disconnected. If the frequency continues to decrease, subsequent thresholds are sequentially activated, and the associated load percentages are shed. This process continues until the system frequency is restored to acceptable values or all UFLS stages have been executed. Accordingly, under the conventional UFLS operating methodology, the following operating parameters can be identified [25]:

1. Total amount of load shedding
2. Number of stages
3. Frequency thresholds
4. Amount of load shedding in each stage

5. Location of load shedding

Although UVLS and UFLS schemes have different control objectives, they share several operating parameters, since the remedial action is essentially the same, albeit applied for different purposes. However, the start parameters of these schemes differ: while UFLS schemes are primarily driven by frequency measurements, UVLS schemes rely on voltage-based measurements.

For many years, these schemes have been widely adopted in practice due to their robustness, simplicity, and ease of implementation. Although they have proven effective under certain operating conditions, conventional UVLS and UFLS schemes assume that local system measurements are sufficient to characterize the operational state of the power system. Moreover, their operating parameters are defined a priori through offline studies and tuned for a limited range of operating conditions. Consequently, as the power system evolves and operating conditions change due to topology modifications and variations in generation dispatch, the static nature of these parameters may affect the effectiveness and selectivity of the schemes. This has motivated significant research efforts aimed at developing new operating methodologies that provide enhanced adaptability and robustness, leading to alternative approaches reported in the literature.

Review of UVLS-UFLS Approaches in the Literature

This subsection reviews the main UVLS and UFLS approaches reported in the literature, with emphasis on their operating methodologies and the selection and design of key operating parameters. This review is motivated by the need to identify the limitations of conventional approaches and to highlight the opportunities for developing more adaptive RAS methodologies. Rather than providing a individual paper review, the focus is on identifying common trends, methodological classifications, the methods used to define operating parameters, and the evolution of these schemes over time.

In the case of UVLS schemes, the literature reveals a broad classification of operating methodologies, which can be summarized as follows [26]:

- Centralized
- Decentralized
- Static
- Dynamic
- Closed-loop
- Open-loop
- Decision-based
- Rule-based
- Response-based
- Event-based

Regardless of the operating methodology, the schemes reported in the literature rely on the same operating parameters as conventional UVLS schemes. While some approaches employ static parameter settings, others introduce flexibility through adaptive design strategies. Accordingly, [Figure 1.3](#) presents a general classification of UVLS schemes, highlighting both the different operating methodologies and the approaches used to design their operating parameters.

[Table 1.2](#) summarizes UVLS schemes reported in the literature, classified according to their operating methodology and operating parameters. The table presents a set of representative papers organized chronologically, showing that event-based and rule-based methodologies remain the most predominant approaches. These methods have been proposed since the early contributions and

continue to be widely adopted to date. However, more recent papers have explored closed-loop methodologies in which operating parameters are adjusted based on dynamic power grid measurements.

In terms of adaptability, the parameters that typically offer the greatest flexibility are the amount of load shedding and its location. A variety of techniques have been proposed to enable adaptive load shedding, including linear programming, data-driven methods, optimization techniques, steady-state models, and stability indices. These methodologies enable the flexible modification of remedial measures in accordance with system operational conditions. The identification of voltage-collapse zones through the use of sensitivity, distance, or stability indicators facilitates the implementation of targeted remedial measures. However, numerous methodologies continue to depend on predefined voltage thresholds and constant disconnection delays. This finding suggests that, despite the increased adaptability of certain operating parameters, conventional UVLS schemes remain contingent on static settings, thereby constraining their comprehensive adaptability.

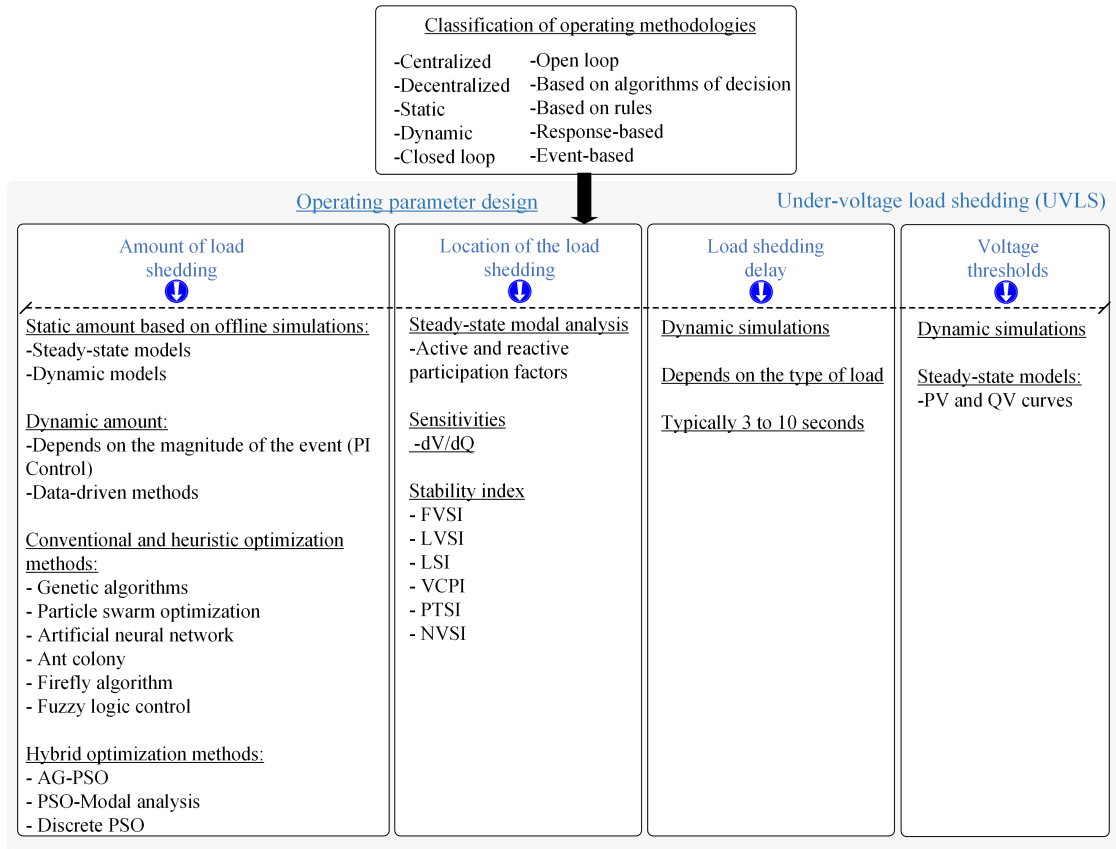


Figure 1.3: General classification of UVLS schemes and operating parameter design methods.

Although rule-based methodologies often rely on static parameters, there is a clear trend toward preserving this operational structure while enhancing adaptability. Indices and complementary methods are increasingly used to incorporate real-time information about the power grid state. These observations indicate that while traditional UVLS schemes maintain a largely static framework, recent trends focus on dynamic adaptability, highlighting the opportunity for further research on fully adaptive schemes.

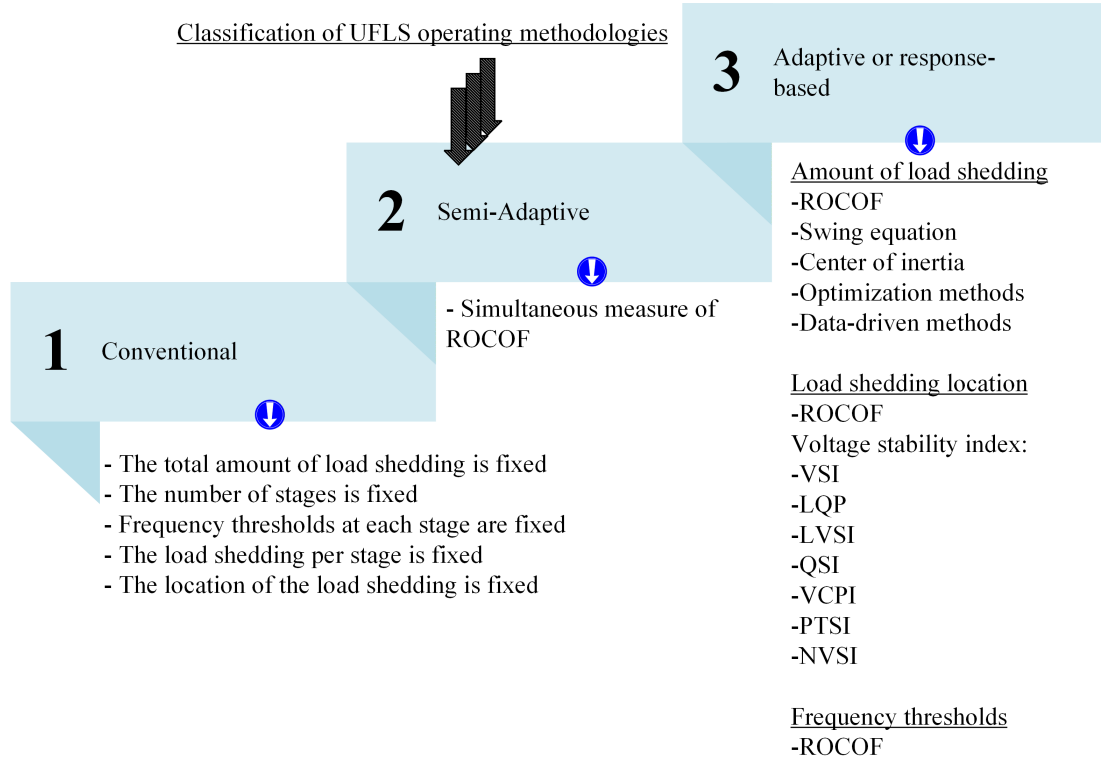
Regarding UFLS, the prevailing academic consensus categorizes operating methodologies broadly as follows [25]:

- Conventional

Table 1.2: Comparison of the characteristics of UVLS schemes reported in the literature

Year	Ref	Operating Methodology	Amount of load shedding		Location		Delay	Threshold (V_{th})
			Method	Dynamic	Method	Dynamic		
1992	[23]	Rule-based/Event-based	Offline simulations	×	Under-voltage	×	×	×
1998	[27]	Rule-based/Event-based	PV curves	×	Under-voltage	×	×	×
2000	[28]	Closed-loop	AG	✓	dV/dQ	×	×	×
2004	[29]	Rule-based/Closed-loop	PI control	✓	dV/dQ	✓	×	×
2007	[30]	Rule-based/Closed-loop	PI control	✓	dV/dQ	✓	×	×
2008	[31]	Closed-loop	Loadability margin	✓	Loadability margin	✓	×	×
2011	[32]	Rule-based/Closed-loop	PI control	✓	dV/dQ	✓	✓	×
2012	[33]	Rule-based/Closed-loop	PI control	✓	dV/dQ	✓	×	✓
2015	[34]	Rule-based/Event-based	VSM-MF-TSGA	×	dV/dQ	×	×	×
2017	[35]	Rule-based/Event-based	Linear programming	✓	Electrical distances	✓	×	×
2017	[36]	Closed-loop	Power measurements	✓	VCPI	✓	×	×
2019	[37]	Rule-based/Event-based	Predefined	×	Predefined	×	×	✓
2019	[38]	Rule-based/Event-based	Tangent vector	✓	Tangent vector	✓	×	×
2020	[39]	Rule-based/Closed-loop	Predefined	✓	Electrical distances	✓	×	×
2020	[40]	Event-based	PV curves	✓	Modal analysis	✓	×	×
2020	[41]	Rule-based/Event-based	Predefined	×	Noncritical load	×	✓	×
2021	[42]	Closed-loop	Data-driven (WKELM)	✓	TVSI	✓	×	×
2022	[43]	Event-based	Index DVPS	×	Index DVPS	×	×	×
2023	[44]	Closed-loop	ANN & PSO	✓	PSO	✓	×	×
2023	[45]	Closed-loop	Data-driven (SGP)	✓	TVSI	×	×	×
2024	[46]	Closed-loop	ICSBEP-PSO	✓	FVSI	✓	×	×
2025	[47]	Closed-loop	DRL-D2DQN	✓	TVRC	✓	×	×
2025	[48]	Closed-loop	AC-OLS+NN	✓	AC-OLS	✓	×	×
2026	[49]	Closed-loop	DRL + Cloud-Edge	✓	Regional Agents	✓	×	×
2026	[50]	Closed-loop	PSO-ANN	✓	VSM	✓	×	✓

- Semi-adaptive
- Adaptive



ding.

In contrast, semi-adaptive approaches partially adjust their operating parameters by incorporating auxiliary measurements, such as the ROCOF. Fully adaptive UFLS schemes are designed to dynamically adjust load shedding parameters, including the amount, location, and frequency thresholds, based on real-time system data.

Similarly to UVLS frameworks, [Table 1.3](#) summarizes key UFLS studies, ordered chronologically, from which a distinct preference for adaptive operational models can be observed.

Regarding adaptability, the operating parameters most frequently considered for enhancement are the amount of load shedding and its location, similar to what has been reported for UVLS schemes. These parameters are traditionally designed using methods based on center of inertia and ROCOF measurements, which are closely related to the classical swing equation model. More recent approaches based on optimization techniques and data-driven methods have also been explored for the design of load shedding actions. In particular, the determination of load shedding locations often relies on auxiliary variables such as ROCOF to identify electrically close areas. In addition, some approaches use voltage stability indices, recognizing the interaction between frequency and voltage dynamic phenomena in power systems.

Table 1.3: Characteristics of UFLS schemes reported in the literature

Year	Ref	Operating Methodology	Amount of load shedding		Location		Threshold (f_{th})
			Method	Dynamic	Method	Dynamic	Dynamic
1968	[51]	Conventional	Offline studies	×	Offline studies	×	×
1988	[52]	Conventional	Offline studies	×	Offline studies	×	×
1992	[53]	Semi-adaptive	ROCOF	✓	Offline studies	×	×
2006	[54]	Adaptive	Swing equation model	✓	ROCOF	✓	×
2008	[55]	Adaptive	Swing equation model	✓	ROCOF	✓	✓
2009	[56]	Semi-adaptive	ROCOF-load shedding curves	✓	ROCOF	×	×
2015	[57]	Adaptive	Offline studies	×	Voltage dips	✓	✓
2017	[58]	Adaptive	COI	✓	ROCOF	✓	×
2018	[59]	Adaptive	Power imbalance measurement	✓	VQS	✓	✓
2018	[60]	Adaptive	Power imbalance measurement	✓	QVSI	✓	✓
2020	[61]	Adaptive	COI	✓	Lagrange multiplier	✓	×
2020	[62]	Adaptive	COI + linear programming	✓	Offline studies	×	×
2020	[63]	Conventional	Offline studies	×	Offline studies	×	×
2020	[64]	Adaptive	COI	✓	ROCOF-FVSI	✓	×
2021	[65]	Adaptive	COI	✓	VSI	✓	×
2021	[66]	Adaptive	COI + PSO-Fuzzy	✓	ROCOF	✓	×
2021	[67]	Adaptive	Data-driven (DQL)	✓	LSCI	✓	×
2022	[68]	Adaptive	Dynamic power flow analysis	✓	Voltage dips	✓	×
2022	[69]	Adaptive	Data-driven methods	✓	Not specified	×	×
2023	[70]	Conventional	MILP	×	Multi-Area SFR	×	×
2023	[71]	Adaptive	COI	✓	TEF	✓	×
2024	[72]	Adaptive	DRL-DDPG	✓	RL	✓	×
2025	[73]	Adaptive	MADDPG	✓	Spectral Clustering	✓	×
2025	[74]	Adaptive	COI-Kalman	✓	Not specified	×	×
2026	[75]	Adaptive	FREPI+Sensitivity Analysis	✓	Frequency sensitivity	✓	×
2026	[76]	Adaptive	NN + Inertia-Aware	✓	Not specified	×	×

Although schemes incorporating adaptability in frequency thresholds have also been proposed, this aspect has been addressed with less depth compared to the adaptability of the load shedding amount and location.

In general, the literature shows a clear evolution of RAS schemes, such as UVLS and UFLS, over recent years, in which adaptive methodologies have become a predominant trend. As a result, the adaptability of the operating parameters has emerged as a topic of significant interest in recent research.

1.4 Research Gap

The literature review reveals a clear trend toward the development of adaptive remedial action schemes, suggesting that they represent the natural evolution of conventional operating methodologies. Numerous adaptive strategies have been proposed over the last decade, demonstrating significant advances in algorithm design and decision-making capabilities. However, despite these developments, fully adaptive RAS have not been widely reported in real power system applications. This indicates that, while the concept of adaptive RAS has matured from a methodological perspective, a significant gap remains between their research development and their practical deployment.

The primary barrier to their adoption is not the ability to develop increasingly sophisticated adaptive algorithms, but rather the ability to demonstrate that such algorithms can operate with the level of security, reliability, and robustness required by critical infrastructures such as power systems. Consequently, system operators are naturally reluctant to adopt adaptive operating methodologies whose performance has not been validated under conditions representative of real-world operation.

Furthermore, a significant portion of the proposed methodologies assumes a level of system observability and controllability that is rarely available in practice, including complete access to system-wide measurements and unrestricted control over loads. These approaches also tend to overlook practical implementation constraints, such as the computational capabilities of industrial controllers deployed in substations, memory and processing limitations, as well as communication delays and latencies introduced by industrial communication protocols and embedded algorithm execution.

An additional limitation is that most methodologies reported in the literature are validated exclusively through offline simulations. Although such validation demonstrates the conceptual effectiveness of the proposed approaches, it does not provide sufficient evidence of their practical feasibility for deployment on industrial protection and control platforms. In highly critical applications such as RAS, where protection decisions must be executed within milliseconds and any failure may compromise power system stability, it is essential to verify that the proposed algorithms can satisfy the timing and hardware constraints imposed by real industrial devices.

Therefore, the current challenge is no longer limited to developing more sophisticated adaptive operating methodologies, but to providing a framework that enables these methodologies to be deployed safely, reliably, and in real-time within existing industrial infrastructures.

As a result, the principal research gap is not the lack of adaptive RAS methodologies, but the absence of practical frameworks that enable their secure adoption in real power systems. Bridging this gap requires architectures capable of supporting adaptive decision-making while simultaneously addressing the safety, implementation, and validation requirements demanded by industrial applications. In this context, a Digital Twin, defined as a real-time digital representation of the physical power system, and a Replica, which reproduces the behavior of the protection and control infrastructure independently of the field equipment, complemented by Hardware-in-the-Loop validation, provide a promising foundation for enabling the next generation of adaptive RAS. These technologies allow adaptive operating methodologies to be developed, verified, and validated on industrial platforms before deployment in the actual power system.

2

Next-Generation Remedial Action Schemes for Modern Power Grids

The state-of-the-art review shows that, in recent years, remedial action schemes have evolved significantly, with a clear trend toward adaptive methodologies [77]. In particular, several approaches have been proposed to adjust RAS operating parameters by incorporating auxiliary variables that provide additional information beyond conventional measurements, such as frequency, voltage, and power. However, these advances have been developed within an operating context that has evolved considerably. For decades, power systems have been dominated by synchronous machine-based generation, resulting in systems with high inertia and relatively well-known dynamics. The increasing penetration of inverter-based resources has altered this paradigm, leading to a significant reduction in system inertia and the emergence of faster and more complex dynamic phenomena [78]. As a result, modern power systems have become more vulnerable to instability scenarios.

This change in power system behavior raises important questions regarding the adequacy of traditional strategies for the operation, control, and protection of power systems, particularly in the context of RAS design. Although adaptability has been widely explored in the literature, it is not sufficient if remedial actions are triggered without a comprehensive understanding of the underlying system dynamics. Moreover, RAS have historically been designed under assumptions of high system inertia and relatively stable operating conditions, which are no longer generally valid in modern power systems [51]. These limitations highlight the need for new RAS design methodologies that can capture the evolving dynamic behavior of modern power systems.

In this context, this chapter introduces the key concepts and operating principles that enable a new generation of RAS. The proposed perspective goes beyond the mere adjustment of operating parameters and instead aims to provide these schemes with a more complete view of the system state. This enhanced situational awareness enables remedial actions to be executed in an informed and coordinated manner, consistent with the dynamic behavior of modern power systems.

2.1 The Challenges of RAS Design in Modern Power Systems

In recent decades, power systems have undergone significant evolution driven by technological advances. These advances have facilitated the integration of new generation technologies, advanced compensation devices, and components with increasingly complex dynamic characteristics. How-

ever, the operational complexity of modern power systems has also increased.

In this context, conventional approaches to system operation, monitoring, and protection have revealed clear limitations. In particular, remedial action schemes designed with static operating parameters (amount and location of load shedding and thresholds) struggle to adapt to the highly variable and uncertain conditions of modern power systems, rendering many conventional RAS design assumptions insufficient to ensure reliable and effective performance [79].

Impact of High Renewable Penetration on RAS Design

During the design stage of RAS, at least under conventional methodologies, several assumptions are adopted regarding the expected behavior of the power system. Historically, these schemes were conceived when the system was dominated by synchronous machine generation, which allowed the assumption of a large and relatively constant system inertia across different operating conditions, leading to a robust and predictable dynamic response over a wide range of operating points. [80]. Under these conditions, it was also assumed that the spinning reserve associated with this type of generation would remain available. In general, the inherent dynamic response of synchronous machines was considered to provide significant support to the power system, effectively contributing to the mitigation of deviations caused by contingency events.

As a consequence of these assumptions, offline studies exhibited similar dynamic responses for contingencies of comparable severity. This led to the development of conservative RAS operating methodologies, in which the different stages of scheme activation, such as those associated with under-frequency or under-voltage conditions, were defined to cover groups of contingencies with similar characteristics and severity levels [51].

However, with the large-scale integration of power electronics-based generation, this paradigm is significantly affected, that is, when the power system exhibits high levels of renewable energy penetration, displacing synchronous machine generation, the assumptions traditionally employed in the design of RAS no longer hold [81, 82]. In particular, under these scenarios, a reduction in the equivalent system inertia is observed, along with significant temporal variations associated with changes in generation dispatch. Additionally, this type of generation does not provide spinning reserve; therefore, the total spinning reserve of the power system is reduced, limiting the available support during contingency events [83]. Furthermore, the interaction between power electronics-based generation and the electrical network has given rise to more complex and highly nonlinear dynamic phenomena, such as sub-synchronous oscillations, which further complicate the prediction of the system dynamic behavior.

In conclusion, maintaining traditional RAS design assumptions under these new operating scenarios may result in unnecessary or overly conservative remedial actions, adversely affecting both the efficiency and selectivity of the schemes. Figure 2.1 summarizes the key differences between conventional and power electronics-dominated power systems.

Offline-Based Design and Static RAS Operating Parameters

Typically, studies used for the design of RAS focus on the analysis of a limited set of credible contingencies, particularly those identified as critical for the power system. Evaluating the full range of possible contingencies is impractical from both computational and operational perspectives. Given the wide range of operating conditions that a power system may experience, these studies are usually conducted under a set of representative scenarios. These scenarios include low, medium, and high demand conditions, as well as different periods of the year, during which generation dispatch is significantly influenced by seasonal factors [84].

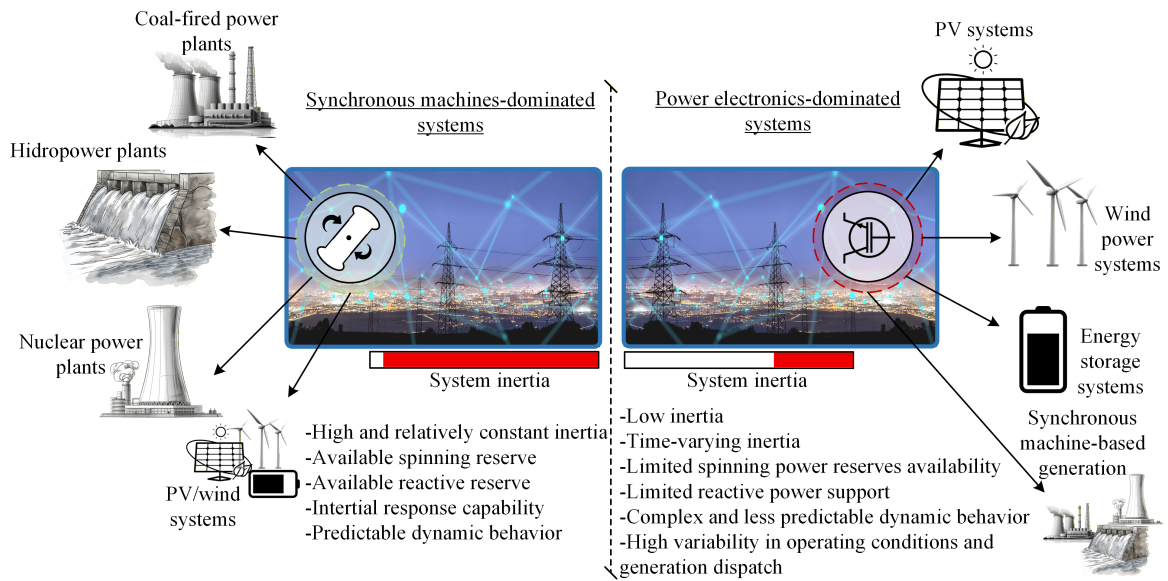


Figure 2.1: Comparison between synchronous machine-dominated and power electronics-dominated power systems, highlighting their main dynamic characteristics and implications for system inertia and stability.

Based on these scenarios, the main RAS operating parameters are defined. These parameters include the amount and location of load shedding, the disconnection stages, and the activation thresholds [2]. However, the operating conditions considered in these studies correspond to projected demand and generation levels estimated for the time horizon in which the RAS is expected to be commissioned. This represents a significant limitation in offline design methodologies, as they implicitly assume that the defined parameters will remain adequate as long as the power system operates within the ranges considered during the design stage. Once the RAS is placed in service, there is no guarantee that these static parameters will continue to be sufficient to maintain acceptable system performance during contingency events, even months or years later.

This limitation is especially pertinent in modern power systems, which demonstrate high operational variability and frequently deviate from the scenarios evaluated offline. In these conditions, design methodologies based on static operating parameters render RAS inherently rigid, reducing their effectiveness and increasing their dependence on periodic manual updates by control centers.

Coexistence of Multiple RAS in Modern Power Systems

Traditionally, RAS design has been limited to defining the remedial actions associated exclusively with the scheme under study. However, in modern power systems, characterized by the coexistence of multiple issues and dynamic phenomena, a poorly designed remedial action may unintentionally trigger the activation of other RAS by exciting the electrical variables monitored by these schemes. This situation has highlighted the need, during RAS design, to explicitly consider and model other schemes installed in the power system, with the objective of achieving adequate coordination among them [85]. Otherwise, a lack of coordination may lead to unintended cascading disconnections, worsening overall system conditions.

As previously mentioned, multiple RAS with different control objectives can coexist within a power system. In particular, for load shedding schemes, it is common for each RAS to have independently assigned load circuits. The purpose of this allocation is to ensure that each scheme has access to sufficient load to shed to mitigate the contingencies for which it was designed. However, since the amount of load shedding is typically predefined and static, the remedial action may prove

insufficient under certain operating conditions. In this context, the coexistence of multiple RAS in modern power systems highlights the need for these schemes to be able to share load resources among themselves, provided that the event affecting the system does not simultaneously require the activation of the same schemes.

The challenges imposed by modern power systems on the design of remedial action schemes highlight the need for a paradigm shift in the design and operation methodologies of RAS. In this context, advances in measurement and monitoring technologies enable access to a richer set of system information, which motivates the development of RAS with enhanced situational awareness and better-informed remedial decisions [86]. From this perspective, incorporating concepts such as digital twins and system replicas emerges as a natural evolution toward the next generation of RAS.

2.2 Digital Twin and Replica Concepts and Their Role in the Next Generation of RAS

In modern power systems, the implementation of remedial action schemes requires continuous updates of the system state through highly accurate virtual representations. These representations must be capable of reflecting system behavior in real time. This capability is essential for evaluating emerging operating conditions and anticipating the impact of remedial actions prior to their execution.

In this context, this thesis introduces the concepts of digital twins and replicas as key enablers to support the design and operation of RAS in modern power systems.

Digital Twin

The concept of a **Digital Twin (DT)** was originally developed in the aerospace and manufacturing sectors as a framework for high-fidelity modeling, simulation, and lifecycle management of complex engineering systems [87]. In recent years, this concept has been adopted across a wide range of application areas, leading to different interpretations and approaches. As a result, the definition of a digital twin often depends on the context in which it is used, and a unified and universally accepted definition has not yet been established. In this thesis, the definition proposed by the IEEE Task Force is adopted, specifically oriented toward large-scale power grids. According to this definition, digital twins are defined as *a digital model—analytical, data-driven, or a combination of both—of a physical system that spans its lifecycle, in which the digital states are updated at an appropriate rate through historical, real-time, or forecasted measurements from the physical system* [88].

Digital twins should not be interpreted as isolated virtual models of the physical system. For the digital twin concept to be fulfilled, regardless of the type of model employed, it must be continuously fed by measurements from the real system. In this context, the nature of a digital twin is not determined solely by the underlying model, but by the mechanisms through which information from the physical system is integrated, synchronized, updated, and exploited. Based on this interaction between the virtual model and system measurements, digital twins can be classified as follows [89]:

- **Descriptive twin:** Corresponds to the most basic level of a digital twin, comprising a visual representation of the system complemented by relevant information about its structure and state, with the purpose of leveraging such data to improve system processes.
- **Informative twin:** Using data obtained from the existing physical system, the informative digital twin enhances real-time monitoring by providing key insights into the state and behavior of the system, thus supporting situational awareness and decision-making.

- **Predictive twin:** This type of digital twin uses data from the physical system, enabling the anticipation of failures at both component and system levels, thus preventing unplanned events and transforming decision-making processes.
- **Comprehensive twin:** A digital twin that integrates real-time data from the physical system with advanced computational capabilities to perform near-real-time system analysis. It enables *what-if* scenario evaluation, supports predictive analytics, and provides a holistic representation of the system state for informed decision-making and optimal system performance.
- **Transformative twin:** This type of digital twin is conceived as a comprehensive strategy for next-generation industrial facilities, based on the unified integration and management of information across all assets. By leveraging simulations and advanced computational capabilities, it enables sophisticated analytics aimed at failure anticipation, maintenance optimization, automation, and operational safety. Unlike approaches focused solely on real-time operation, the transformative digital twin extends its scope across the entire system lifecycle.

Figure 2.2 summarizes the digital twin concept, and the classification described above.

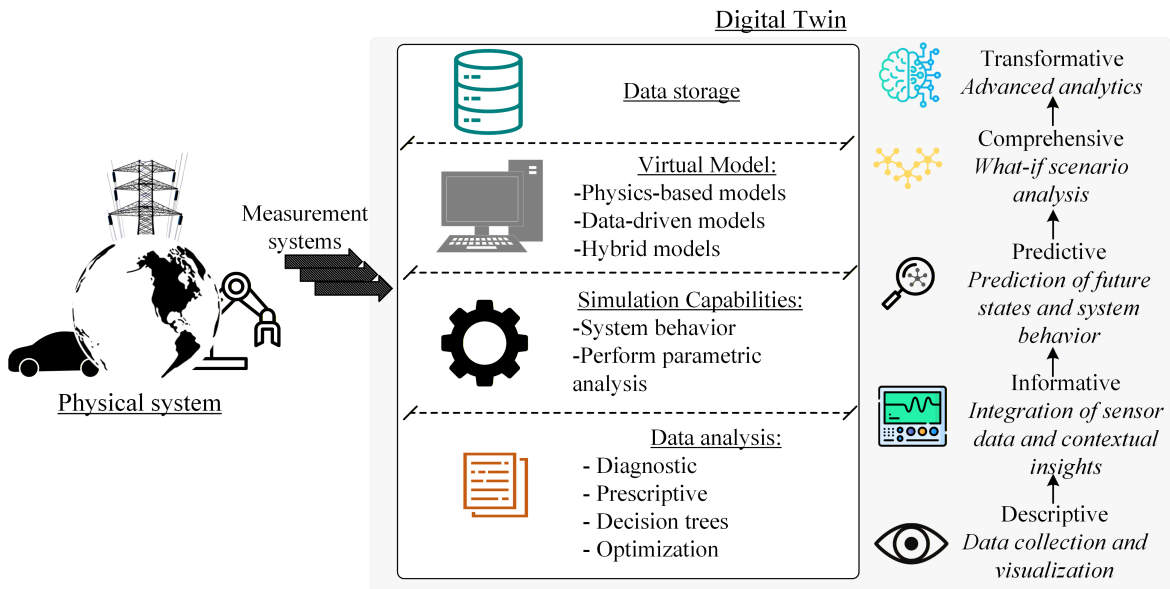


Figure 2.2: Flow diagram of the general digital twin framework and its classification.

The classification of digital twins may suggest that several applications already implemented in power systems fall within this concept. A representative example is **Supervisory Control and Data Acquisition (SCADA)** systems used in control centers, many of which rely on state estimation algorithms. This situation has led to misconceptions, where a state estimation algorithm is assumed, by itself, to constitute a digital twin. However, an isolated state estimator is merely an algorithm. When it is continuously fed with measurements from the physical system, periodically updated, and its outputs are used for monitoring and decision-making, it can be framed within the digital twin concept.

Although the digital twin concept has been widely adopted in recent years across various engineering domains, it remains an emerging paradigm in power systems due to their scale and complexity. In this context, the application of digital twins in power systems can be approached from two distinct perspectives [88, 89]. On the one hand, digital twins can be developed for specific equipment or components of the electrical network. On the other hand, digital twins can be defined at the system level.

At the equipment level, digital twins are conceived as individual representations of specific elements of the power system, such as motors, circuit breakers, transformers, inverters, wind energy systems, or energy storage systems. Their primary purpose is to support condition monitoring, predictive maintenance, health assessment, and performance enhancement [90]. From an implementation perspective, this type of digital twin is relatively less complex, as measurements are typically obtained locally and individual assets can be accessed or taken out of service during the integration process.

In contrast, system-level digital twins in large-scale power systems aim to provide a global representation of the system and the interactions among its components [91]. These digital twins support functions such as load balancing, operational planning, decision-making, and *what-if* scenario analysis, enabling the evaluation of system behavior under diverse operating conditions.

The implementation of system-level digital twins is inherently more complex due to the large volume of data, its wide geographical distribution, and the need for advanced communication infrastructures. Moreover, the associated models aim to represent the physical interactions among multiple system components, encompassing steady-state and dynamic formulations under different modeling approaches, such as RMS and EMT. This broader representation capability enables the assessment of system-wide interactions and stability phenomena that cannot be captured through isolated equipment-level models.

Table 2.1: Classification of digital twin applications in power systems

Year	Reference	Category	DT Object	Level	Objective	HIL
2020	[92]	Protection	PVECU	Equipment	Fault diagnosis and identification in photovoltaic systems	–
2023	[93]	Protection	Relay protection system	Equipment	DT-based mirror operation of relay protection for protection logic validation, parameter verification, debugging, and real-time operation	–
2024	[94]	Operation	Distribution network	System	Real-time load estimation and load shedding	–
2024	[95]	Operation	Electrothermal power cable	Equipment	Real-time thermal forecasting for proactive power flow management and thermal constraint prevention	–
2025	[96]	Planning	European power grid	System	Observability, congestion management, and renewable integration	✓
2025	[97]	Control	DERs	System	Coordinated control and dispatch for frequency regulation	✓
2025	[98]	Stability and Control	Grid-connected PV system	Equipment	Dynamic stability assessment using a real-time synchronized DT and stability margin monitoring	✓
2025	[99]	Frequency Control	HVAC loads and equivalent power system	System	Load participation in primary and secondary frequency control using adaptive DTs and online inertia estimation	✓
2026	[100]	Resilience	IEEE 30-bus system	System	Weather-related fault prediction and preventive control	–
2026	[101]	Operation and Control	Hybrid AC/DC microgrid	System	Dual optimization (OPF) and islanding response using scenario-aware DTs	–
2026	[102]	Restoration	Transmission power system	System	Post-blackout restoration acceleration, restoration plan assessment, and adaptive protection	✓

Despite this complexity, system-level digital twins are particularly valuable for RAS applications because they provide an additional evaluation layer operating in parallel with the real system [103]. Through this layer, the expected physical behavior of the power system can be assessed under prospective contingencies and remedial actions before these actions are executed in the actual grid. Although digital twin technology has experienced significant growth in recent years and has demonstrated capabilities that support protection, operation, planning, control, resilience, restoration, and stability assessment, its application to RAS remains largely unexplored. Table 2.1 summarizes representative digital twin developments in power systems, classifying them according to their application domain, digital twin level (equipment or system), primary objective, and HIL implementation. As shown, most contributions focus on conventional protection, operation, planning, and control functions, while very limited attention has been given to the development of digital twins specifi-

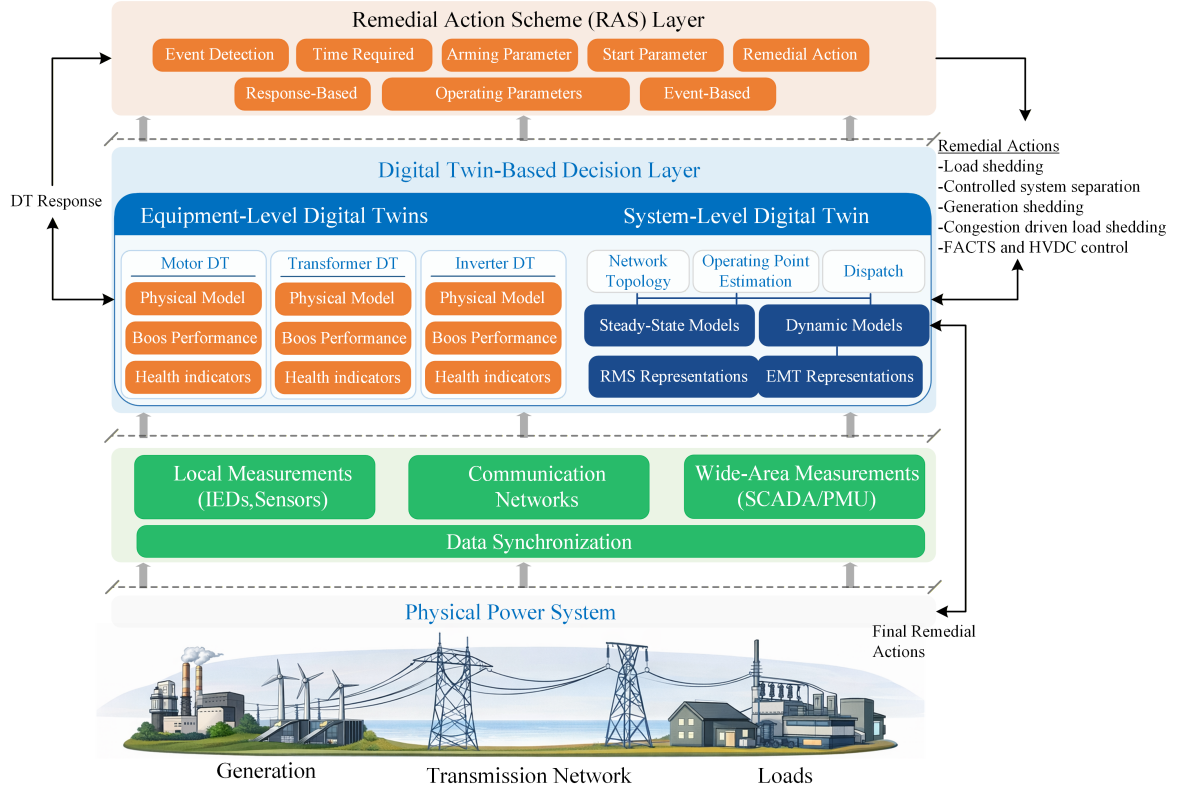


Figure 2.3: Layered architecture of equipment-level and system-level digital twins and their integration within a RAS framework.

cally intended to enhance RAS functionalities. This gap suggests that the predictive, real-time, and decision-support capabilities enabled by digital twins remain underutilized and could provide a key technological enabler for the next generation of adaptive and intelligent RAS.

Accordingly, digital twins enable RAS to evaluate operating parameters, test remedial actions, and support decision-making under changing operating conditions. However, although system-level digital twins can provide valuable information regarding the expected physical behavior of the power system, they do not necessarily reproduce the implementation-related characteristics associated with real control and protection hardware. In this context, the concept of a replica becomes particularly relevant, since it enables the integration of actual control and protection devices within a real-time simulation environment. Figure 2.3 illustrates how equipment-level and system-level digital twins can provide situational awareness and support decision-making for RAS in power systems.

Control and Protection Replica

The concept of a replica has been widely adopted in the field of FACTS devices and HVDC links installed worldwide, where it is primarily used for testing, validation, and operator training purposes [104]. In this context, a replica is typically based on an exact copy of the control hardware or protection schemes deployed in the field [105]. In modern power systems, the term replica is sometimes used interchangeably with other emerging concepts, such as digital twins. However, replicas are generally conceived as isolated representations deployed in laboratory environments and are not necessarily continuously synchronized with the physical system.

In practice, replicas are commonly implemented using **Real-Time Simulator (RTS)** based on elec-

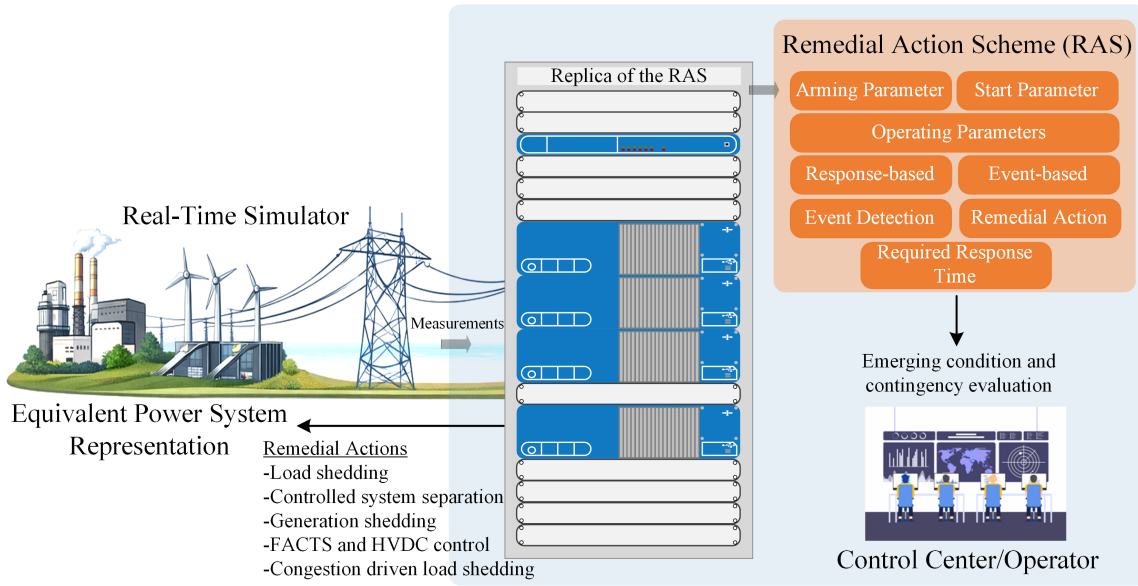


Figure 2.4: Conceptual framework of a replica-based RAS.

tromagnetic transient modeling [106]. These platforms include detailed representations of HVDC links, transmission lines, transformers, and equivalent portions of the surrounding power system. The RTS is physically interfaced with a replica of the HVDC control and protection hardware, while the main controllers remain installed in the field. When control and protection replicas are deployed in laboratory environments operated by the control center, power system operators gain a unique opportunity to perform a wide range of tests under both normal and extreme operating conditions [107]. This approach supports the verification of control and protection performance, enhances system-level understanding, and enables the early identification of potential vulnerabilities and operational limitations associated with HVDC link operation.

In this regard, replicas provide a controlled and risk-free environment to assess the behavior of remedial action schemes and their operating parameters under a wide range of operating conditions. Furthermore, incorporating a hardware replica of the RAS enhances overall reliability, since it allows the reproduction of controller-related phenomena that are difficult to capture accurately through purely model-based representations. This framework is illustrated in Figure 2.4.

Digital twin and replica concepts can enhance situational awareness and decision-making, enabling remedial actions aligned with system-wide dynamics. These capabilities are key to next-generation RAS but require rigorous validation under realistic conditions. Because these schemes are crucial for power system security, offline model-based studies alone cannot guarantee reliable field performance. Hardware-in-the-loop testing therefore provides an essential validation method, offering a controlled yet realistic environment to assess advanced RAS before deployment.

Although both digital twins and replicas represent the physical system, their purposes differ: a digital twin is a continuously updated, model- and data-based representation intended to support monitoring, prediction, and decision-making, whereas a replica is a hardware-oriented or functionally equivalent reproduction of field control and protection systems, mainly intended for testing, validation, and operator training. Table 2.2 presents a comparison of the main characteristics of digital twins and replicas.

Table 2.2: Comparison between digital twins and replicas for power system applications

Characteristic	Digital Twin	Replica
Principal purpose	Monitoring and prediction	Hardware replication and validation
Representation approach	Virtual model	Exact copy
Real controller implementation	×	✓
Behavioral representation	✓	✓
Physical system representation	✓	✓
Synchronization with physical system	✓	Not necessary
State estimation capability	✓	Limited
Operational optimization	✓	Limited
HIL testing	✓	✓
FAT/SAT validation	Limited	✓
Controller performance assessment	Limited	✓
Training applications	✓	✓
Scalability to large systems	High	Medium
Model fidelity to physical controller	Medium	Very High
Adaptive RAS validation	Limited	✓
Protection and control logic testing	Limited	✓

2.3 Hardware-in-the-Loop Assessment of RAS Enhancement

The operation of a remedial action scheme under real-world conditions depends on the coordinated interaction of multiple physical elements. These include the industrial controllers where the decision logic is executed, the scheme configuration and operating parameters, and the measurement, detection, and actuation devices. Together, these elements monitor the state of the power system, detect contingencies associated with the scheme, and execute remedial actions on different system components, such as loads, transformers, generators, and other network elements.

In practice, due to the large geographical scale of modern power systems, the physical elements that constitute a RAS are typically distributed over long distances. This condition requires synchronized measurement technologies, such as **Phasor Measurement Units (PMUs)**, as well as a robust and reliable communication infrastructure. Measurements, control signals, and operational states are exchanged through multiple communication links and advanced industrial communication protocols. This introduces additional layers of complexity and imposes stringent requirements on latency and time synchronization. As a result, the reliable field operation of a RAS requires multiple heterogeneous devices to operate in a coordinated and consistent manner.

As discussed previously, the RAS operating methodology and the selection of its operating parameters are derived from offline, model-based studies. Although this type of analysis provides fundamental information for scheme design, it also presents inherent limitations. Representing a physical system through mathematical models necessarily requires assumptions and simplifications, so that only the phenomena considered relevant to the study are captured. Some of these simplifications are introduced deliberately, under the assumption that certain phenomena have a negligible impact on the study objectives. However, other phenomena may be excluded because their relevance is underestimated, or because their effects are not yet fully known or understood during the modeling stage.

In particular, the physical devices that constitute a RAS exhibit phenomena associated with real operation, such as communication delays, non-ideal behavior, processing limitations, and implementation-specific characteristics. These effects are difficult to reproduce faithfully using purely model-based simulations. As a result, they are often omitted or underestimated during the modeling stage, which leads to the implicit assumption of ideal and perfectly coordinated behavior among all scheme components. Given the critical nature of RAS operation, such assumptions introduce a significant

gap in the assessment of actual field performance. Therefore, preserving the physical and operational characteristics of the involved elements requires incorporating the real devices themselves into the testing and validation process. For this reason, factory-level testing methodologies constitute a fundamental step in RAS validation prior to field deployment.

Before field deployment, the physical components of a RAS, together with its overall architecture, are subjected to **Factory Acceptance Test (FAT)** [108]. FAT is a structured and standardized testing process aimed at verifying the correct performance of the RAS logic and algorithms, assessing the physical and computational limitations of the industrial controllers where these logics are implemented, and validating the communication architecture and the associated communication protocols. In addition, these tests allow the evaluation of the overall RAS processing time to determine whether the response times satisfy the requirements for executing timely remedial actions on the power system. Although FAT remains an essential validation stage, it is not sufficient to reproduce the closed-loop interaction between the RAS and the power system.

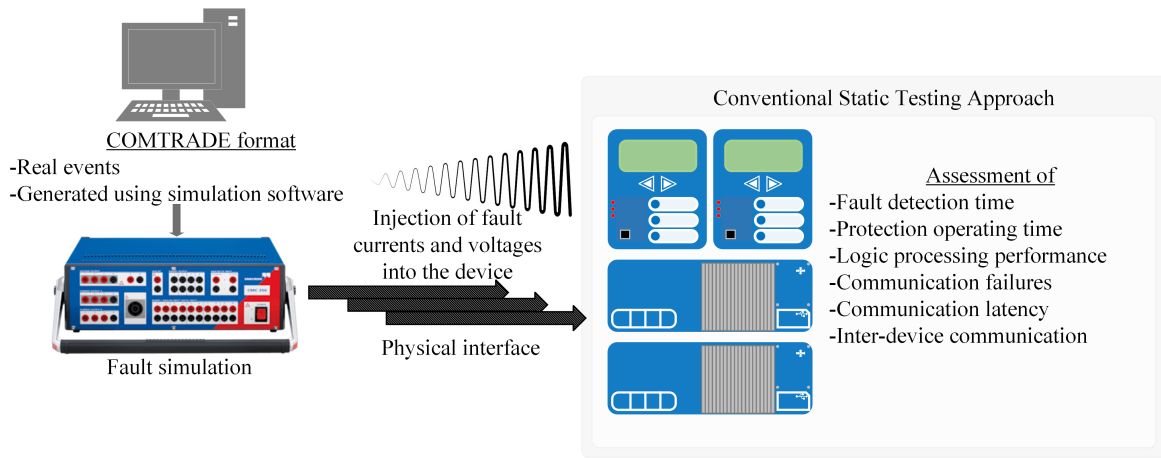


Figure 2.5: General overview of conventional FAT based on static injection test equipment.

For decades, FAT has been conducted using programmable static test sources, which inject electrical signals representative of fault conditions directly into the devices under test. Among the most widely used commercial platforms are those developed by OMICRON®, Doble Engineering®, and other vendors.

These tools operate through dedicated software that allows the definition of fault sequences, either in a fully programmed manner or through the playback of **Common Format for Transient Data Exchange (COMTRADE)** records obtained from real power system events or from simulations generated using professional power system analysis tools. Figure 2.5 presents a general diagram of this testing methodology. However, static injection testing approaches exhibit inherent limitations when applied to the complex dynamics of modern power systems. The increasing integration of power-electronics-based devices introduces fast and nonlinear dynamic phenomena that cannot be captured or reproduced using conventional static testing methodologies. Furthermore, the interaction between RAS devices and the underlying power system dynamics becomes critical and cannot be adequately assessed using this approach.

To address these limitations, hardware-in-the-loop testing has emerged as an advanced approach for the validation of protection and control schemes, particularly for novel and advanced solutions. By integrating the physical components of a RAS within a closed-loop, real-time power system simulation environment, HIL extends conventional FAT methodologies. It enables the evaluation of RAS controllers under realistic dynamic operating conditions. HIL-based FAT methodologies allow the physical connection of RAS devices to a real-time simulator, so that they operate as if they were

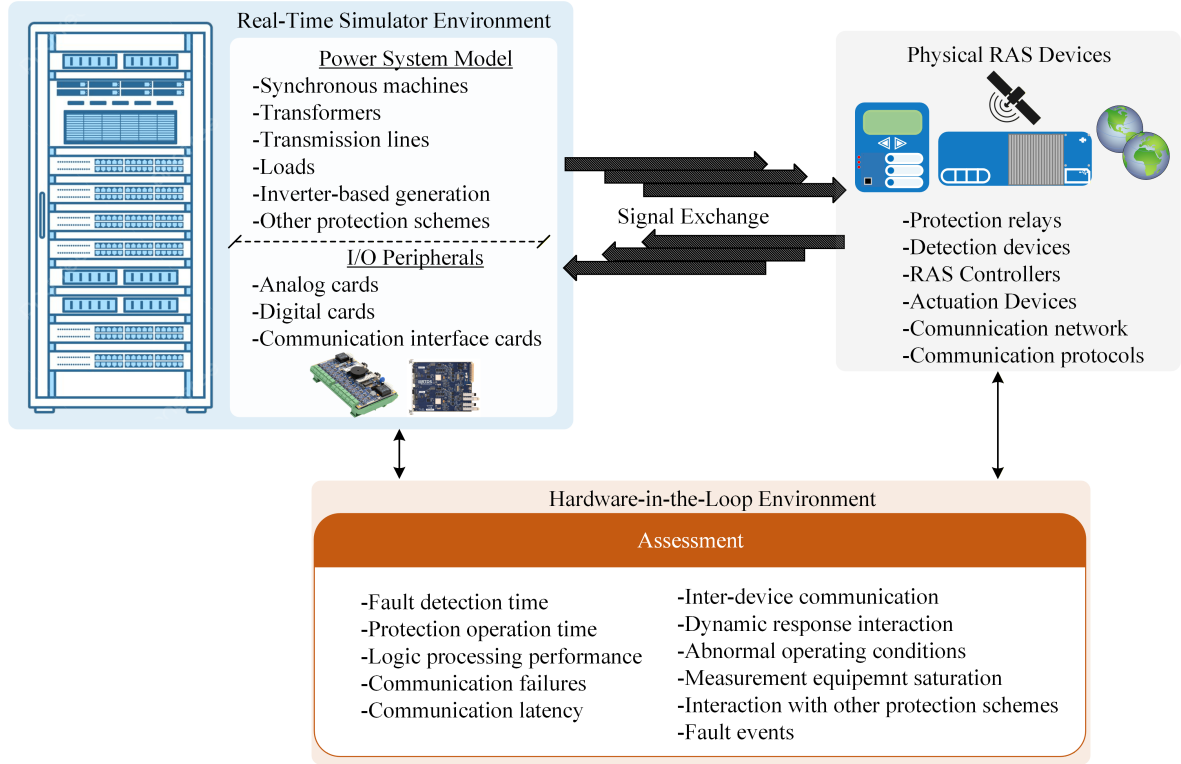


Figure 2.6: General overview of a HIL-based FAT environment.

integrated into an actual power system. This approach requires a high level of modeling fidelity within the simulator [109]. Such fidelity involves a detailed representation of the system, including synchronous machines and their associated control systems, transformers, transmission lines, loads, and power-electronics-based generation.

Table 2.3: Comparison of conventional and HIL-based FAT capabilities for RAS validation

Capability	Conventional FAT	HIL-based FAT
Relay logic verification	✓	✓
IED functional verification	✓	✓
Closed-loop testing	×	✓
Real-time power system simulation	×	✓
Assessment of system-wide interactions	×	✓
Validation of RAS operation under contingencies	Restricted	✓
Testing under realistic operating conditions	Restricted	✓
Dynamic system response evaluation	×	✓
Communication latency emulation	Restricted	✓
Communication failure testing	Restricted	✓
Wide-area protection testing	Restricted	✓
PMU-based scheme validation	Restricted	✓
Testing of multiple IEDs simultaneously	Restricted	✓
Verification of coordinated control actions	Restricted	✓
Hardware integration testing	Restricted	✓
Scalability to large power systems	Low	High
Repeatable testing scenarios	✓	✓
Automatic test execution	Restricted	✓
Interaction between protection schemes	×	✓
Implementation cost	Low	High

Figure 2.6 presents a general overview of a HIL-based FAT environment. To achieve realistic integration between the simulated power system and the physical devices, real-time simulators are equipped with a wide range of input-output peripherals. These peripherals allow electrical variables to be extracted from the model and exchanged with RAS devices through dedicated hardware interfaces. These interfaces support multiple communication protocols, ensuring interoperability with RAS devices and their proper integration within the HIL environment. This testing environment enables the explicit evaluation of device interactions and the overall behavior of the RAS under both steady-state conditions and real-time dynamic responses during critical events. In this context, both event-based and response-based RAS implementations can be analyzed. Furthermore, HIL testing provides a controlled and safe environment for executing scenarios that are difficult, economically prohibitive, or unsafe to reproduce in the field. These scenarios include electrical faults, saturation of measurement equipment, communication losses, and abnormal operating conditions, among others.

Furthermore, since certain protection schemes are already deployed in the power system, their physical availability for testing is often limited. In such cases, these schemes can be represented through models within the RTS. This approach enables more comprehensive evaluations that simultaneously consider power system dynamics, physical devices, and interactions with previously deployed schemes. In this context, HIL-based testing evolves from being merely an advanced validation tool into a fundamental enabler for the design, evaluation, and commissioning of next-generation RAS. Such schemes inherently dependent on system dynamics and multi-device interactions. Table 2.3 compares the capabilities of conventional FAT and HIL-based FAT approaches for RAS validation.

3

Model-Based Digital Twin for a Voltage Stability–Oriented Remedial Action Scheme

Based on the limitations of conventional remedial action scheme operational methodologies described in [Chapter 1](#), as well as on the concepts and enabling technologies introduced in the previous chapter, this chapter presents a remedial action scheme aimed at preserving voltage stability in power systems. The proposed approach is framed within the new generation of model-based RAS relying on virtual representations of the power system.

Voltage stability issues have long represented a major concern in power system operation. However, as modern power systems operate increasingly close to their operational limits, characterized by higher loading levels, stressed transmission infrastructures, and congested network topologies, voltage instability has become a critical and recurrent operational challenge. This situation is further aggravated by the limited reactive power support inherently provided by power-electronic-based resources. Under these conditions, conventional RAS implementations, typically based on fixed operating parameters and offline settings, exhibit significant limitations in coping with the dynamic and highly variable nature of modern voltage stability problems.

To address these limitations, this chapter proposes a model-based remedial action scheme that incorporates a system-level digital twin continuously synchronized with the physical power system through real-time measurements. This approach enables the RAS to access quantitative and qualitative information that more accurately represents the actual voltage stability condition of the system, complementing traditional measurements with structural and sensitivity-based information derived from the network model. Consequently, the RAS decision-making process is supported by deeper and continuously updated evaluations consistent with the current operating condition of the power system.

The remainder of this chapter is organized as follows. First, the fundamental concepts of voltage stability relevant to remedial action schemes are reviewed. Next, the overall framework of the proposed RAS is introduced, followed by the theoretical foundations supporting its operation. Finally, the implementation of the scheme and its validation through a hardware-in-the-loop platform are presented.

3.1 Voltage Stability

Power system stability is strongly linked to the physical limitations and phenomena inherent to the network. The complex interconnection of the system, the diversity of its constituent technologies, and the wide range of dynamic responses that may arise under different operating conditions require a multifaceted approach to stability analysis. Each stability category addresses specific physical mechanisms of the power system. Within this framework, power system stability can be classified into several categories. The following categories are among the most relevant in the context of this work [110]:

- **Transient stability:** refers to the ability of the power system to maintain rotor synchronism when subjected to a severe disturbance or contingency, such as a short circuit, sudden loss of generation, or major line outage.
- **Small-signal stability:** refers to the ability of the power system to maintain synchronism under small perturbations around an operating point.
- **Frequency stability:** refers to the ability of the power system to maintain frequency within acceptable limits following a significant imbalance between active power generation and demand.
- **Voltage stability:** refers to the ability of the power system to maintain acceptable voltage magnitudes at all buses under normal operating conditions and after being subjected to disturbances.

Among the different stability categories, voltage stability has acquired increasing importance in modern power grids. Its relevance has become clearer in operating points characterized by high loading levels and long-distance power transfers.

From a physical perspective, voltage instability refers to the progressive loss of the power system's ability to maintain acceptable voltage magnitudes following a disturbance or an increase in loading. This phenomenon is closely associated with the capability of the network to supply the reactive power required to support bus voltages. As loading increases, the demand for reactive power also increases, while the capability of the transmission network and generation units to provide voltage support may become limited. Under these conditions, the system may gradually lose its ability to maintain a stable operating equilibrium, leading to voltage instability. If the instability is not arrested through appropriate corrective actions, the system may eventually experience voltage collapse, which corresponds to the final condition characterized by an uncontrollable reduction of bus voltages to unacceptable levels. Several physical and operational constraints can initiate or accelerate the development of voltage instability. The following are particularly relevant:[111]:

- Operation under high loading conditions, particularly when large concentrations of load are far from generation centers.
- Congested network topologies, which reduce the effective voltage support capability.
- Limitations in the voltage regulation capability of synchronous generators, particularly when excitation limits are reached.
- Serious contingency events, for example the outage of key transmission lines or major generating units.
- The availability and geographical distribution of reactive power compensation devices, such as capacitor banks, reactors, and FACTS devices.

The interaction of these factors determines the proximity of the operating point to a voltage collapse condition. To identify voltage collapse in power systems, several analytical methods have been developed, some based on steady-state approaches and others on dynamic modeling frameworks.

Among steady-state methods, one of the most widely used tools for characterizing voltage collapse is the analysis of power–voltage (PV) curves, as illustrated in Figure 3.1 [112]. Each point along the PV curve represents a steady-state equilibrium solution for a given loading level. In particular, point C corresponds to the maximum power transfer limit of the power system. The **Voltage Stability Margin (VSM)** is therefore defined as the distance between the current operating point and the maximum power transfer point [113]. This distance quantifies the remaining loadability margin of the system. Beyond the maximum power transfer point, no physically feasible equilibrium solution exists, and the system undergoes voltage collapse [114].

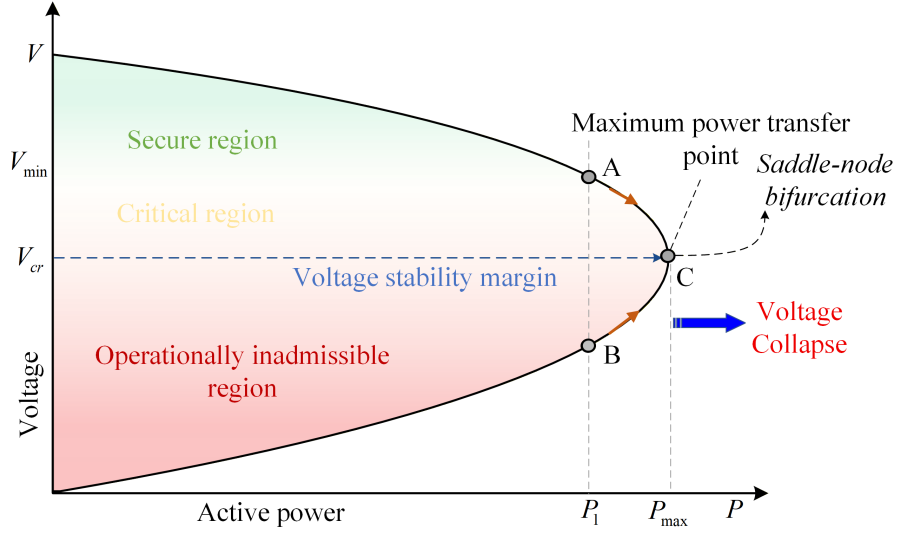


Figure 3.1: Power–voltage (PV) characteristic curve and operating regions.

Although all points along the PV curve mathematically satisfy the steady-state equations, not all of them are operationally admissible. From an operational and stability perspective, three distinct operating regions can be identified [111]: the secure region, the critical region, and the uncontrollable region.

The secure region corresponds to operating points sufficiently far from the maximum power transfer limit. In this region, the voltage magnitudes remain close to their nominal values, and the system maintains adequate voltage stability margins and good voltage regulation. Operation within this region ensures acceptable performance, robustness against disturbances, and compliance with operational and power quality requirements.

The critical region comprises operating points located near the maximum loadability limit of the system. In this region, voltage magnitudes become significantly lower and voltage regulation deteriorates considerably. Although the maximum power transfer point still represents a steady-state equilibrium solution, it constitutes a physical stability boundary of the power system. Any further increase in load, or the occurrence of a disturbance, may move the operating point beyond this limit, where no physically feasible equilibrium exists, leading to voltage collapse. For this reason, operation at or near this boundary is operationally unacceptable.

The uncontrollable region corresponds to the lower branch of the PV curve, located beyond the maximum loadability point. The equilibrium points in this region satisfy the steady-state power flow equations; however, they do not represent operationally admissible states of the power system. Along this branch, the voltage magnitude increases as the loading level increases, which is contrary to the voltage response expected in normal power system operation under increasing demand. This feature is incompatible with the assumptions underlying practical operation, voltage control, and

voltage stability assessment. Consequently, despite their mathematical existence, these equilibrium points are not regarded as feasible operating conditions. For a given loading level below the maximum loadability point, there are two equilibrium solutions. However, only the solution located on the upper branch of the PV curve, namely point A, corresponds to an admissible operating point. As the loading level increases, the upper and lower equilibrium branches approach each other until they coalesce at the maximum loadability point. This occurrence is a hallmark of a saddle-node bifurcation within the static voltage stability framework [115]. At this point, the power flow Jacobian matrix becomes singular, and beyond it, no equilibrium solution exists.

It is essential to clearly delineate the scope of the methods used to assess voltage stability. In particular, PV curves are constructed using a steady-state model that accounts for the terminal voltages of synchronous machines and their reactive power limits. As a static representation, this approach does not capture the dynamic response of the machines or the interactions between their control systems and other dynamic components in the network. Nevertheless, its primary strength lies in its ability to identify the maximum loadability limit imposed by the network structure. Within the steady-state framework, voltage stability is fundamentally associated with the existence of operationally feasible equilibrium solutions.

It is important to note that the existence of a steady-state equilibrium solution does not guarantee the overall stability of the power system. Documented cases show that, even when a static equilibrium exists near the nose point of the PV curve, Hopf bifurcations may arise, leading to oscillatory instability and, eventually, voltage collapse [116]. Such phenomena are revealed through small-signal analysis based on dynamic models formulated as systems of differential-algebraic equations (DAEs). These models incorporate both the network interconnections and the dynamic states of the power system components, together with their associated control systems, thereby providing a more comprehensive representation of voltage stability.

From a theoretical standpoint, a detailed analysis of voltage stability can be carried out using bifurcation theory, which relies on differential-algebraic models rather than purely algebraic formulations. However, in practical power system studies, voltage stability is usually assessed through simpler steady-state approaches, such as PV curve computation based on the power flow equations. Even though bifurcation theory is not commonly employed in routine studies, identifying the most relevant bifurcations remains important for a rigorous understanding of the mechanisms underlying voltage instability. In this context, the most relevant bifurcations associated with voltage stability are the following [117]:

- **Saddle-Node Bifurcation:** This bifurcation is typically identified through steady-state power flow analysis and occurs when two equilibrium solutions merge and subsequently disappear. At this critical condition, the power flow Jacobian matrix becomes singular. Mathematically, this singularity is characterized by the presence of a zero eigenvalue. Physically, it indicates that the system has reached its maximum loadability limit, beyond which no equilibrium solution exists, leading to voltage collapse.
- **Hopf Bifurcation:** This bifurcation occurs when a complex conjugate pair of eigenvalues crosses the imaginary axis as a critical parameter varies. In this case, stability is lost through the emergence of oscillations.

These dynamic and bifurcation-based approaches are employed in comprehensive voltage stability studies; however, due to their high computational complexity, they are typically restricted to offline analyzes. This limitation is particularly significant because modern power systems are represented by large-scale mathematical models, whose real-time evaluation poses considerable challenges. Consequently, conventional RAS primarily rely on local electrical variables or measurements

obtained from selected strategic locations within the network. Based on this limited information, they infer either global or local voltage stability conditions and trigger remedial actions accordingly. Nevertheless, such approaches are generally based on relatively simple indicators that do not fully capture the overall behavior of modern power systems.

The increasing size and complexity of modern power systems have made the traditional information used by RAS insufficient for accurately assessing the system state. Therefore, it becomes necessary to incorporate information that more accurately reflects the behavior of the overall system, enabling more informed and reliable decision-making.

3.2 Proposed RAS Framework

Based on the limitations identified in conventional remedial action schemes in [Chapter 1](#), this section introduces a model-based RAS framework aimed at preserving voltage stability under contingency conditions. Unlike conventional schemes, where corrective actions are triggered directly from pre-defined measurements and thresholds, the proposed framework introduces an intermediate system assessment layer based on a system-level digital twin continuously synchronized with the physical power system. This assessment layer continuously evaluates the current operating condition, estimates the voltage stability margin, and provides the information required to support remedial action decisions. Consequently, the digital twin is not merely a digital representation of the system but an active decision-support component that enables model-informed operation. Within this framework, the operating parameters of remedial actions are dynamically adjusted according to the current operating conditions and the estimated stability margins. In this way, the operating methodology is supported by quantitative indicators of proximity to voltage collapse.

In addition, the proposed design methodology includes an initialization stage compatible with conventional RAS structures, thereby facilitating its integration and progressive implementation in real-world environments.

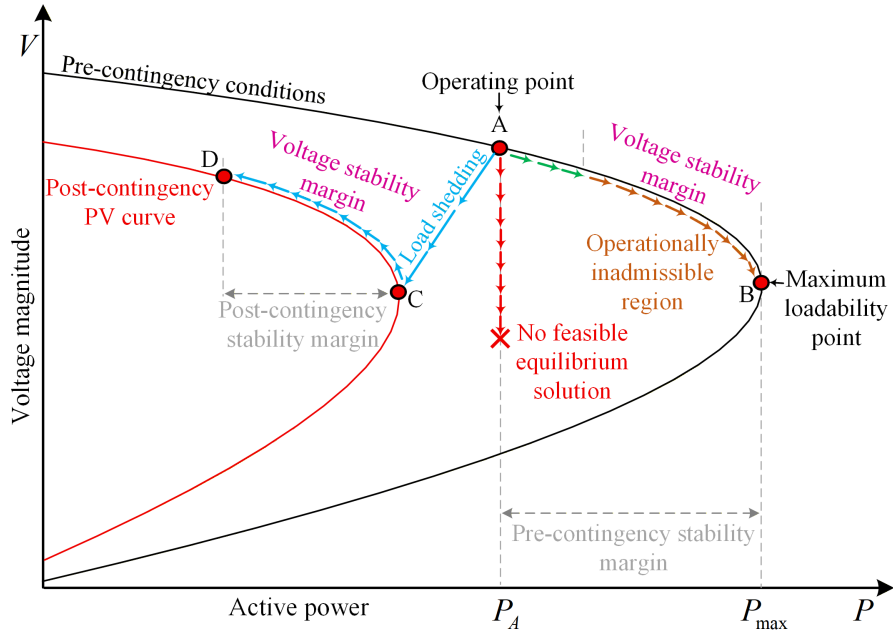


Figure 3.2: Conceptual representation of pre- and post-contingency stability margins in the proposed PV-curve-based RAS design methodology.

The design methodology of the proposed RAS begins with an offline study stage based on multi-

ple simulations, in which the stability margin is adopted as an index to evaluate the proximity of the power system to the voltage stability limit. Under normal operating conditions, the power system has a pre-contingency stability margin defined as the distance between the operating point A and the maximum power transfer point B on the PV curve, as shown in Figure 3.2. Owing to uncertainties associated with power system modeling, variations in load models, measurement inaccuracies, and unforeseen operating conditions, the methodology establishes that the system should not operate too close to this limit, thereby incorporating an additional stability margin. In practice, control centers define these minimum margins according to their reliability criteria and the characteristics of the power system under their responsibility. For example, National Center for Energy Control (CENACE) adopts a margin of 12%, whereas other operators use values close to 5%, depending on the robustness of the power system.

When a contingency occurs, the post-contingency stability margin decreases according to the severity of the event, and the new equilibrium point may shift significantly with respect to the new stability limit at point C, potentially driving the power system into a voltage collapse condition. In this context, the offline stage determines the minimum amount of load shedding required to move the power system from the operating point A to a secure operating point D under contingency conditions. Based on this analysis, critical contingencies are identified together with their corresponding minimum load shedding requirement, defined as static load shedding ($LS-S$), since it is obtained from a steady-state model. This value constitutes an operating design parameter of the RAS and is stored as an initial condition for its subsequent online operation, as illustrated in Figure 3.3.

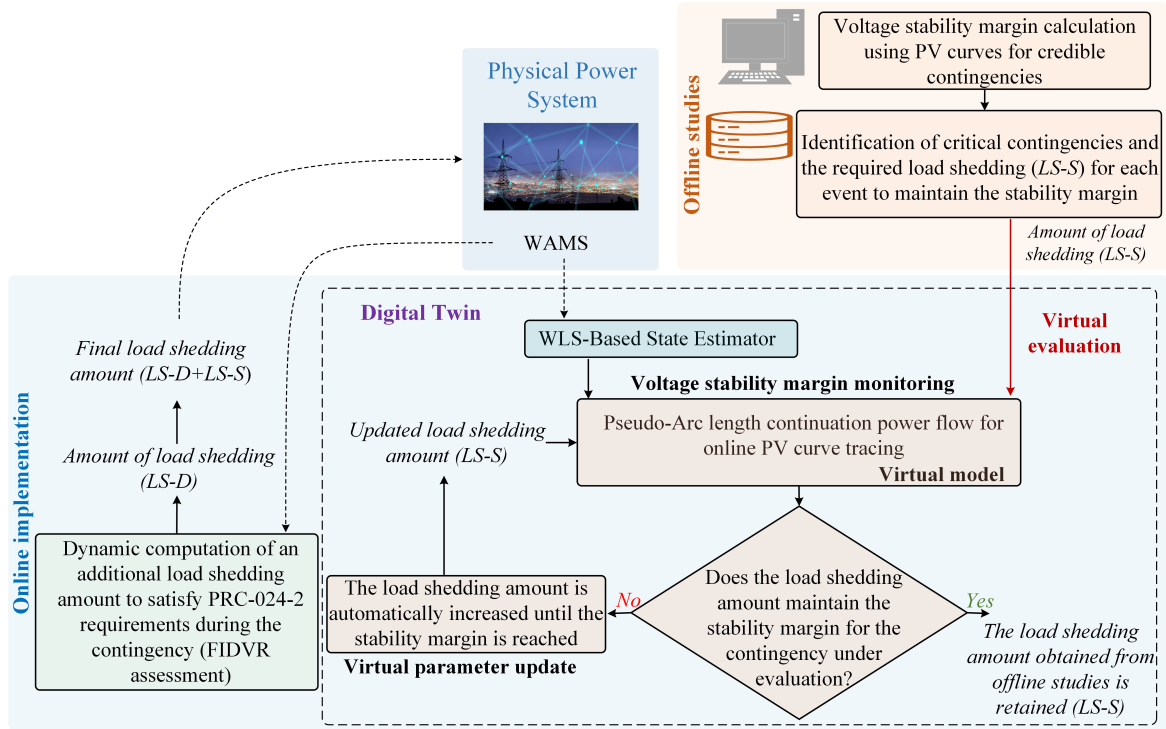


Figure 3.3: Operational flowchart of the proposed RAS framework.

Subsequently, during online operation, the proposed RAS employs a system-level digital twin of the power system. This digital twin is initialized with the $LS-S$ value determined during the offline stage and is continuously updated according to the current system state. To ensure synchronization with the physical system, the digital twin can be supplied with data from a Wide-Area Monitoring System **Wide Area Monitoring System (WAMS)** or SCADA measurements. In order to enhance the

reliability of the link between the physical system and its digital representation, a **Weighted Least Squares (WLS)** state estimator with redundancy functions is also incorporated. The WLS estimator was selected because it represents the most widely adopted state estimation methodology in both the literature and practical Energy Management systems (EMS) [118]. Since the objective of this work is not to develop a new state estimation algorithm, but rather to propose a new adaptive RAS framework, the use of a conventional WLS estimator provides a representative and well-established basis for evaluating the proposed methodology.

The state estimator provides a complementary backup function in the event of measurement losses in the primary monitoring system. In this way, the digital twin is continuously supplied with the estimated system state, enabling an accurate determination of the current operating point. This information continuously feeds the digital twin for voltage stability margin monitoring. For this purpose, the digital twin employs the **Pseudo Arc-Length Continuation Power Flow (Pseudo-Arc-CPF)** method, which allows online PV curve tracing in parallel with the real power system, thereby acting as a synchronized system-level virtual representation of the physical grid.

Within this virtual environment, contingencies are simulated and the remedial actions corresponding to the load shedding amount calculated during the offline stage (*LS-S*) are virtually performed. Based on these simulations, the digital twin estimates in real time the voltage stability margin under current operating conditions. At this stage, the proposed RAS performs an online assessment of the voltage stability margin using the digital twin. If the previously computed load shedding amount (*LS-S*) maintains a secure stability margin under the current power system conditions, it is retained. Otherwise, the RAS considers two alternatives:

1. Notify the control center so that the *LS-S* value can be updated through a new offline study.
2. Autonomously increase the amount of load shedding within the digital twin using an online PV curve tracing algorithm until the stability margin reaches an acceptable level, updating the *LS-S* value accordingly.

The second alternative, namely the automatic updating of the load shedding parameter, is adopted, resulting in a dynamic operating parameter that adapts to the current conditions of the real power system.

The amount of load shedding *LS-S* ensures that the power system reaches a new steady-state equilibrium point under the contingency condition. However, as previously discussed, this approach does not guarantee an acceptable dynamic voltage response during the transient period. Therefore, once a contingency is detected, the RAS instantaneously sheds *LS-S* and, during the subsequent voltage recovery process, computes a second load shedding stage (*LS-D*) based on the voltage deviations observed at the load buses throughout the event transient, as proposed in [29].

The objective of the second load shedding stage (*LS-D*) is to ensure compliance with ride-through requirements and to ensure an adequate recovery profile in accordance with the PRC-024-2 standard [119], which defines acceptable transient voltage recovery characteristics, as shown in **Figure 3.4**. By maintaining voltage levels within the mandatory operation region and the continuous operation region, the RAS prevents the activation of undervoltage protection schemes in nearby generation facilities during the presence of **Fault-Induced Delayed Voltage Recovery (FIDVR)** phenomena [120]. This avoids uncontrolled cascading disconnections and significantly reduces the risk of a widespread blackout.

In summary, the proposed RAS framework is structured around three core components:

- A first-stage load shedding action, *LS-S*, determined through offline studies and continuously updated in real time through a digital twin based on voltage stability margin tracing.

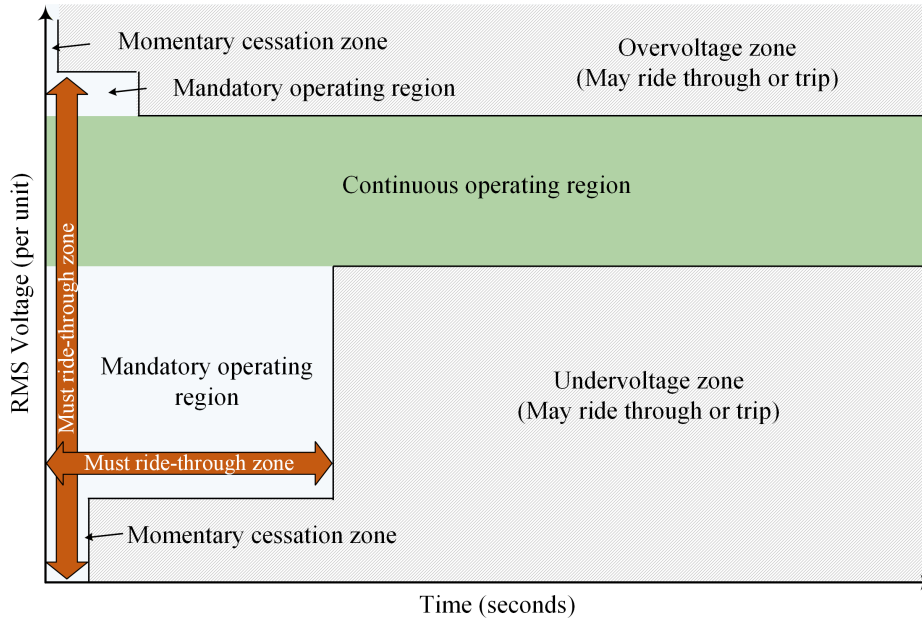


Figure 3.4: Operational limits for voltage ride-through.

- A WLS-based state estimator that links the real power system and the digital twin.
- A second-stage load shedding action, *LS-D*, intended to support voltage ride-through during FIDVR phenomena.

While this section has introduced the general operational methodology of the proposed RAS framework, a comprehensive understanding of its functionality requires a formal description of the theoretical foundations supporting each of its stages. Therefore, the following section presents the analytical principles underlying the proposed RAS, including the mathematical formulation of its main stages.

3.3 Theoretical Foundations

The theoretical formulation of the proposed RAS is based on the nonlinear steady-state representation of the power system. Since both voltage stability margin assessment and corrective action synthesis depend on an accurate characterization of the operating point, a mathematical model relating network states and measurements is required.

This section develops the analytical framework supporting the three core components of the proposed RAS. It begins with the nonlinear power flow model and the WLS-based state estimation process, followed by the continuation power flow formulation employed for voltage stability margin tracing and, finally, the online evaluation of FIDVR phenomena.

Measurement Configuration for RAS Initialization

The operation of the proposed RAS begins with the acquisition of real-time measurements through the monitoring system, which in this implementation corresponds to a SCADA-based architecture. These measurements are used to feed the WLS-based state estimator. To initialize the estimator, the RAS operator defines the measurement configuration, including both the measurement locations and their corresponding types. The input measurement set may include bus voltage magnitudes (V_i), active and reactive power injections (P_i , Q_i), as well as active and reactive power flows through

network elements such as transmission lines or transformers (P_{ij}, Q_{ij}). These measurements are organized according to the structure presented in Table 3.1. This structured arrangement directly determines the construction of the measurement vector and the corresponding measurement matrix used in the WLS formulation, thereby defining the analytical relationship between system states and acquired data. The data are acquired through the **Distributed Network Protocol (DNP)** protocol, which, although slower than phasor-based systems, provides sufficient temporal resolution for the steady-state stability assessment performed by the proposed RAS. The WLS-based estimator is inherently scalable: the incorporation of additional measurements or newly installed devices does not require modifications to its core formulation, since the estimator automatically adapts to the expanded measurement configuration.

Table 3.1: Structure of the measurement set for the WLS-based state estimator

No. Measurement	Type	From	To	Value
1	V_i	Bus _{<i>i</i>}	–	DNP3 measurement
2	P_i	Bus _{<i>i</i>}	–	DNP3 measurement
3	Q_i	Bus _{<i>i</i>}	–	DNP3 measurement
4	P_{ij}	Bus _{<i>i</i>}	Bus _{<i>j</i>}	DNP3 measurement
5	Q_{ij}	Bus _{<i>i</i>}	Bus _{<i>j</i>}	DNP3 measurement

Measurement Jacobian

Once the measurement configuration is defined and the corresponding measurement vector is constructed, the state estimation problem can be formulated. In this formulation, the state vector is defined in polar coordinates as:

$$\mathbf{x} = \begin{bmatrix} \delta \\ |\mathbf{V}| \end{bmatrix} \quad (3.1)$$

where δ is the vector of bus voltage phase angles and $|\mathbf{V}|$ is the vector of bus voltage magnitudes. The voltage angle of the reference bus is fixed and is not included as an independent state variable.

For a given set of measurements, the nonlinear measurement model is expressed as follows [121]:

$$\mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_c \end{bmatrix} = \begin{bmatrix} h_1(\mathbf{x}) \\ h_2(\mathbf{x}) \\ \vdots \\ h_c(\mathbf{x}) \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_c \end{bmatrix} = \mathbf{h}(\mathbf{x}) + \mathbf{e} \quad (3.2)$$

where $\mathbf{z} \in \mathbb{R}^c$ is the measurement vector, $\mathbf{x} \in \mathbb{R}^q$ is the state vector, $\mathbf{h}(\mathbf{x}) \in \mathbb{R}^c$ represents the nonlinear measurement model relating the system states to the available measurements, and $\mathbf{e} \in \mathbb{R}^c$ is the measurement error vector. In this formulation, c denotes the total number of measurements, whereas q denotes the number of state variables.

The WLS formulation determines the optimal state vector by iteratively minimizing the weighted least-squares objective function, defined as the weighted sum of squared measurement residuals, until convergence is achieved:

$$J(\mathbf{x}) = \sum_{i=1}^c \frac{(z_i - h_i(\mathbf{x}))^2}{R_{ii}} \quad (3.3)$$

where $J(\mathbf{x})$ is the WLS objective function, which represents the weighted sum of squared measurement residuals. The minimization of $J(\mathbf{x})$ determines the state vector that best fits the available

measurements according to their assigned confidence levels. Assuming uncorrelated measurement errors, $\mathbf{R}_{meas} \in \mathbb{R}^{c \times c}$ is the diagonal measurement covariance matrix, whose entries define the confidence assigned to each measurement and directly influence the convergence and numerical behavior of the estimator. The covariance matrix is given by:

$$\mathbf{R}_{meas} = \begin{bmatrix} R_{11} & 0 & \cdots & 0 \\ 0 & R_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & R_{cc} \end{bmatrix} \quad (3.4)$$

The measurement Jacobian matrix is defined as $\mathbf{H}_{SE} \in \mathbb{R}^{c \times n}$ and is given by

$$\mathbf{H}_{SE} = \frac{\partial \mathbf{h}(\mathbf{x})}{\partial \mathbf{x}} = \begin{bmatrix} \frac{\partial \mathbf{P}_{inj}}{\partial \delta} & \frac{\partial \mathbf{P}_{inj}}{\partial |\mathbf{V}|} \\ \frac{\partial \mathbf{P}_{flow}}{\partial \delta} & \frac{\partial \mathbf{P}_{flow}}{\partial |\mathbf{V}|} \\ \frac{\partial \mathbf{Q}_{inj}}{\partial \delta} & \frac{\partial \mathbf{Q}_{inj}}{\partial |\mathbf{V}|} \\ \frac{\partial \mathbf{Q}_{flow}}{\partial \delta} & \frac{\partial \mathbf{Q}_{flow}}{\partial |\mathbf{V}|} \\ \frac{\partial |\mathbf{I}|}{\partial \delta} & \frac{\partial |\mathbf{I}|}{\partial |\mathbf{V}|} \\ \mathbf{0} & \frac{\partial |\mathbf{V}|}{\partial |\mathbf{V}|} \end{bmatrix} \quad (3.5)$$

where $\mathbf{P}_{inj}$ and $\mathbf{Q}_{inj}$ denote the vectors of active and reactive power injection measurement functions, respectively, while $\mathbf{P}_{flow}$ and $\mathbf{Q}_{flow}$ denote the vectors of active and reactive power flow measurement functions through network elements. In addition, $|\mathbf{V}|$ and $|\mathbf{I}|$ represent the vectors of voltage and current magnitude measurement functions, respectively. The rows associated with current magnitude measurements are included only when such measurements are available in the measurement set.

Gain Matrix

The gain matrix is computed using the measurement Jacobian matrix $\mathbf{H}_{SE}$ and the covariance matrix $\mathbf{R}_{meas}$. Accordingly, the gain matrix $\mathbf{G}_{SE}(\mathbf{x})$ is formulated as:

$$\mathbf{G}_{SE}(\mathbf{x}) = \mathbf{H}_{SE}^T \mathbf{R}_{meas}^{-1} \mathbf{H}_{SE} \quad (3.6)$$

which can also be expressed as:

$$\mathbf{G}_{SE} = \sum_{i=1}^m \mathbf{H}_{SE,i}^T R_{ii}^{-1} \mathbf{H}_{SE,i} \quad (3.7)$$

The iterative solution of the WLS-based state estimation problem is obtained through the following expressions:

$$\begin{aligned} \mathbf{G}_{SE}(\mathbf{x}^k) &= \mathbf{H}_{SE}^T(\mathbf{x}^k) \mathbf{R}_{meas}^{-1} \mathbf{H}_{SE}(\mathbf{x}^k) \\ \Delta \mathbf{x}^{k+1} &= [\mathbf{G}_{SE}(\mathbf{x}^k)]^{-1} \mathbf{H}_{SE}^T(\mathbf{x}^k) \mathbf{R}_{meas}^{-1} [\mathbf{z} - \mathbf{h}(\mathbf{x}^k)] \end{aligned} \quad (3.8)$$

Once the iterative process satisfies the convergence criterion,

$$\max(|\Delta \mathbf{x}|) \leq \epsilon,$$

the estimated state vector $\mathbf{x}$ is obtained. Based on this state estimated, the active power generation at each generating unit (P_{gi}) and the active and reactive power demand at each load bus (P_{li}, Q_{li}) can

be derived through the network power-flow relationships, thereby fully characterizing the current steady-state operating condition of the power system.

This estimated operating point provides the initialization required by the continuation power flow method employed within the system-level digital twin for PV curve tracing. In the proposed framework, the WLS-based state estimation stage constitutes the model-driven analytical interface between the real-time measurements of the physical system and the digital twin, since the CPF algorithm is initialized directly from the reconstructed steady-state operating point.

For the results presented in this work, it is assumed that the WLS-based state estimator serves as the sole interface between the physical power system and its digital twin representation. Under this configuration, all subsequent stages of the proposed RAS are initialized exclusively from the estimated state vector.

CPF-Based Digital Twin for Voltage Stability Margin Assessment

The design and operational methodology of the proposed RAS is based on the voltage stability margin index; therefore, the digital twin must rely on a model capable of estimating this quantity accurately. The selection of the mathematical formulation is thus not arbitrary. Although modeling approaches of different levels of complexity exist, the system-level model must remain computationally efficient to enable real-time execution and, at the same time, be compatible with the data available from conventional monitoring systems.

Traditionally, PV curve tracing is performed through successive power flow solutions using the Newton–Raphson method [122]. This procedure consists of progressively increasing the system loading and generation levels in order to compute new equilibrium operating points, repeating the process until the maximum power transfer point is approached. Although this methodology provides a reasonable approximation of the maximum loading condition, it exhibits numerical limitations when the power system operates near the critical point. In particular, near the maximum loading point, the power flow Jacobian becomes singular, leading to numerical instability and convergence problems. To overcome these limitations, continuation power flow methods have emerged as a robust alternative [123]. These methods reformulate the classical steady-state power flow equations by incorporating predictor–corrector schemes and parametrization strategies [124, 125, 126], thereby avoiding the Jacobian singularity at the maximum loading point and enabling complete tracing of the PV curve.

Among the different CPF variants, the digital twin proposed in this work is based on the Pseudo–Arc Length method, which is widely used for the analysis of saddle-node bifurcations and has been adopted in specialized tools such as AUTO [127]. In addition, specific modifications are incorporated to enhance its operational flexibility, aligning its PV tracing capabilities with those available in professional software platforms such as *Power System Simulator for Engineering (PSS/E)* [128].

The CPF formulation starts from the classical steady-state power flow equations, which compute a solution for a system of the form

$$\mathbf{F}(\boldsymbol{\delta}, \mathbf{V}) = 0 \quad (3.9)$$

where $\mathbf{F}$ denotes the set of nonlinear power flow equations, $\boldsymbol{\delta}$ represents the vector of voltage phase angles, and $\mathbf{V}$ corresponds to the vector of voltage magnitudes. By introducing a loading parameter λ , the system in (3.9) can be reformulated as

$$\mathbf{F}(\boldsymbol{\delta}, \mathbf{V}, \lambda; \mathbf{T}_{\text{system}}) = 0 \quad (3.10)$$

where $\mathbf{T}_{\text{system}}$ is the participation vector that defines the buses at which load or generation is

allowed to vary during the tracing of the PV curve. Its entries are equal to one at the selected buses and zero elsewhere, thereby enabling selective increases in power transfer within the system-level digital twin. The load and generation increments are defined as percentages of the power connected at each selected bus with respect to the total system generation or demand. This configuration is specified by the RAS operator.

From this formulation, the CPF method uses the arc-length parameter s as the continuation variable, treating the state vector $\mathbf{u} = [\delta, \mathbf{V}]$ and the loading factor λ as functions of s , as described in [127]:

$$\mathbf{F}(\delta(s), \mathbf{V}(s), \lambda(s); \mathbf{T}_{\text{system}}) = 0 \quad (3.11)$$

Differentiating (3.11) with respect to s , and noting that $\mathbf{T}_{\text{system}}$ remains fixed during each tracing process, yields

$$\begin{bmatrix} \mathbf{F}_\delta & \mathbf{F}_V & \mathbf{F}_\lambda \end{bmatrix} \begin{bmatrix} d\delta \\ d\mathbf{V} \\ d\lambda \end{bmatrix} = 0 \quad (3.12)$$

Expression (3.12) can be rewritten in compact form as

$$\begin{bmatrix} \mathbf{F}_u & \mathbf{F}_\lambda \end{bmatrix} \begin{bmatrix} d\mathbf{u} \\ d\lambda \end{bmatrix} = 0 \quad (3.13)$$

where the tangent vector is defined as

$$\mathbf{t} = \begin{bmatrix} d\mathbf{u} \\ d\lambda \end{bmatrix} \quad (3.14)$$

On the other hand, in order to remove the non-uniqueness of (3.13), the Euclidean arc-length constraint is introduced as an additional equation:

$$d\mathbf{u}^T d\mathbf{u} + d\lambda^2 = 1 \quad (3.15)$$

To compute the tangent vector, the following system of linear algebraic equations is first solved for ξ :

$$\mathbf{F}_u \xi = -\mathbf{F}_\lambda \quad (3.16)$$

Then, due to the linearity of (3.13) in $d\mathbf{u}$ and $d\lambda$,

$$d\mathbf{u} = \xi d\lambda \quad (3.17)$$

Substituting (3.17) into the Euclidean arc-length constraint, the value of $d\lambda$ is obtained as

$$d\lambda = \pm \left(1 + \xi^T \xi \right)^{-1/2} \quad (3.18)$$

The sign in (3.18) determines the direction of the solution along the PV curve. Once the tangent vector $\mathbf{t}$ is obtained, the state variables of the next solution point are predicted as

$$\begin{bmatrix} \mathbf{u}_p \\ \lambda_p \end{bmatrix} = \begin{bmatrix} \mathbf{u}_k \\ \lambda_k \end{bmatrix} + \sigma \begin{bmatrix} \mathbf{t} \end{bmatrix} \quad (3.19)$$

where the subscript p denotes the predicted values of $\mathbf{u}$ and λ , σ is the continuation step size, and the subscript k denotes the previously corrected solution point. For the first continuation step, these initial values correspond to the operating point of the physical power system reconstructed from the state vector estimated by the WLS-based state estimator.

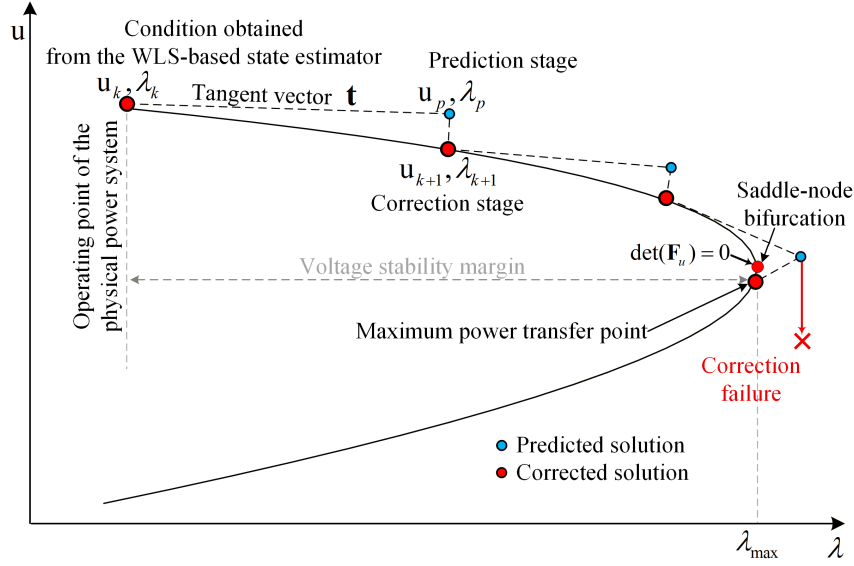


Figure 3.5: Predictor–corrector scheme of the pseudo–arc-length CPF implemented in the system-level digital twin.

From the predicted values $(\mathbf{u}_p, \lambda_p)$, the pseudo–arc-length CPF performs a correction step based on a hyperplane orthogonal to the tangent vector computed at the previous corrected solution point. This strategy reduces the risk of loss of convergence during PV curve tracing, since the correction is performed in a direction for which the Newton–Raphson method exhibits improved numerical robustness. In this way, the corrected solution $(\mathbf{u}_{k+1}, \lambda_{k+1})$ satisfies both the steady-state power flow equations in (3.11) and the following hyperplane constraint:

$$G(\mathbf{u}, \lambda) = (\mathbf{u} - \mathbf{u}_k)^T d\mathbf{u}_k + (\lambda - \lambda_k)d\lambda_k - \sigma = 0 \quad (3.20)$$

Accordingly, the pseudo–arc-length CPF consists of computing the predictor and corrector stages through (3.19), (3.11), and (3.20). This leads to the following augmented system of equations:

$$\begin{bmatrix} \mathbf{F}_u & \mathbf{F}_\lambda \\ \mathbf{G}_u & \mathbf{G}_\lambda \end{bmatrix} \begin{bmatrix} \Delta \mathbf{u} \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ 0 \end{bmatrix} \quad (3.21)$$

Finally, Figure 3.5 illustrates the PV curve tracing process using the Pseudo–Arc Length CPF method, which constitutes the system-level digital twin. Starting from the operating point reconstructed by the WLS-based state estimator, the tangent vector computation, prediction, and correction stages are executed iteratively, generating successive equilibrium points until the maximum power transfer point is reached. This point defines the voltage stability margin of the system. The estimation of this margin is carried out by evaluating contingencies and virtual load-shedding actions previously identified during the offline stage. In this way, the LS-S scheme can be validated and adjusted within a secure virtual environment before implementing any load shedding action on the physical system. The evaluation stage of the system-level digital twin by the RAS is summarized in Algorithm 1.

Through this procedure, the first-stage LS-S is fully defined and continuously updated, remaining armed for any of the assessed contingencies. However, in order to ensure a successful voltage re-

Algorithm 1 *Digital-Twin-Based Pseudo–Arc-Length CPF Method*

Input: Generation dispatch, voltage references, active and reactive load demands obtained from the WLS-based state estimator, LS -S amount, and $\mathbf{T}_{\text{system}}$

Output: Voltage stability margin and updated LS -S amount (if necessary)

- 1: Apply the contingency under evaluation
- 2: Apply LS -S at the selected buses according to the offline stage
- 3: Scale ΔP for each P_{g_i} and P_{l_i} according to $\mathbf{T}_{\text{system}}$
- 4: Compute the initial Newton–Raphson power flow solution
- 5: **while** $\lambda_k < \lambda_{\max}$ **do**
- 6: Compute $\mathbf{F}_u$ and $\mathbf{F}_\lambda$
- 7: Compute ξ using (3.16)
- 8: Compute the tangent vector $\mathbf{t}$ using (3.17) and (3.18)
- 9: Compute the predicted point $(\mathbf{u}_p, \lambda_p)$ using (3.19)
- 10: Form the augmented function $G(\mathbf{u}, \lambda)$
- 11: Solve the corrector step using (3.21)
- 12: Update $(\mathbf{u}_{k+1}, \lambda_{k+1})$
- 13: **end while**
- 14: Compute the voltage stability margin as $\lambda_{\max} - \lambda_0$
- 15: **if** Voltage stability margin < minimum stability margin **then**
- 16: Increase the LS -S amount
- 17: **end if**

covery within ride-through limits, the proposed RAS computes a second load-shedding stage aimed at providing additional voltage support during the post-contingency recovery period. This second stage is described in the following subsection.

Voltage Recovery- and FIDVR-Oriented RAS Strategy

The dynamic voltage response of a power system depends on several factors. Among them, load dynamics play a critical role and may drive the system toward voltage instability. In power systems with thermostatically controlled loads and stalling induction motors, a phenomenon known as fault-induced delayed voltage recovery may occur [120]. This phenomenon is characterized by system voltages remaining at significantly low levels for several seconds after fault clearance [129]. Such prolonged voltage depression may trigger undervoltage protection schemes at generation and load facilities, potentially leading to cascading disconnections and, ultimately, voltage collapse. Since the FIDVR phenomenon is not captured by steady-state approaches such as the PV-curve-based digital twin, ensuring an acceptable dynamic voltage response during contingencies requires maintaining the voltage trajectory within predefined limits, typically represented by the red bands in Figure 3.6. Failure to recover within these limits may activate protective mechanisms, resulting in uncontrolled generation disconnection and, in severe cases, a widespread blackout.

Accordingly, the proposed RAS incorporates a secondary load-shedding stage (LS -D) computed in real time and adapted to the severity of the contingency. This stage is based on the methodology presented in [29], with certain adjustments. In particular, the strategy considers an individual evaluation carried out exclusively at load buses within the protected area. Nevertheless, load shedding is applied only at those buses that exhibit critical voltage drops.

During the voltage transient, the voltage deviation at each bus, denoted as ΔV_i , is evaluated with respect to its pre-contingency value. For buses where ΔV_i exceeds a predefined threshold ΔV_i^{th} , the average voltage deviation ΔV_i^{av} is determined relative to a reference voltage V_i^{th} , as expressed below:

$$\Delta V_i^{av} = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} (V_i^{th} - V_i(t)) dt \quad (3.22)$$

In this formulation, τ denotes the integration interval, whereas t_0 corresponds to a time instant

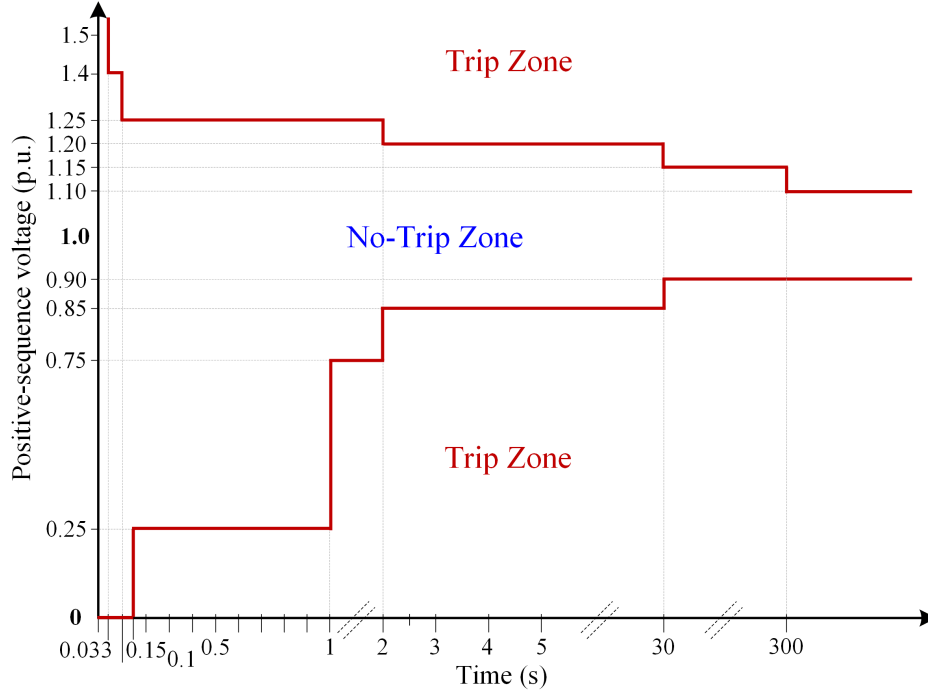


Figure 3.6: PRC-024-2 voltage ride-through requirements during transient voltage disturbances.

defined after the first load-shedding action (LS-S) in order to incorporate its effect into the evaluation of the average voltage deviation ΔV_i^{av} . Furthermore, the reference voltage V_i^{th} must remain within the operational constraint bands shown in Figure 3.6. The methodology adopted to estimate the parameters τ and V_i^{th} is presented in the Results section. Using these variables, the corresponding expression for the required load shedding is obtained as follows:

$$\Delta P_i^{shed} = K_i \Delta V_i^{av} \quad (3.23)$$

The gain K_i characterizes the sensitivity of the load-shedding action to voltage deviations at each bus. Conventionally, this gain is treated as a fixed parameter and tuned through extensive offline simulations. However, under conditions of increased demand, maintaining a fixed gain may lead to disproportionate load-shedding actions. Therefore, in the proposed RAS, K_i is defined as a dynamic parameter assigned proportionally to the load level at each bus. Moreover, to ensure a controlled response, the load-shedding action is constrained by imposing an upper bound on the maximum power that can be disconnected at each bus, thereby preventing excessive shedding:

$$\Delta P_i^{shed} \leq \Delta P_{\max}^{shed} \quad (3.24)$$

Finally, the second load-shedding amount is defined as

$$LS-D_i = \Delta P_i^{shed} \quad (3.25)$$

Once the second load-shedding action is applied at buses exhibiting significant voltage deviations, the integrators associated with each controller are reset. This reinitialization enables the scheme to execute a third emergency load-shedding stage if the voltage within the protected area does not recover to the specified thresholds within the defined time window, as described below:

$$\mu(t) = \begin{cases} 0.00 \leq V_i(t) \leq 1.40, & \forall t \in [0.033, 0.1] \\ 0.00 \leq V_i(t) \leq 1.25, & \forall t \in [0.1, 0.15] \\ 0.25 \leq V_i(t) \leq 1.25, & \forall t \in [0.15, 1] \\ 0.75 \leq V_i(t) \leq 1.25, & \forall t \in [1, 2] \\ 0.85 \leq V_i(t) \leq 1.20, & \forall t \in [2, 30] \\ 0.90 \leq V_i(t) \leq 1.15, & \forall t \in [30, 300] \\ 0.90 \leq V_i(t) \leq 1.10, & \forall t \in [300] \end{cases} \quad (3.26)$$

The region defined in (3.26) establishes the acceptable dynamic recovery criterion and is consistent with the limits illustrated in Figure 3.6. It should be emphasized that the parameters τ and V_i^{th} require offline calibration for each contingency scenario. Accordingly, a dedicated design methodology is applied during the HIL implementation to properly adjust these parameters, taking into account the coordinated operation of all system devices, as well as the overall system response. This procedure is detailed in the Results section.

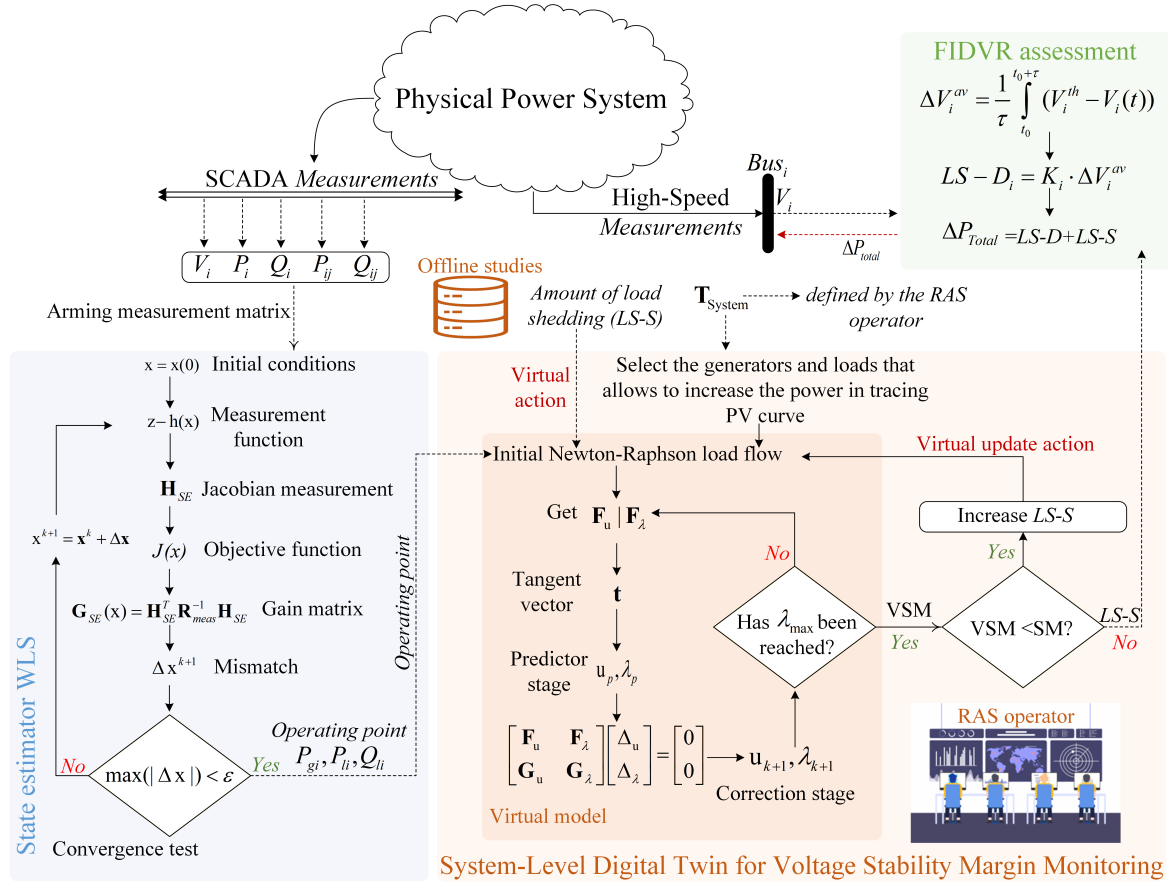


Figure 3.7: Overall operational framework of the proposed digital twin-based RAS.

The theoretical foundations of the proposed RAS have been established in this section through the formulation of the system-level digital twin, based on the pseudo-arc-length CPF method for voltage stability margin estimation, the definition of the staged load-shedding strategy, and the coupling between the physical system and the digital twin through the WLS-based state estimation framework.

For completeness, Figure 3.7 presents a general flowchart summarizing the overall operational sequence and illustrating the interaction among the different stages of the RAS. The diagram provides

an integrated representation of the methodology developed in this section. With the conceptual and mathematical framework now fully defined, the following section describes the hardware-in-the-loop implementation, in which the proposed RAS is validated under realistic operating conditions.

3.4 Hardware-in-the-Loop Implementation

This section describes the hardware-in-the-loop implementation used to validate the proposed RAS under relevant operating conditions. The presentation is organized into two subsections. The first subsection introduces the test power system, including a detailed description of the protection problem addressed and the operating modifications applied to create stressed conditions. The second subsection presents the HIL experimental setup, detailing the real-time simulation platform, hardware devices, and communication architecture employed for the implementation.

Test Power System Description and Problem Definition

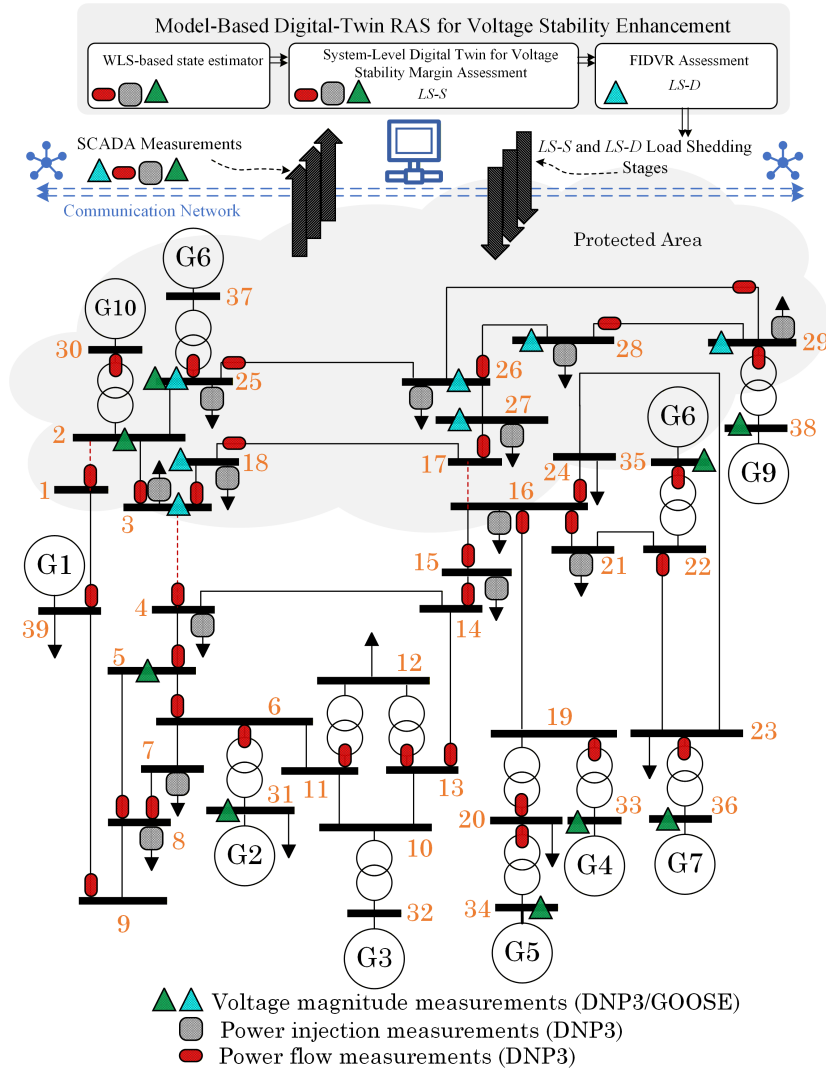


Figure 3.8: IEEE 39-bus test system with measurement points and protected area.

To evaluate the performance of the proposed RAS, the IEEE 39-bus test system is employed. This system constitutes a widely recognized benchmark in the academic literature, as it represents

an equivalent of the New England power system. It is selected because it adequately reproduces relevant characteristics and dynamic phenomena observed in real power systems, particularly those associated with voltage stability. As such, it provides an appropriate framework for the analysis and validation of remedial action schemes aimed at preserving voltage stability in large-scale systems.

Figure 3.8 illustrates the topology of the system, which consists of 39 buses, 10 synchronous machines, and 19 load buses. In order to represent operating conditions more consistent with those of modern power systems, the original operating point was slightly modified. These modifications included adjusting the generation dispatch of synchronous machines 2, 3, 4, 5, and 6, as well as proportionally increasing the load demand at buses 3, 18, 25, 26, 27, 28, and 29. As a result, the system exhibits a more stressed operating point, characterized by large generation areas transmitting significant amounts of power to highly concentrated load centers. This configuration reflects the typical behavior of regions susceptible to voltage collapse in real power systems. The load area of interest is highlighted in Figure 3.8. This area receives approximately 864 MW through transmission lines 1–2, 4–3, and 16–17, which represent the main interconnection corridors between the analyzed load area and the remainder of the test system.

Under these operating conditions, contingencies involving the loss of generation within the load area may cause a sudden increase in power flow through the interconnection corridors, driving the system operating point close to, or even beyond, the maximum power transfer point. Furthermore, if during the post-contingency transient the voltages in the load area violate the established ride-through limits, the remaining generation units may trip. This situation would further increase the power transfer through the interconnection corridors, accelerating the degradation of the voltage stability margin and potentially leading the system toward voltage collapse.

In this context, the proposed RAS is designed to prevent such scenarios and protect the load area against generation contingencies occurring within the load zone. Accordingly, the scheme is configured to perform load shedding within the area of interest, specifically at buses 3, 18, 25, 26, 27, 28, and 29. Finally, Figure 3.8 also illustrates the measurement points selected from the test system to supply the proposed RAS. These signals serve as inputs to the WLS-based state estimator, which acts as the interface between the physical system and the system-level digital twin. In addition, the diagram identifies the communication protocol associated with each measurement, either DNP3 or Generic Object-Oriented Substation Event (GOOSE), thereby providing a clear representation of the information exchange between the physical power system and the different stages of the proposed RAS.

With the test system clearly defined, the following subsection describes the hardware-in-the-loop experimental setup adopted to implement and validate the proposed RAS under real-time operating conditions.

Hardware-in-the-Loop Validation Platform

The validation platform consists of two main types of equipment:

- Real-Time Digital Simulator (RTDS):** The RTDS is used to model the IEEE 39-bus test system. This platform performs electromagnetic transient (EMT) simulations and employs the Dommel method for the numerical solution of the power system equations [130]. Synchronous machines are modeled together with their corresponding Automatic Voltage Regulators (AVRs) and speed governors. Transmission lines are represented using Bergeron distributed-parameter models, while loads are modeled using a Constant Impedance, Current, and Power (ZIP) representation composed of 70% constant power and 30% constant impedance. The power system model is executed with an integration time step of 50 μ s.

- **Industrial-grade controller:** The SEL-3555 **Real-Time Automation Controller (RTAC)** is employed as the central control and processing unit. Equipped with a multiprocessor IEC 61131 logic engine, programmed using a CODESYS-based environment, the SEL-3555 is capable of handling large datasets and executing complex computational tasks in real time. Within this device, the core algorithms of the proposed RAS are implemented, including the WLS-based state estimator, the system-level digital twin, and the FIDVR assessment stage.

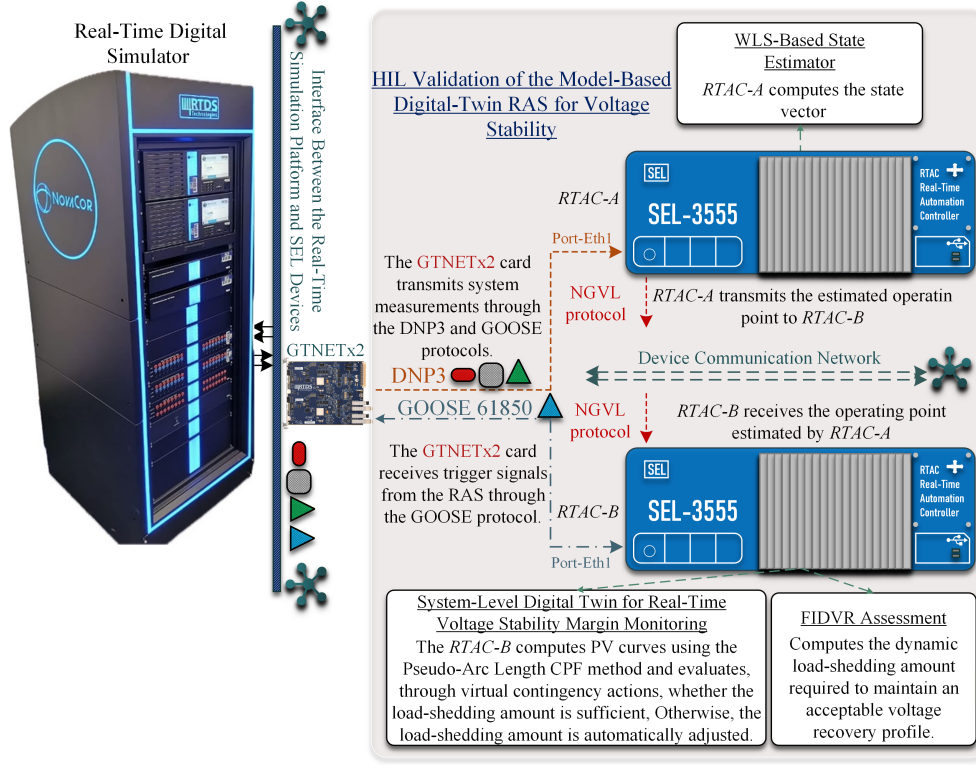


Figure 3.9: Architecture of the hardware-in-the-loop validation platform.

Figure 3.9 illustrates the architecture of the HIL validation platform. The information flow originates from the model implemented in the RTDS, which represents the physical power system. Within the RTDS, the GNETx2 communication card is configured to manage signal exchange through the DNP3 and GOOSE protocols, as well as to establish the corresponding communication parameters. Through DNP3, the RTDS transmits to RTAC-A, every 100 ms, the voltage magnitudes, active and reactive power injections, and power flows corresponding to the measurement points indicated in Figure 3.8. Using this information, the WLS-based state estimator implemented in RTAC-A reconstructs the system state vector every second. Once the estimation is completed, the generation dispatch, reference voltages, and estimated load demand are transmitted to RTAC-B through the **Next Generation Virtual Link (NGVL)** protocol every 10 ms. In addition, RTAC-B directly receives the voltage magnitudes of the load buses within the area of interest through the GOOSE protocol, enabling the evaluation of the FIDVR stage.

In RTAC-B, a parallel execution structure is implemented to support processes with different execution cycles. Specifically, two main functions are executed: the system-level digital twin of the power system and the FIDVR evaluation stage. The digital twin operates with an execution period of one second and is assigned to the main task, which allows configurable processing times between 4 and 1000 ms. In contrast, the FIDVR evaluation requires a faster execution cycle and runs with a 4 ms period; therefore, it is implemented within the automation environment, which supports

processing times ranging from 1 to 1000 ms.

In addition, since load shedding must be executed as quickly as possible, the GOOSE protocol is used to transmit the trip signals. This requires internal information exchange between the main task and the automation environment, because the total load-shedding amount, ΔP_{total} , is determined from both the results of the system-level digital twin ($LS-S$) and the FIDVR evaluation stage ($LS-D$). This information exchange is carried out through a library in the SEL RTAC called *Cross-Task Data*, which enables bidirectional communication between the main task and the automation environment, as shown in Figure 3.10. The exchange of information between the two processes occurs whenever the processing cycles of both tasks coincide and therefore depends on the configured processing times of the main task and the automation environment.

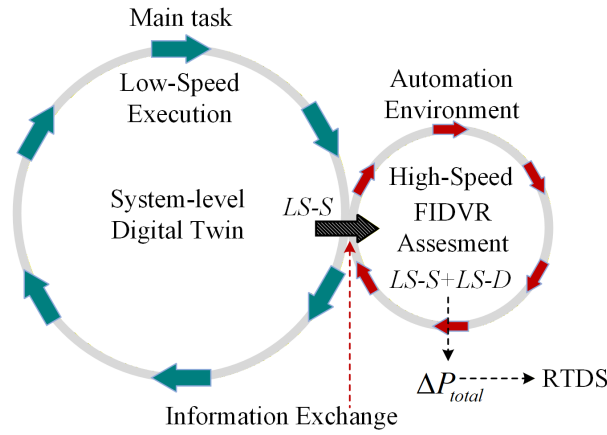


Figure 3.10: Cross-task data exchange between the main task and the automation environment.

In the FIDVR assessment stage, which runs in the automation environment, it is necessary to compute the solution for ΔV_i^{av} as defined in (3.22). To achieve this, the integration of the voltage-deviation signal is performed using a PID controller implemented in the RTAC. The PID library of the SEL-3555 is employed for this FIDVR evaluation stage. The RTAC PID algorithm implements the ideal form of a positional PID controller with dependent gains. The time-domain expression for the PID controller is given below:

$$CO = K_c \left[E + \frac{1}{T_i} \int E \, dt + T_d \frac{dE}{dt} \right] \quad (3.27)$$

where CO is the controller output, E is the error signal, K_c is the controller gain, T_i is the integral time, and T_d is the derivative time. For this implementation, the derivative action is deactivated.

For the FIDVR assessment stage, it is necessary to tune the parameters V_i^{th} and τ for all controllers at each load bus within the protected area. This tuning is carried out through multiple hardware-in-the-loop simulations of the power system equipped with the proposed RAS, assessing both the system response and the effectiveness of the remedial actions under different combinations of V_i^{th} and τ . To automate this process, a script was developed in the RTDS. The script configures a series of tests in which the performance of the FIDVR assessment implemented in *RTAC-B* is evaluated. For each predefined contingency, the test begins with a specific set of V_i^{th} and τ values, which are sent to *RTAC-B*. The RAS then computes the total load-shedding amount ΔP_{total} and evaluates its impact on the test power system under the contingency scenario. Once the simulation concludes, the results are stored.

Subsequent tests are conducted by assigning new values to V_i^{th} and τ , repeating the procedure to assess how the updated ΔP_{total} influences the system performance. This iterative tuning method-

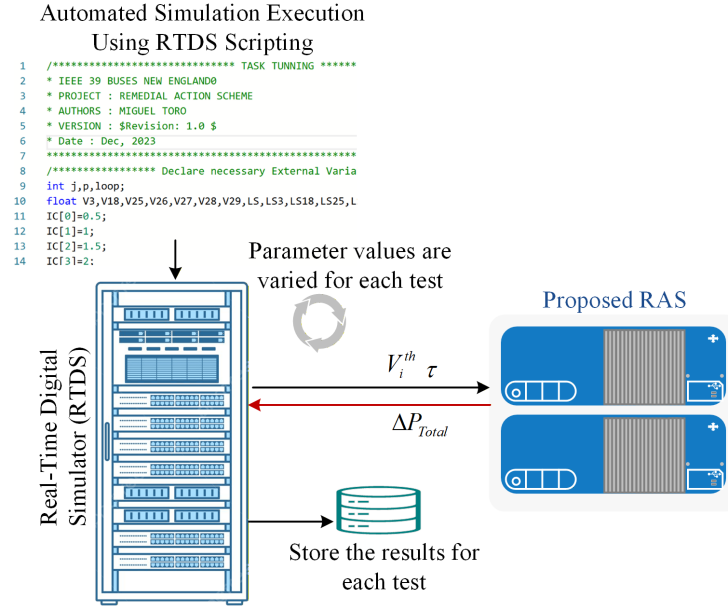


Figure 3.11: Automated FIDVR assessment using RTDS scripting in a HIL environment.

ology is illustrated in [Figure 3.11](#). Also, [Table 3.2](#) summarizes the communication delays associated with the data exchange paths between the devices, as well as the processing times required for each task executed by the RTAC industrial-grade controllers.

Table 3.2: Processing times associated with the HIL validation platform

Communication path and device	Protocol	Time
Physical system GTNETx2 → RTAC-A (Measurements of the system)	DNP3	100 ms
RTAC-A (WLS-Based state estimator)	-	1 s
RTAC-A → RTAC-B (Operating point)	NGVL	10 ms
RTAC-B (Digital twin)	-	1 s
RTAC-B (FIVDR assessment)	-	4 ms
Physical system GTNETx2 ↔ RTAC-A (Breaker status and trip signals)	GOOSE	4 ms

With the HIL validation platform fully implemented and configured, a testing environment is available to evaluate the performance of the proposed RAS under realistic operating conditions, using industrial-grade controllers similar to those deployed in actual substations. This setup provides a high degree of realism, bridging the gap between simulation-based assessment and real-world implementation. The results obtained from these experiments enable a detailed evaluation of load-shedding effectiveness, system response under contingencies, and FIDVR performance. In the following section, the simulation results are presented, highlighting the capability of the proposed RAS to maintain voltage stability within the protected area.

3.5 Results of the HIL Implementation

This section presents the validation and performance assessment of the proposed RAS using the developed HIL platform. The results are organized into two main subsections. The first subsection focuses on validating the computational models implemented within the RAS, namely the WLS-based state estimator and the pseudo-arc-length CPF used as a system-level digital twin, both deployed on industrial-grade controllers. This validation verifies the accuracy and reliability of the core algorithms prior to evaluating the overall scheme. The second subsection assesses the integrated perfor-

mance of the proposed RAS, examining its behavior from the design phase to its real-time operation on the HIL validation platform described in the previous section.

WLS-Based State Estimator and Digital Twin Validation

To verify the correct implementation of the WLS-based state estimator in *RTAC-A*, a validation procedure was conducted. Measurements generated by the RTDS at the locations shown in [Figure 3.8](#) were processed offline using a WLS estimator developed in MATLAB. The resulting state vector was compared with both the actual RTDS operating point and the estimates produced by *RTAC-A*. As shown in [Figure 3.12](#), a high level of agreement is observed among the three references. These results confirm the accurate implementation of the WLS algorithm in *RTAC-A* and validate its capability to provide a reliable state representation of the physical power system for the system-level digital twin within the RAS information flow.

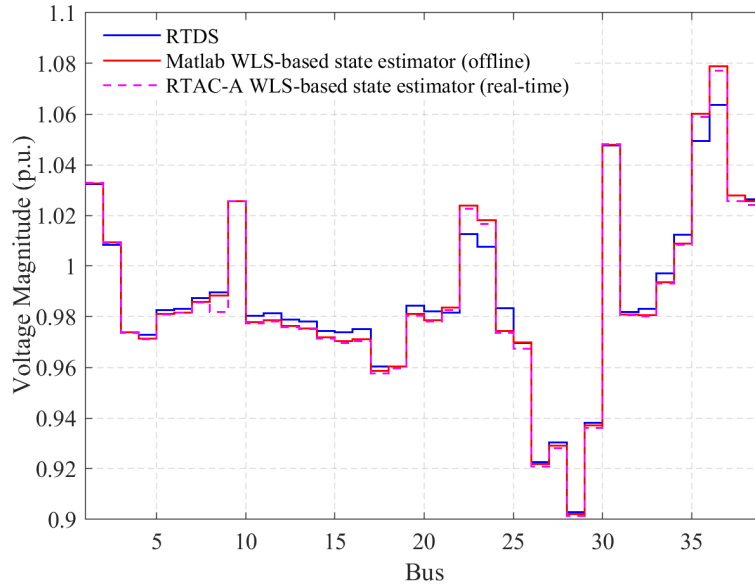


Figure 3.12: Comparison of voltage magnitude estimation results: *RTAC-A*, *MATLAB*, and *RTDS*.

Regarding the system-level digital twin, the voltage stability margin computed in real time by *RTAC-B* must be consistent with the results obtained during the offline design stage using professional power system analysis tools. This consistency ensures that the stability indices used to dimension the RAS remain representative of the physical system under actual operating conditions. If the voltage stability margin is inaccurately estimated, the resulting load shedding may significantly deviate from the values defined in the offline study, leading to insufficient or excessive corrective actions and increasing the vulnerability of the power system to voltage instability under real contingencies. Therefore, the pseudo-arc-length CPF implemented in *RTAC-B* is validated to verify that both the PV curve tracing process and the estimated voltage stability margins reproduce the results obtained from established analysis software.

[Figure 3.13](#) compares the PV curve obtained from the offline PSS/E analysis with the curve computed in real time by the pseudo-arc-length CPF implemented as the system-level digital twin in *RTAC-B*, considering the RTDS operating point as the initial condition. A high level of agreement is observed between both curves across the analyzed loading range, including the vicinity of the maximum power transfer point.

[Table 3.3](#) presents a quantitative comparison of the maximum power transfer point, expressed in MW, computed using PSS/E, *MATLAB*, and *RTAC-B*, considering the same operating condition for

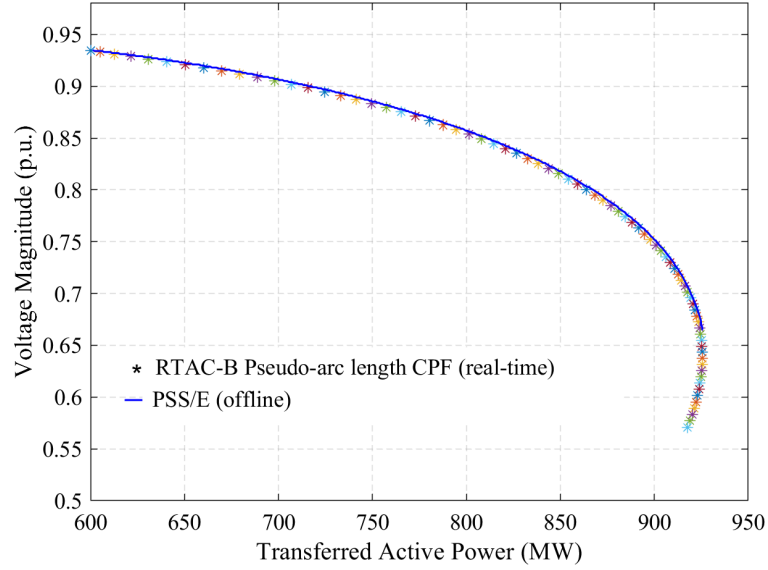


Figure 3.13: Comparison of PV curves computed using PSS/E and the system-level digital twin.

load buses 4, 8, 16, 18, 24, and 27. The PSS/E results are taken as the reference, and the percentage errors associated with the MATLAB and RTAC-B implementations are reported accordingly. A high level of agreement is observed among the three platforms, with a maximum deviation of RTAC-B relative to PSS/E not exceeding 0.012%.

Table 3.3: Maximum power transfer point comparison among PSS/E, MATLAB, and RTAC-B

Bus	PSS/E (MW)	MATLAB (MW)	RTAC-B (MW)	MATLAB Error (%)	RTAC-B Error (%)
4	871.95	871.87	871.85	0.009	0.011
8	910.32	910.52	910.21	0.022	0.012
16	573.74	573.81	573.67	0.012	0.012
18	275.53	275.63	275.50	0.036	0.011
24	538.16	538.31	538.10	0.028	0.011
27	490.04	490.01	489.98	0.006	0.012

This level of accuracy confirms the capability of the system-level digital twin to reproduce the PV curves obtained in offline studies. Consequently, it validates its use for real-time voltage stability margin monitoring and for adjusting the load-shedding amounts executed by the proposed RAS.

Performance Results of the Proposed RAS

As defined in the proposed RAS framework, the design stage relies on offline voltage stability studies using the voltage stability margin as the primary security index. The following results are derived under this previously established methodology. The voltage stability margin is characterized through PV curve tracing by monitoring the voltage at bus 28 as a function of the power transferred through transmission lines 1–2, 4–3, and 16–17. These lines constitute the electrical interconnection between the protected area and the remainder of the power system, enabling a direct assessment of the relationship between interconnection power transfer and the corresponding voltage stability margin. Regarding the configuration of T_{system} , the selected load buses are 3, 15, 16, 18, 20, 21, 23, 24, 25, 26, 27, and 29, and the generator buses considered are 31, 32, and 39. These buses are selected due to their high sensitivity during PV curve tracing, as they exhibit the greatest impact on the voltage stability margin associated with the power transferred through the interconnection of interest.

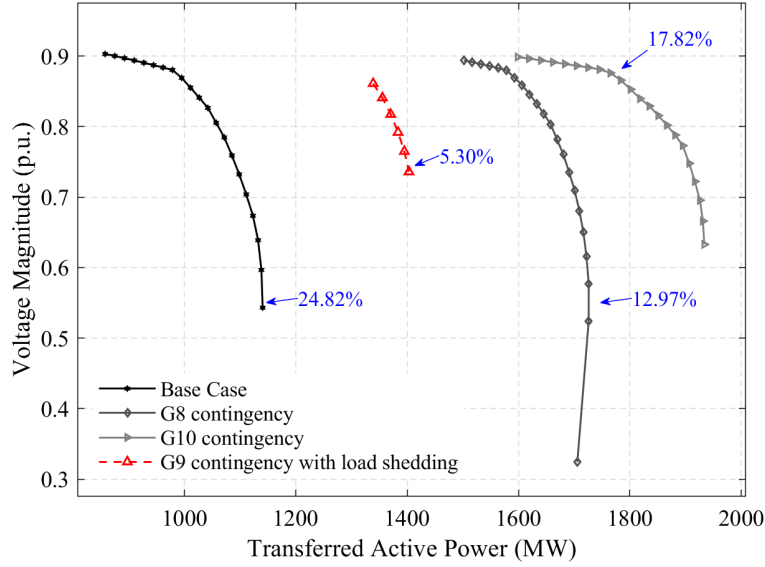


Figure 3.14: Voltage stability margins for generation-loss contingencies (offline study).

For the RAS design stage, a minimum stability margin of 5% is adopted, consistent with criteria used in previous studies of the Panamanian power system. This threshold defines the minimum acceptable operating condition before corrective action by the scheme is required. Figure 3.14 presents the PV curves obtained offline for contingencies associated with the loss of generators G8, G9, and G10. Under normal operating conditions, corresponding to the base case, the power system exhibits a voltage stability margin of 24.82%, indicating an operating condition well separated from both the voltage collapse point and the established minimum stability margin. Following the G8 and G10 contingencies, the initial operating point shifts toward higher levels of power transfer across the interconnection, partially compensating for the lost generation. Nevertheless, the resulting stability margins, 12.97% and 17.82%, respectively, remain significantly above the 5% threshold. This indicates that the power system maintains a secure operating condition under these scenarios and does not require load-shedding actions.

However, for the G9 contingency, no feasible post-contingency equilibrium point is identified at the initial operating condition, indicating a voltage collapse scenario. To restore an acceptable operating condition, an offline load-shedding action of 440 MW is determined, distributed between buses 28 and 29. Following this corrective measure, a voltage stability margin of 5.30% is achieved, satisfying the predefined minimum stability margin. These offline results define the initialization operating parameters of the RAS for real-time operation, establishing static load-shedding settings of $LS-S_{28} = 220$ MW and $LS-S_{29} = 220$ MW.

Prior to the real-time FIDVR assessment, Figure 3.15 presents the results of the offline tuning process of the FIDVR assessment stage for the G9 contingency, using the simulation environment described in Figure 3.11. In this stage, different combinations of the parameters V_i^{th} and τ_i are analyzed to evaluate their impact on voltage recovery and on the load-shedding amounts determined by the FIDVR assessment stage. It is important to note that the total load-shedding values already include the contribution previously estimated by the system-level digital twin. The results indicate that ΔP_{total} increases for small values of τ and decreases for large values of τ , revealing the sensitivity of the scheme to this parameter. Consequently, not all τ settings are capable of computing a load-shedding amount that guarantees compliance with the ride-through constraints. For $\tau < 1.5$ s, all values of V_i^{th} satisfy the ride-through requirements in the area of interest. Therefore, $V_i^{th} = 0.85$ p.u. and $\tau = 1.5$ s are selected as the final parameter settings for the FIDVR stage. These values

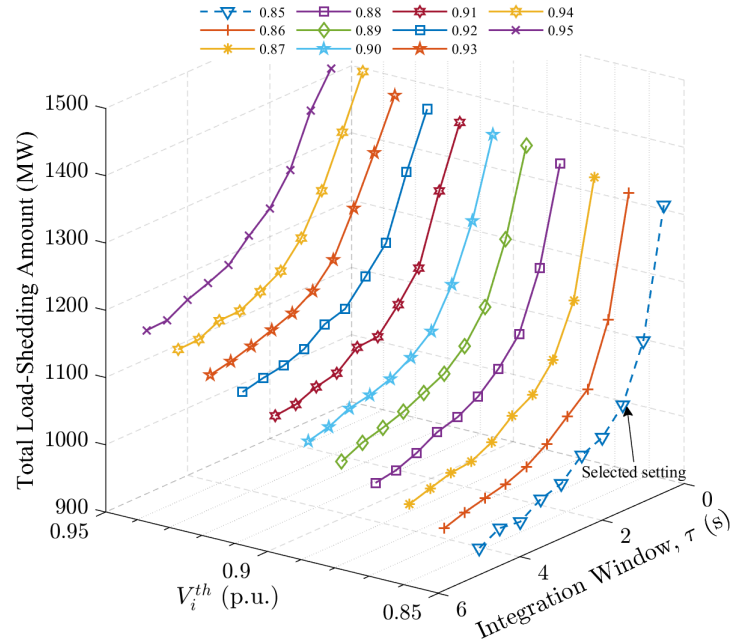


Figure 3.15: HIL-based offline tuning of the FIDVR assessment stage under G9 contingency.

provide adequate voltage recovery while avoiding excessive and unnecessary load shedding.

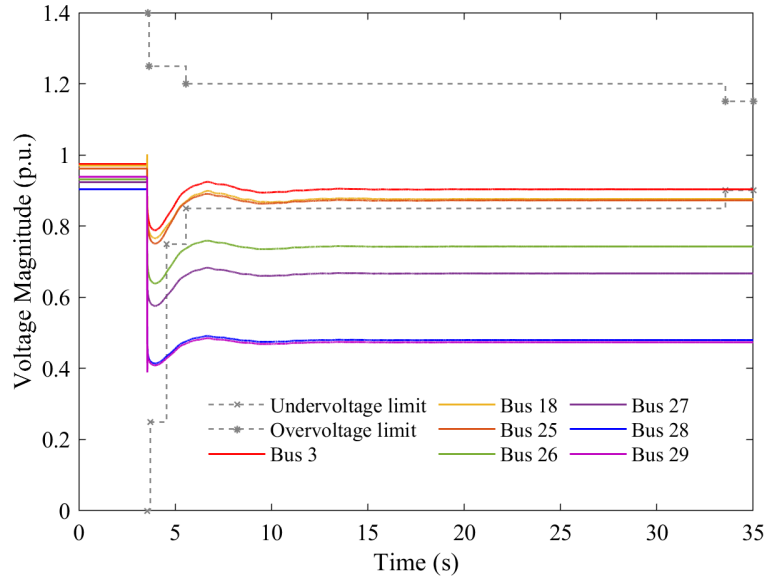


Figure 3.16: Dynamic voltage response of the protected area under G9 contingency without RAS.

Considering the real-time operation of the physical test system, **Figure 3.16** presents the dynamic voltage response of the buses in the area of interest under contingency G9, in the absence of the proposed RAS. Although the power system maintains angular stability and no loss of synchronism is observed, the buses closest to the event experience the most severe voltage drop. Furthermore, the power system fails to restore voltage levels within the time window defined by the ride-through requirements, resulting in a sustained violation of the undervoltage limits. This operating condition is unacceptable from a security perspective, as it may trigger auxiliary undervoltage protection schemes, potentially leading to additional disconnections and progressive degradation of the overall power system performance.

When only the system-level digital twin stage in *RTAC-B* is activated, **Figure 3.17** illustrates the corresponding dynamic voltage response under contingency G9. In this scenario, the load-shedding actions $LS-S_{28}$ and $LS-S_{29}$ are determined exclusively through the DT-based evaluation, without activating the subsequent FIDVR stage. Compared with the no-RAS condition, a noticeable improvement in voltage recovery is observed. The depth of the voltage depression is reduced, and the post-contingency voltage levels increase accordingly. However, the voltage profiles still fail to comply with the undervoltage ride-through limits within the required time window. Therefore, although the system-level digital twin stage mitigates the severity of the contingency, it is not sufficient to guarantee secure system operation.

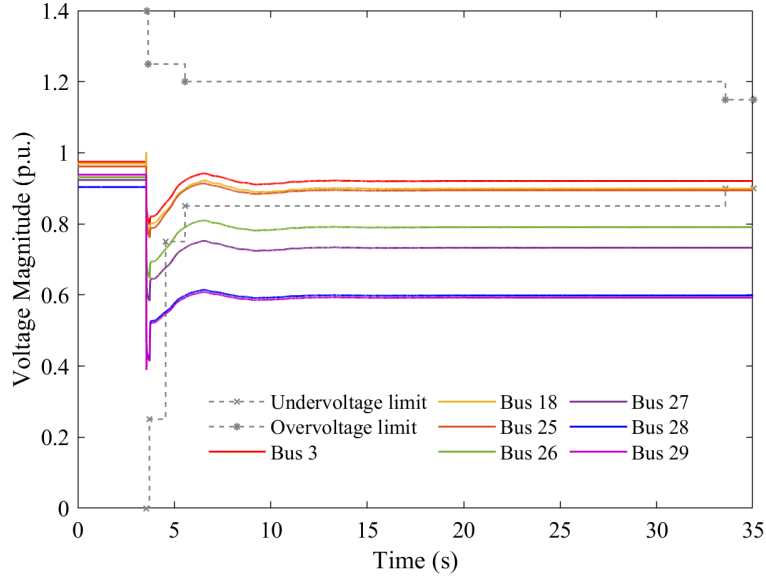


Figure 3.17: Dynamic voltage response of the protected area under G9 contingency with only the system-level digital twin stage activated.

Finally, **Figure 3.18** presents the voltage response with the complete RAS in service, incorporating both the static load-shedding stage ($LS-S$) and the FIDVR-oriented load-shedding stage ($LS-D$). Following the occurrence of contingency G9 and the associated breaker operating times, the load shedding previously validated through the system-level digital twin is implemented. At this stage, 440 MW are shed, distributed between buses 28 and 29.

Subsequently, *RTAC-B* processes the voltage trajectory, explicitly accounting for the impact of the first load-shedding action. Once the updated dynamic condition is assessed, the FIDVR stage is activated at those buses exhibiting a voltage deviation greater than 0.1 p.u. with respect to their pre-contingency values. Under this criterion, buses 26, 27, 28, and 29 satisfy the triggering condition.

Accordingly, the RAS executes the FIDVR-oriented load shedding with the following amounts:

- $LS-D_{26} = 41$ MW
- $LS-D_{27} = 46$ MW
- $LS-D_{28} = 232$ MW
- $LS-D_{29} = 297$ MW

Considering both the $LS-S$ and $LS-D$ stages, the total amount of load shedding reaches 1056 MW. As a result of both stages, the voltage recovery remains within the prescribed ride-through limits during the transient period. The voltage trajectories exhibit a controlled and sustained recovery, thereby preventing the activation of auxiliary undervoltage protection schemes within the area of interest and ensuring post-contingency operational stability.

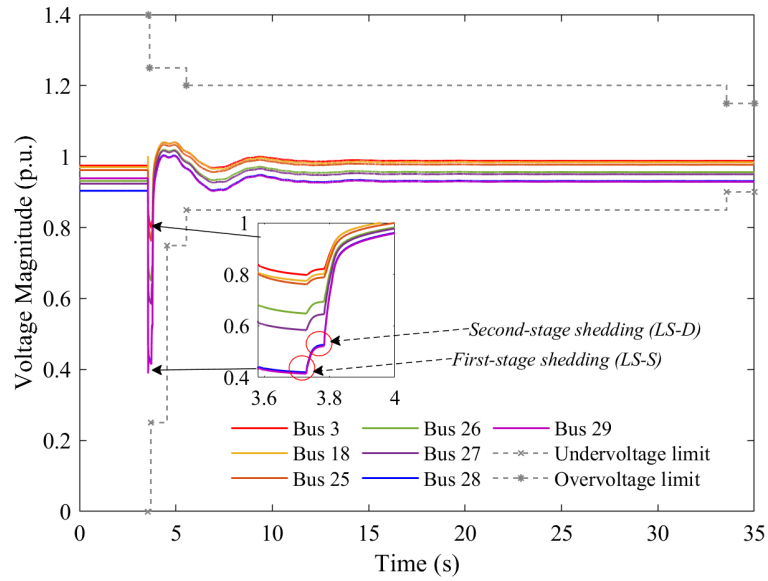


Figure 3.18: Dynamic voltage response of the protected area under G9 contingency with both LS-S and LS-D stages activated.

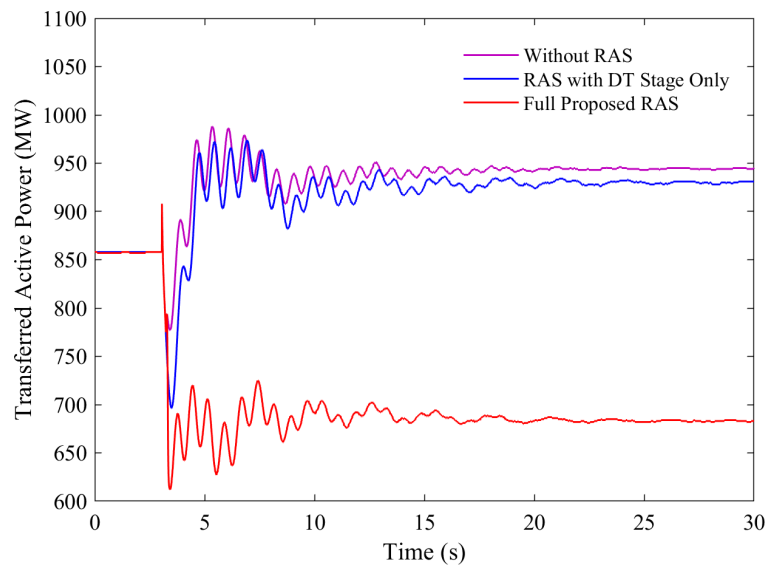


Figure 3.19: Active power transfer through the interconnection under G9 contingency for different RAS configurations.

Figure 3.19 illustrates the evolution of the active power transmitted through the interconnection supplying the protected area under three operating conditions: without the proposed RAS, considering only the system-level digital twin stage, and with the complete RAS in service. When both the system-level digital twin and the FIDVR assessment are fully deployed, the coordinated load-shedding action substantially reduces the active power transferred through the interconnection. This reduction effectively counteracts the post-contingency flow increase caused by the generation loss associated with contingency G9. Although the implemented load shedding is significant, the power system remains within a secure operating region under emergency conditions. The resulting operating point is less critical, thereby improving the system capability to withstand subsequent contingencies.

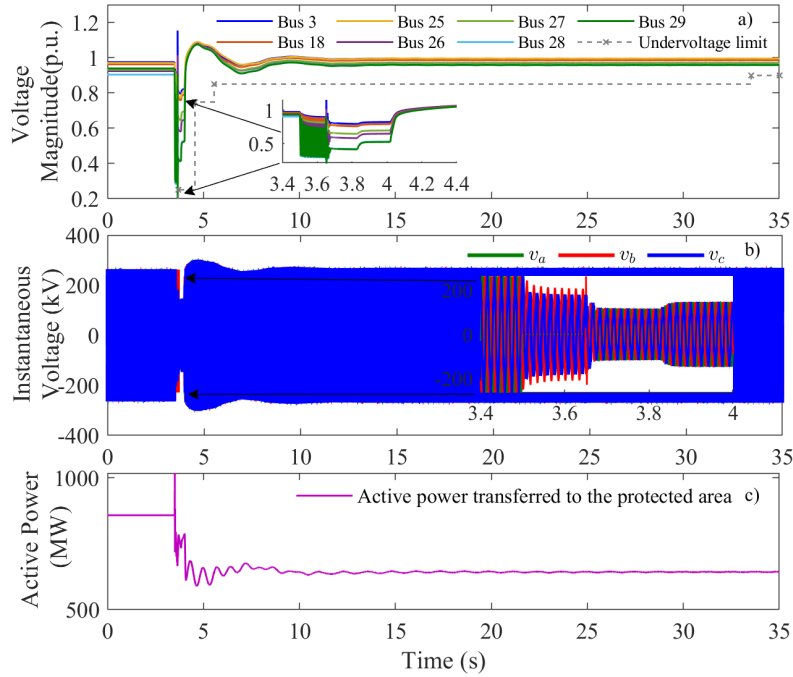


Figure 3.20: Dynamic response under single-phase fault followed by the G9 contingency with proposed RAS operation.

Contingencies involving the loss of a system element may originate from operational errors; however, in practical operation, they are more frequently initiated by electrical faults occurring near critical equipment, which subsequently activate conventional protection schemes. Such events produce severe voltage drops in the vicinity of the disturbance, potentially challenging the performance of the proposed RAS.

To evaluate this condition, a six-cycle single-phase fault is applied at bus 29, followed by the execution of contingency G9 once the fault is cleared, thereby reproducing a realistic cascading sequence. As shown in Figure 3.20, this sequence results in pronounced voltage deviations within the protected area. Under this condition, the proposed RAS sheds 1135 MW, providing sufficient corrective action to restore voltage profiles within ride-through limits while simultaneously reducing the power transferred to the protected area. The resulting post-contingency operating state remains secure despite the severity of the disturbance.

To further evaluate the robustness of the RAS, a more severe three-phase fault of the same duration is applied at bus 29. The corresponding response, presented in Figure 3.21, exhibits a deeper voltage drop. Under this more critical condition, the RAS sheds 1209 MW, enabling effective voltage recovery and maintaining system operation within acceptable ride-through limits. In addition, the active power delivered to the protected area is substantially reduced, reinforcing a stable post-

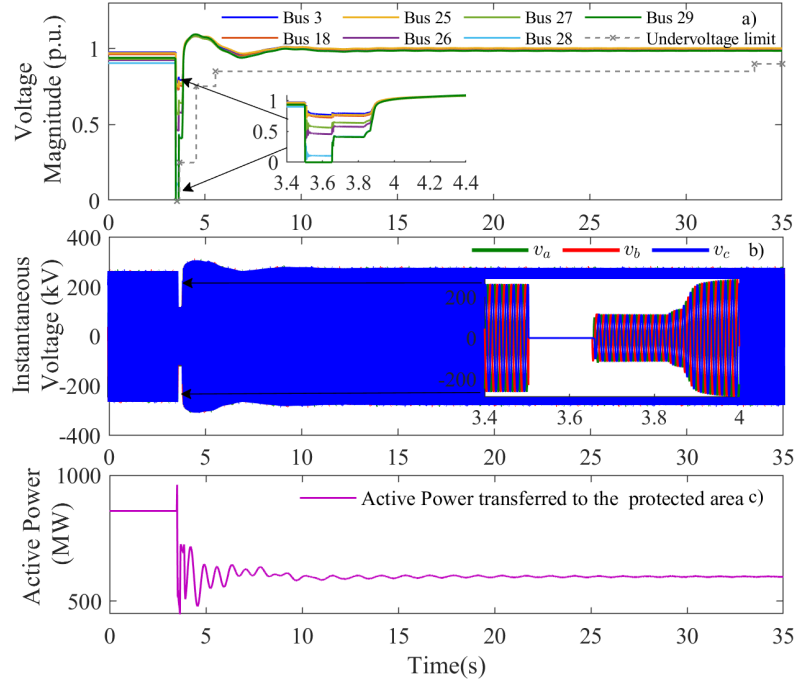


Figure 3.21: Dynamic response under three-phase fault followed by the G9 contingency with proposed RAS operation.

contingency operating state.

Table 3.4 summarizes the RAS performance under contingency G9, including cases preceded by single-phase and three-phase faults. The load shedding computed by the system-level digital twin stage in *RTAC-B* remains unchanged across all scenarios, as it is derived from a steady-state representation of the power system and is therefore not affected by transient fault dynamics. In contrast, the FIDVR assessment implemented in *RTAC-B* requires higher load-shedding levels under faulted conditions due to the deeper voltage depression, which increases the average voltage deviation ΔV_i^{av} . Nevertheless, the coordinated RAS action ensures compliance with ride-through voltage performance criteria, maintaining a secure post-contingency operating condition.

Table 3.4: Comparison of load shedding (MW) under different fault types

Event	Digital Twin			FIDVR Assessment			Total Amount	Meets Criteria
	$LS-S_{28}$	$LS-S_{29}$	$LS-D_{26}$	$LS-D_{27}$	$LS-D_{28}$	$LS-D_{29}$		
G9 Contingency	220	220	41	46	232	297	1056	✓
Single-Phase G9 Contingency	220	220	51	66	261	317	1135	✓
Three-Phase G9 Contingency	220	220	57	75	285	352	1209	✓

To evaluate the adaptability of the proposed RAS, its performance is assessed under an operating condition different from the one considered in the initial design and compared with a conventional fixed-setting RAS. A 50 MW load increase is distributed across buses 27, 28, and 29 to represent an increase in demand within the protected area. Under this modified condition, the system-level digital twin implemented in *RTAC-B* detects a reduction of the voltage stability margin below the 5% threshold and recalculates the required load shedding. The adaptive process increases the corrective action until the stability margin exceeds 5%, resulting in updated static shedding settings of 230 MW at bus 28 and 230 MW at bus 29, with a calculated margin of 5.31%. These updated settings replace the load-shedding values previously determined through offline studies for contingency G9.

Figure 3.22 compares the post-contingency voltage responses obtained with the conventional and the proposed RAS. The conventional fixed-setting scheme, which applies 1056 MW of load shedding,

Table 3.5: Load-shedding comparison (MW): proposed RAS vs. conventional RAS

Event	Digital Twin		FIDVR Assessment						Total Amount	Meets Criteria
	LS-S ₂₈	LS-S ₂₉	LS-D ₁₈	LS-D ₂₅	LS-D ₂₆	LS-D ₂₇	LS-D ₂₈	LS-D ₂₉		
G9 Contingency, Conventional RAS	–	–	–	–	–	–	–	–	1056	×
G9 Contingency, Proposed RAS	230	230	18	441	49	59	286	351	1664	✓
Three-Phase G9 Contingency, Conventional RAS	–	–	–	–	–	–	–	–	1056	×
Three-Phase G9 Contingency, Proposed RAS	230	230	21	441	51	63	290	357	1683	✓

involving a three-phase fault. In both cases, the proposed RAS readjusts the required load shedding according to the updated operating point, characterized by increased demand levels. Conversely, the conventional RAS maintains a fixed amount of load shedding that proves insufficient to satisfy the ride-through limits.

The results obtained in this section confirm that the proposed RAS preserves voltage stability under contingencies. Both steady-state and transient evaluations demonstrate that the system-level digital twin and the FIDVR assessment provide adequate load shedding to maintain the voltage stability margin and satisfy the established ride-through limits. In addition, the adaptive behavior of the proposed RAS allows the load shedding to be updated when operating conditions change. This prevents the power system from operating with insufficient load shedding, as observed with the conventional RAS. Consequently, the proposed RAS maintains a secure post-contingency operating point and reduces the risk of progressive voltage degradation following severe contingencies.

4

Data-Driven Digital Twin and Replica for a Frequency Stability-Oriented Remedial Action Scheme

While [Chapter 3](#) addressed voltage stability through a new generation of RAS supported by a digital twin-based operational methodology, power systems also face critical challenges associated with frequency stability. Frequency stability is inherently associated with the active power balance between generation and demand. A sudden generation loss may lead to severe frequency deviations, potentially activating conventional RAS based on underfrequency load shedding.

As discussed in [Chapter 1](#), conventional UFLS schemes operate with fixed parameters, such as predefined frequency thresholds and multi-stage load-shedding structures. Their design has traditionally assumed relatively high and slowly varying levels of power system inertia. However, the increasing penetration of power-electronics-based resources has progressively reduced the effective inertia of modern power systems, limiting the capability of conventional UFLS schemes to respond efficiently to severe generation-loss events and to restore the generation-load balance.

To overcome these limitations, this chapter extends the digital twin-based RAS operational methodology introduced previously toward frequency stability. The proposed framework integrates real-time measurements into a system-level digital twin in order to adjust UFLS operating parameters according to the current operating condition and the severity of the contingency. By incorporating the replica concept for enhanced representation fidelity and leveraging data-driven methods to extract dynamic power system indicators, the framework enables load-shedding actions that are contingency-aware and condition-dependent.

The chapter is organized as follows. First, the fundamentals of frequency stability are reviewed. Next, the proposed RAS framework is presented, followed by the theoretical foundations of the data-driven components and the digital twin. Finally, the hardware-in-the-loop implementation is described, and the experimental results are analyzed.

4.1 Frequency Stability

Frequency is a vital and continuously monitored variable in power system operation, as it represents an indicator of the instantaneous balance between generation and demand. Under normal operating conditions, this balance remains close to zero, allowing the frequency to remain near its nominal value. However, following disturbances such as the sudden loss of generation, the disconnection of an interconnected area, or abrupt load variations, an active power imbalance arises and manifests as a frequency deviation.

Within this framework, frequency stability describes the ability of the power system to keep frequency within acceptable operational limits, arrest its deviation, and reach a new equilibrium following a disturbance [131]. Frequency stability is governed by active power dynamics and is therefore closely related to the elements capable of injecting active power, a role historically performed by synchronous machines. From a physical perspective, power system frequency is directly related to the angular speed of the synchronous machines connected to the grid. Because these machines are electrically coupled through the network, their electromechanical dynamics evolve in a coordinated manner. As a result, the dynamic behavior of frequency can be locally described through the simplified swing equation of the i -th synchronous machine. Assuming per-unit quantities on the machine base and neglecting damping effects, network losses, control dynamics, and higher-order electromechanical dynamics, the swing equation is expressed as

$$2H_i \frac{d\omega_i}{dt} \simeq P_{m_i} - P_{e_i} = \Delta P_i \quad (4.1)$$

where the subscript i denotes the i -th synchronous machine connected to the power system, H_i is its inertia constant, ω_i is its rotor angular speed in per unit, P_{m_i} is the mechanical input power, P_{e_i} is the electrical output power, and ΔP_i is the active power imbalance associated with that machine. Powers are also expressed in per unit. The symbol $\simeq$ emphasizes that this expression is a simplified electromechanical representation that neglects higher-order electromagnetic and control dynamics while retaining the dominant frequency behavior associated with primary frequency regulation.

This equation shows that any active power imbalance produces rotor acceleration or deceleration, leading to frequency deviations. In large-scale power systems, the dynamic frequency response is commonly represented using a **Center of Inertia (COI)** equivalent model. However, in modern low-inertia power systems, this aggregated representation must be interpreted with caution, since spatially distributed frequency dynamics and non-uniform inertial contributions may become more relevant.

In this context, the frequency trajectory is the consequence of the aggregated electromechanical dynamics described above. **Figure 4.1** shows the time evolution of the power system frequency following a power imbalance, together with the intervals during which different frequency control mechanisms act. Initially, the power system operates under normal conditions at nominal frequency. At point A, a sudden loss of generation occurs, causing an imbalance between the mechanical power supplied by the generators and the electrical power demanded by the load, which results in a frequency deviation. During the first instants after the event, the kinetic energy stored in the rotating masses of synchronous machines is injected into the grid. This inertial response, inherent to the electromechanical dynamics of these machines, initially mitigates the frequency decrease and constitutes the first line of defense of the power system.

After the first few seconds, and before primary control fully compensates for the imbalance, the frequency reaches its minimum value, known as the frequency nadir, identified as point B. This point represents the lowest frequency recorded during the post-event transient. From the nadir onward, primary frequency control is activated through turbine governors, which adjust the me-

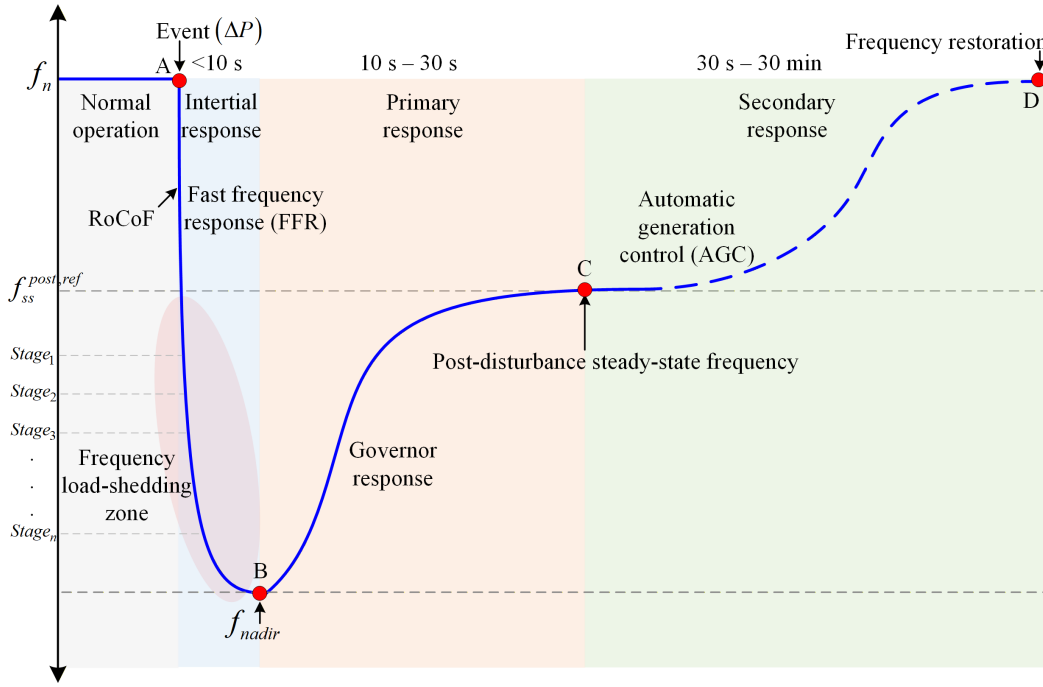


Figure 4.1: Dynamic frequency response of the power system after a generation imbalance.

chanical power of synchronous machines to reduce the generation-demand imbalance. As a result, the frequency settles at a new steady-state value, identified as point C. This value depends on the control strategy implemented in the governors. Under isochronous control, the frequency can be restored to its nominal value. However, in practice, droop-based schemes are more common, in which the final steady-state frequency deviates from nominal according to the regulation slope and the active power reserve assigned to primary frequency control. Subsequently, secondary frequency control is activated through the automatic generation control system. Its objective is to eliminate the remaining frequency deviation after primary control by adjusting the operating setpoints of generating units, thereby restoring the power system frequency to its nominal value, as indicated by point D.

On the other hand, large generation outages may occur whose magnitude exceeds the compensation capability of primary and secondary frequency control. Under such conditions, the frequency may continue to decline until it reaches the operating thresholds of UFLS schemes. These schemes operate through a multi-stage logic designed to reduce the active power imbalance, arrest the frequency decline, and stabilize the power system. In modern power systems with high penetration of power-electronics-based renewable generation, frequency dynamics have become more severe. Reduced power system inertia and limited availability of spinning reserve lead to lower nadir values, higher RoCoF values, and more pronounced steady-state frequency deviations following an event. As a consequence, UFLS schemes may trigger a greater number of load-shedding stages, resulting in excessive load shedding that does not necessarily reflect the actual magnitude of the power deficit, but rather the speed and depth of the transient frequency response.

Although control strategies providing virtual inertia or **Fast Frequency Response (FFR)** from renewable resources have been proposed, their implementation typically requires additional resources, particularly large-scale **Energy Storage System (ESS)**. Consequently, RAS must evolve beyond conventional frequency- and RoCoF-based triggering logic by incorporating additional system-state information, enabling more informed and selective UFLS actions suited to modern low-inertia power systems.

4.2 Proposed RAS Framework

The proposed RAS framework is based on the limitations of conventional UFLS schemes identified in Chapter 1 and extends the model-based RAS methodology previously developed for voltage stability toward a frequency-stability-oriented application. The proposed RAS combines a system-level digital twin, continuously synchronized with the physical system, with data-driven techniques to extract deeper information from the dynamic behavior of the power system. This hybrid structure enables a more accurate characterization of the frequency response under severe contingencies. The primary objective of the RAS is to ensure that, following a severe contingency, the power system reaches a reference post-contingency steady-state frequency, denoted as $f_{ss}^{\text{post,ref}}$, such that primary and secondary frequency controls can subsequently restore the frequency to its nominal value.

The methodology proposed in this work assumes the prior existence of a conventionally designed UFLS scheme, in which the load-shedding stages, including frequency thresholds and associated load blocks, have already been defined. Unlike conventional UFLS schemes, which generally assume that the load circuits assigned to each stage are available and operating at their nominal load levels, the proposed methodology explicitly accounts for the actual load availability at each shedding stage.

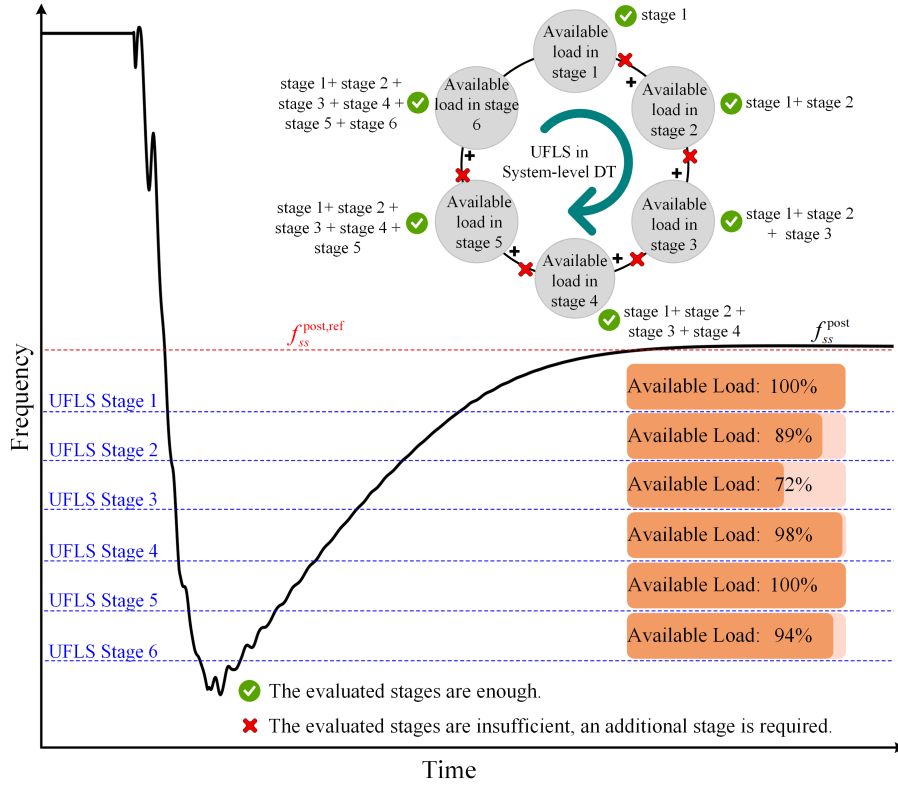


Figure 4.2: Operational flowchart of the initial stage of the proposed UFLS-RAS framework.

Figure 4.2 illustrates the initial operating methodology of the proposed RAS. In this stage, the multistage structure of the conventional UFLS scheme is preserved, while the actual load power available at each stage is explicitly considered. A steady-state power flow model with primary frequency regulation is employed as a system-level digital twin and is continuously updated using measurements from the physical power system. Based on this digital representation, the RAS evaluates the n -th contingency through virtual load shedding within the system-level digital twin. The objective is to determine the minimum number of UFLS stages required for the post-contingency

steady-state frequency, f_{ss}^{post} , to exceed the predefined reference value, $f_{ss}^{\text{post,ref}}$, while explicitly considering the actual load available in the circuits associated with each shedding stage.

Figure 4.3 provides a more detailed view of the stage that determines the number of UFLS stages required for the n -th contingency. Once the minimum number of stages has been identified, the RAS performs a second step through a multi-run simulation stage. During this stage, multiple virtual load-shedding scenarios are executed within the system-level digital twin in order to fine-tune the total amount of load shedding.

The objective of this stage is to obtain a value of f_{ss}^{post} as close as possible to the desired reference value, $f_{ss}^{\text{post,ref}}$, while avoiding excessive load shedding. At this stage, the proposed RAS establishes a preliminary estimate of the required amount of load shedding, denoted as static load shedding ($LS-S$), since it is obtained from a steady-state model. The load-shedding amount estimated through the system-level digital twin stage, $LS-S$, seeks to identify a steady-state equilibrium point following a contingency in the power system. However, since this estimate is derived from a steady-state model, it does not allow the assessment of the dynamic frequency performance during the transient period following the contingency.

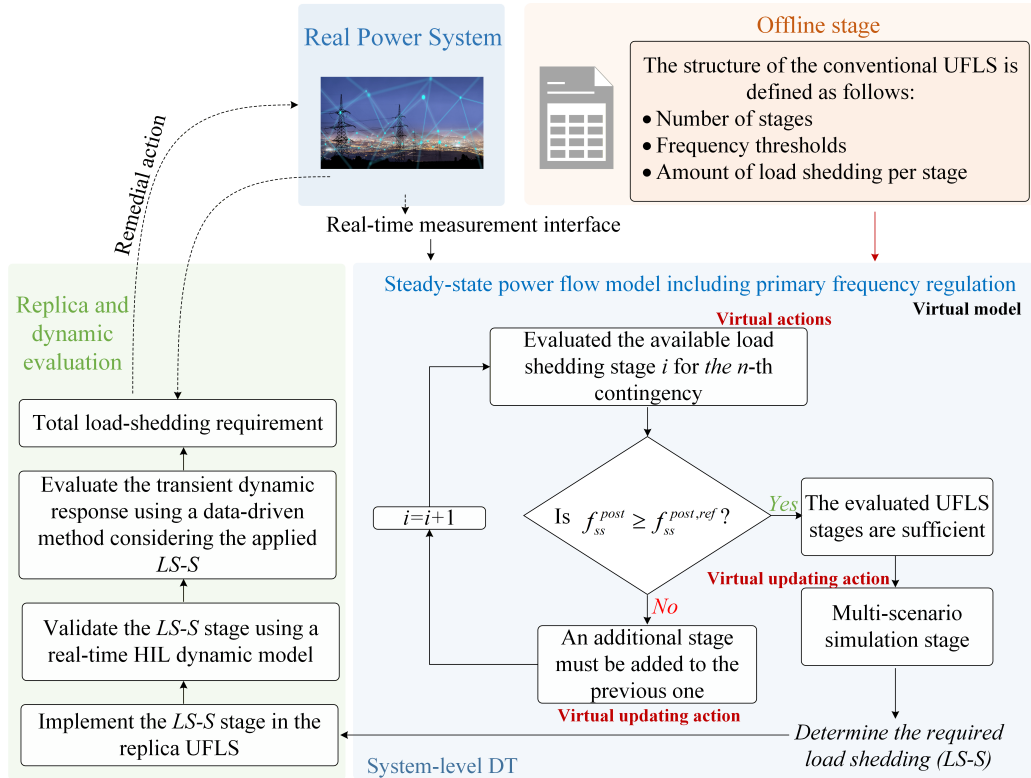


Figure 4.3: Flowchart of the proposed UFLS-RAS framework integrating the system-level digital twin, replica-based validation, and data-driven dynamic assessment.

To overcome this limitation, the proposed RAS incorporates a second stage based on a dynamic model of the power system implemented in a real-time simulator, which interacts with a physical replica of the UFLS scheme. The objective of this stage is to validate the impact of the previously estimated $LS-S$, evaluating its effect on the transient response of frequency and other relevant system variables. This stage also captures the physical interaction with the industrial-grade controllers in which the UFLS algorithm is deployed. If the power system exhibits an adequate dynamic response and stability is preserved throughout the transient period, the $LS-S$ value is retained as the final load-shedding amount. Otherwise, an incremental adjustment is performed to improve the dynamic

performance, resulting in an additional load-shedding amount, denoted as $LS-D$.

The amount $LS-S$ is implemented as a single-stage load-shedding action using the threshold associated with the first stage of the conventional UFLS scheme. The remaining UFLS stages remain enabled as backup actions in case significant mismatches arise between the model-based assessment and the actual power system response. However, because the load shedding is concentrated in a single stage, large load-shedding actions may produce unfavorable dynamic behavior, such as sustained or poorly damped low-frequency oscillations, potentially compromising the overall stability of the power system.

To assess these issues, the proposed RAS incorporates a data-driven spatio-temporal analysis based on the Dynamic Mode Decomposition (DMD) method. This method enables the extraction of modal information from the dynamic response of the power system and facilitates a global assessment of the stability implications associated with the UFLS action. The DMD-based data-driven assessment stage is executed within the replica-based environment and the real-time dynamic model, allowing a comprehensive evaluation of the UFLS impact on power system dynamics. If the load-shedding action introduces poorly damped oscillatory behavior or modes with insufficient damping, the RAS can adjust the load-shedding amount to achieve a more conservative dynamic performance.

In summary, the proposed RAS framework is structured around the following components:

- A first-stage load-shedding action, $LS-S$, evaluated through a power-flow-based system-level digital twin incorporating primary frequency regulation.
- A second-stage load-shedding action, $LS-D$, in which the initially determined $LS-S$ action is first validated within a replica-based environment using a real-time simulator. If the dynamic response is insufficient, the framework is prepared to support an additional corrective load-shedding adjustment, denoted as $LS-D$.
- A data-driven assessment stage based on Dynamic Mode Decomposition to evaluate the impact of the UFLS action on power system dynamics.

This section introduced the operational methodology of the proposed RAS framework, extending the voltage-stability-oriented approach toward frequency stability. In order to provide a deeper understanding of the RAS architecture and its underlying principles, the theoretical foundations of each stage are described in detail. Accordingly, the following section presents the mathematical formulation upon which each stage of the RAS is built.

4.3 Theoretical Foundations

The theoretical formulation of the proposed frequency-oriented RAS remains grounded in steady-state models; however, the formulations considered here are specifically designed to capture frequency response characteristics. Consequently, a careful selection and understanding of these modeling approaches are required. This section analytically describes the core components employed within the proposed RAS framework, including the power-flow-based digital twin incorporating primary frequency regulation and the data-driven modal assessment stage based on Dynamic Mode Decomposition (DMD). The replica-based validation stage is addressed in greater detail in the implementation section.

Steady-State Detection Criterion for Power System Measurements

Since the system-level digital twin employed in the proposed RAS is based on a steady-state model, its updating process relies exclusively on measurements obtained from the physical power system

under steady-state or quasi-steady-state operating conditions. This ensures consistency between the model and the measurements used to feed it, thereby preventing inconsistencies that could arise from incorporating transient measurements into a steady-state representation. Accordingly, a criterion for steady-state detection is required.

To this end, the RAS continuously collects active and reactive power measurements from representative buses of the physical power system, from which the following measurement vector is constructed:

$$\mathbf{y} = [P_1 \cdots P_{N_m} Q_1 \cdots Q_{N_m}]^T \quad (4.2)$$

where N_m denotes the number of monitored buses considered for the steady-state detection criterion.

Using the measurement vector $\mathbf{y}$, the Euclidean norm of the difference between the current operating point and that recorded a few seconds earlier is computed in order to assess the degree of displacement of the power system operating point over this time interval, as expressed by:

$$\|\Delta \mathbf{y}\|_2 = \sqrt{\sum_{i=1}^{2N_m} (\Delta y_i)^2} \quad (4.3)$$

where

$$\Delta \mathbf{y} = \mathbf{y}(t) - \mathbf{y}(t - \Delta t) \quad (4.4)$$

A low value of the Euclidean norm indicates that the physical power system has remained operating under similar conditions during the observation interval. This norm is continuously monitored over a 3-second time window. If it remains below a predefined threshold throughout this interval, the RAS identifies that the physical power system has reached a steady-state condition. The 3-second window is selected because it encompasses the characteristic time scale of electromechanical oscillation modes. Once these modes are sufficiently damped, their oscillatory behavior is no longer significantly reflected in the measurement vector $\mathbf{y}$ and, consequently, in the Euclidean norm.

Detection of the steady-state condition enables the transmission of measurements to both the system-level digital twin and the replica-based dynamic evaluation stage. Conversely, the measurement update process is immediately suspended whenever the steady-state criterion is not satisfied.

Power-Flow-Based Digital Twin with Primary Frequency Regulation

The proposed RAS operating methodology is based on the frequency response of the power system. Therefore, the digital twin must be capable of capturing and representing this characteristic. Conventional steady-state power flow models have been widely used for power system analysis; however, traditional formulations are solved at nominal frequency and therefore do not explicitly represent frequency deviations. To overcome this limitation, a steady-state power flow formulation that explicitly incorporates frequency variations is required.

The proposed RAS employs the Universal Power Flow (UPF) model as a system-level digital twin [132, 133]. This formulation extends the conventional steady-state power flow by incorporating droop-controlled generation units in primary frequency regulation. Since the proposed RAS requires only the post-contingency steady-state frequency to determine the corrective load shedding, rather than the complete transient response, the UPF provides an appropriate balance between model fidelity and computational efficiency for real-time operation. Within this framework, the active power output of these units varies as a function of frequency deviations according to:

$$\Delta P_{\text{Droop},\gamma} = \frac{(1 - f_{\text{pu}})S_{\text{Droop},\gamma}}{R_{\gamma}} \quad (4.5)$$

where $\Delta P_{\text{Droop},\gamma}$ represents the active power variation of the γ -th generation unit operating under droop control, f_{pu} denotes the system frequency in per unit, $S_{\text{Droop},\gamma}$ is the base power of unit γ , and R_{γ} is its droop coefficient.

Consequently, the active power output of a generation unit operating under droop control is expressed as:

$$P_{\text{Droop},\gamma} = P_{\text{Droop},\gamma}^{\text{Ref}} + \frac{(1 - f_{\text{pu}})S_{\text{Droop},\gamma}}{R_{\gamma}} \quad (4.6)$$

where $P_{\text{Droop},\gamma}^{\text{Ref}}$ is the active power reference setpoint of unit γ at nominal frequency.

Generation units operating under constant-power control deliver an active power output independent of frequency deviations:

$$P_{\text{Const},\gamma} = P_{\text{Const},\gamma}^{\text{Ref}} \quad (4.7)$$

where $P_{\text{Const},\gamma}^{\text{Ref}}$ is the scheduled power setpoint of unit γ .

From the previous formulation, the active power flow equations at bus i containing droop-controlled generation units are written as:

$$\begin{aligned} P_{\text{Droop},i}^{\text{Ref}} = & P_{\text{Load},i} - P_{\text{LS-S},i} - \sum_{\gamma=1}^{m_i} \frac{(1 - f_{\text{pu}})S_{\text{Droop},\gamma}}{R_{\gamma}} \\ & + |V_i| \sum_{n=1}^N |Y_{in}| |V_n| \cos(\delta_i - \delta_n - \theta_{in}) \end{aligned} \quad (4.8)$$

where $P_{\text{Droop},i}^{\text{Ref}}$ denotes the aggregate active power reference of the generation units connected to bus i , m_i is the total number of generation units connected to that bus, $P_{\text{LS-S},i}$ represents the amount of load shedding at bus i , and $Y_{in} = |Y_{in}| \angle \theta_{in}$ denotes the (i, n) element of the bus admittance matrix.

Similarly, the active power flow equations at bus i comprising generation units operating under constant-power control are represented as:

$$\begin{aligned} P_{\text{Const},i}^{\text{Ref}} = & P_{\text{Load},i} - P_{\text{LS-S},i} \\ & + |V_i| \sum_{n=1}^N |Y_{in}| |V_n| \cos(\delta_i - \delta_n - \theta_{in}) \end{aligned} \quad (4.9)$$

In general, the active power flow equations are expressed as:

$$\begin{aligned} P_i^{\text{Ref}} = & P_{\text{Load},i} - P_{\text{LS-S},i} - \beta_i \\ & + |V_i| \sum_{n=1}^N |Y_{in}| |V_n| \cos(\delta_i - \delta_n - \theta_{in}) \end{aligned} \quad (4.10)$$

where

$$\beta_i = \sum_{\gamma=1}^{m_i} \frac{(1 - f_{\text{pu}})S_{\text{Droop},\gamma}}{R_{\gamma}} \quad (4.11)$$

and $\beta_i = 0$ for generation units operating under constant-power control.

Following the conventional power flow formulation, the reactive power equations are expressed as:

$$Q_i^{\text{Ref}} = Q_{\text{Load},i} - Q_{\text{LS-S},i} + |V_i| \sum_{n=1}^N |Y_{in}| |V_n| \sin(\delta_i - \delta_n - \theta_{in}) \quad (4.12)$$

where P_i^{Ref} and Q_i^{Ref} denote the specified nodal active and reactive power references used in the power balance equations.

Accordingly, the power flow problem is formulated as an extended system of equations in which frequency is treated as an additional state variable and updated at each Newton–Raphson iteration according to the load variations and the control modes of the generation units. Assuming that one bus angle is selected as the angular reference of the power system, the resulting Newton–Raphson formulation is expressed as:

$$\begin{bmatrix} \Delta \mathbf{P}^{\text{Ref}} \\ \Delta \mathbf{Q}^{\text{Ref}} \end{bmatrix} = \begin{bmatrix} \frac{\partial \mathbf{P}^{\text{Ref}}}{\partial f_{\text{pu}}} & \frac{\partial \mathbf{P}^{\text{Ref}}}{\partial \delta} & \frac{\partial \mathbf{P}^{\text{Ref}}}{\partial |V|} \\ \frac{\partial \mathbf{Q}^{\text{Ref}}}{\partial f_{\text{pu}}} & \frac{\partial \mathbf{Q}^{\text{Ref}}}{\partial \delta} & \frac{\partial \mathbf{Q}^{\text{Ref}}}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta f_{\text{pu}} \\ \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (4.13)$$

where $\Delta \mathbf{P}^{\text{Ref}}$ and $\Delta \mathbf{Q}^{\text{Ref}}$ denote the active and reactive power residual vectors associated with the UPF reference-power equations, following the notation adopted in [132].

Consistent with the CPF-based system-level digital twin previously developed for voltage stability assessment, the proposed UPF-based formulation extends the digital twin framework toward frequency stability analysis. By explicitly incorporating frequency as a state variable, the proposed system-level digital twin enables the RAS to estimate the post-contingency steady-state frequency and consequently determine the amount of load shedding, $LS-S$, required to drive the power system toward a desired post-contingency frequency target, $f_{ss}^{\text{post,ref}}$, for a given contingency.

However, since the computed load-shedding amount guarantees only the existence of a steady-state equilibrium point, its impact on the dynamic behavior of the power system must be further evaluated. To this end, the $LS-S$ stage is validated within a physical replica-based testing environment, described later in this chapter, where a real-time dynamic model of the power system is implemented. The primary objective of this stage is to evaluate the dynamic response of the power system under the previously determined $LS-S$ action. In particular, low-frequency oscillatory behavior is assessed using the Dynamic Mode Decomposition method, which is detailed in the following section.

Data-driven dynamic assessment based on dynamic mode decomposition

The transition toward modern power grids has led to operation increasingly close to transfer limits and to reduced effective inertia, largely due to the growing penetration of power-electronics-based generation. As a consequence, power grids have become more vulnerable to poorly damped low-frequency electromechanical oscillations [134]. In this context, the deployment of RAS, particularly load shedding actions implemented without adequate dynamic assessment, may inadvertently excite weakly damped modes, potentially degrading power grid stability instead of enhancing it [135].

Modal analysis is commonly used to assess oscillatory behavior, typically relying on small-signal state-space models [136]. However, obtaining accurate state-space representations in practical environments is often infeasible, primarily due to restricted access to detailed dynamic models of generation units and their control systems, especially in renewable plants where black-box implemen-

tations are predominant [137]. Since small-signal modal analysis requires explicit knowledge of the state-space structure, limited model transparency significantly constrains its applicability under real-time operating conditions [138].

To overcome these limitations, data-driven methods have emerged as an effective alternative for estimating oscillatory parameters directly from measurement data, without requiring an explicit dynamic model [139, 140]. Among the various methods proposed for modal identification, such as Prony and Eigensystem Realization Algorithms (ERA), many are sensitive to noise, prone to overfitting, or dependent on relatively long data windows for accurate estimation, which complicates their deployment in industrial-grade controller environments [141, 142].

In contrast, dynamic mode decomposition provides a computationally efficient spatio-temporal framework for extracting coherent dynamic structures directly from measured signals [143]. By approximating the dominant linear dynamics underlying nonlinear transients, DMD decomposes power grid responses into modes characterized by specific frequencies, damping ratios, and spatial patterns. Furthermore, it enables dimensionality reduction while preserving essential dynamic information. Therefore, the data-driven dynamic assessment framework complements the system-level digital twin by extending the overall stability assessment through the physical replica and real-time dynamic model environment.

Dynamic mode decomposition overview

Several algorithms have been proposed for DMD. The proposed RAS is based on the *exact* DMD framework [144]. The DMD method considers a sequence of measurement snapshots obtained from PMUs over a discrete-time observation window:

$$\mathbf{s}_k = \begin{bmatrix} s_1(k\Delta t) & s_2(k\Delta t) & \cdots & s_m(k\Delta t) \end{bmatrix}^T \in \mathbb{R}^m \quad (4.14)$$

where m denotes the number of synchronized PMU channels obtained from PMUs distributed throughout the power system, Δt represents the sampling period, and k is the discrete-time index. Assuming that the power grid evolution over a short observation window can be approximated by linear dynamics, the temporal progression of the snapshots is described by the discrete-time linear mapping [143]

$$\mathbf{s}_{k+1} = \mathbf{A}\mathbf{s}_k, \quad k = n, n+1, \dots, n+p-2 \quad (4.15)$$

where $\mathbf{A} \in \mathbb{R}^{m \times m}$ is the best-fit linear operator that advances the snapshot measurements forward in time. The operator $\mathbf{A}$ also represents a finite-dimensional approximation of the Koopman operator restricted to the subspace of the observed measurements [145]. The p snapshots are synchronized through their time stamps and arranged into two consecutive data matrices, each formed by $p-1$ snapshot pairs:

$$\begin{aligned} \mathbf{S}_1 &= \begin{bmatrix} | & | & & | \\ \mathbf{s}_n & \mathbf{s}_{n+1} & \cdots & \mathbf{s}_{n+p-2} \\ | & | & & | \end{bmatrix} \in \mathbb{R}^{m \times (p-1)}, \\ \mathbf{S}_2 &= \begin{bmatrix} | & | & & | \\ \mathbf{s}_{n+1} & \mathbf{s}_{n+2} & \cdots & \mathbf{s}_{n+p-1} \\ | & | & & | \end{bmatrix} \in \mathbb{R}^{m \times (p-1)}. \end{aligned} \quad (4.16)$$

The linear relationship (4.15) extended to all snapshot pairs in (4.16) yields the matrix equation $\mathbf{S}_2 \approx \mathbf{A}\mathbf{S}_1$. The best-fit linear operator is then obtained as the least-squares solution

$$\mathbf{A} = \mathbf{S}_2 \mathbf{S}_1^\dagger \quad (4.17)$$

where $\dagger$ denotes the Moore–Penrose pseudo-inverse. In large-scale power grids, constructing $\mathbf{A}$ explicitly from (4.17) becomes computationally prohibitive. To address this limitation, DMD computes a low-rank approximation of $\mathbf{A}$ by projection onto the dominant subspace obtained through the compact (economy-sized) Singular Value Decomposition (SVD) of $\mathbf{S}_1$ [146, 147]:

$$\mathbf{S}_1 = \mathbf{U}_r \mathbf{\Sigma}_r \mathbf{V}_r^T \quad (4.18)$$

where $r = \text{rank}(\mathbf{S}_1)$ and $\mathbf{U}_r \in \mathbb{R}^{m \times r}$, $\mathbf{\Sigma}_r \in \mathbb{R}^{r \times r}$, and $\mathbf{V}_r \in \mathbb{R}^{(p-1) \times r}$ contain the left singular vectors, the diagonal matrix of strictly positive singular values arranged in descending order, and the right singular vectors, respectively. Since $\mathbf{\Sigma}_r$ is invertible by construction, the pseudo-inverse admits the closed form $\mathbf{S}_1^\dagger = \mathbf{V}_r \mathbf{\Sigma}_r^{-1} \mathbf{U}_r^T$, which substituted into (4.17) yields the projected operator

$$\tilde{\mathbf{A}} = \mathbf{U}_r^T \mathbf{A} \mathbf{U}_r = \mathbf{U}_r^T \mathbf{S}_2 \mathbf{V}_r \mathbf{\Sigma}_r^{-1} \in \mathbb{R}^{r \times r} \quad (4.19)$$

The eigendecomposition of $\tilde{\mathbf{A}}$ provides the dynamic information of the system:

$$\tilde{\mathbf{A}} \mathbf{W} = \mathbf{W} \mathbf{\Lambda} \quad (4.20)$$

where $\mathbf{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_r)$ contains the discrete-time DMD eigenvalues and $\mathbf{W}$ the corresponding eigenvectors. The DMD modes, representing the spatial shape of each dynamic pattern, are obtained as

$$\mathbf{\Phi} = \mathbf{S}_2 \mathbf{V}_r \mathbf{\Sigma}_r^{-1} \mathbf{W} \quad (4.21)$$

Modal characterization from DMD eigenvalues. Each discrete-time DMD eigenvalue λ_j is mapped to its continuous-time counterpart through

$$\mu_j = \frac{\ln(\lambda_j)}{\Delta t} \quad (4.22)$$

from which the oscillation frequency f_j and damping ratio ζ_j associated with mode j are computed as

$$f_j = \frac{|\text{Im}(\mu_j)|}{2\pi}, \quad \zeta_j = -\frac{\text{Re}(\mu_j)}{\sqrt{\text{Re}(\mu_j)^2 + \text{Im}(\mu_j)^2}} \quad (4.23)$$

These two quantities constitute the dynamic indicators used by the data-driven assessment to evaluate the electromechanical response of the power grid after the contingency and the load-shedding action.

Real-time considerations. To integrate the DMD-based assessment within the proposed RAS, careful consideration must be given to the computational requirements of the method, particularly under real-time constraints in industrial-grade controllers with finite resources. The compact SVD of $\mathbf{S}_1$ and the eigendecomposition of $\tilde{\mathbf{A}}$ constitute the most computationally demanding stages and may compromise real-time feasibility if not properly addressed. Moreover, many industrial-grade controllers deployed in power grid substations lack native support for advanced matrix operations, which further complicates the integration of data-driven methods such as DMD within remedial action schemes. The following subsections describe how these stages are handled efficiently in the proposed RAS to ensure reliable performance.

Compact singular value decomposition

The singular value decomposition is one of the most fundamental matrix factorizations in modern computational mathematics and is widely used in applications such as optimal low-rank approximation and the computation of pseudo-inverses for non-square matrices. Its relevance becomes particularly evident in systems that generate large volumes of measurement data organized into high-dimensional matrices. In complex infrastructures such as power grids, measurements collected from multiple devices can be structured into large-scale data matrices whose dimensionality grows with temporal and spatial resolution. Despite this structural complexity, such data typically exhibit an inherent low-rank structure: a few dominant patterns explain most of the high-dimensional behavior [148]. In this context, the SVD provides a robust and efficient framework to extract these dominant components and construct meaningful low-dimensional representations of the data. A key practical advantage of the SVD is that it exists for every matrix, which makes it reliable for embedded implementations. For these reasons, the SVD plays a central role in enabling the data-driven dynamic assessment based on DMD within the proposed RAS framework.

Considering the full SVD of $\mathbf{S}_1 \in \mathbb{R}^{m \times (p-1)}$, when $m > p - 1$ the diagonal matrix $\mathbf{\Sigma}$ has at most $p - 1$ non-zero elements on its diagonal and can therefore be partitioned as [149]

$$\mathbf{\Sigma} = \begin{bmatrix} \mathbf{\Sigma}_r \\ \mathbf{0} \end{bmatrix} \quad (4.24)$$

where $\mathbf{\Sigma}_r \in \mathbb{R}^{r \times r}$ contains the $r = \text{rank}(\mathbf{S}_1)$ strictly positive singular values arranged in descending order, and the trailing zero block accounts for both the structural zero singular values (due to $m > p - 1$) and any zero singular values produced by rank deficiency. Retaining only the non-zero singular values and their associated singular vectors yields the *compact* (also known as *economy-sized*) SVD of $\mathbf{S}_1$:

$$\mathbf{S}_1 = \begin{bmatrix} \mathbf{U}_r & \mathbf{U}_r^\perp \end{bmatrix} \begin{bmatrix} \mathbf{\Sigma}_r \\ \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{V}_r^T \\ \mathbf{V}_r^{T\perp} \end{bmatrix} = \mathbf{U}_r \mathbf{\Sigma}_r \mathbf{V}_r^T \quad (4.25)$$

where the columns of $\mathbf{U}_r^\perp$ and the rows of $\mathbf{V}_r^{T\perp}$ span subspaces orthogonal and complementary to those spanned by $\mathbf{U}_r$ and $\mathbf{V}_r^T$, respectively. By construction, $\mathbf{\Sigma}_r$ is invertible, which is essential for the explicit computation of the pseudo-inverse used in the DMD formulation. Figure 4.4 illustrates the difference between the full and compact SVD.

A more aggressive reduction can be obtained by computing an optimal rank- k truncation with $k < r$. However, in this work the compact SVD is adopted because it removes only the components associated with zero singular values, without imposing an additional modal truncation criterion. By preserving all strictly positive singular values, the dynamic information represented within the numerical rank of the data matrix is retained, and the need to select a truncation rank- k *a priori* is avoided, preventing the unintended removal of oscillatory modes whose excitation cannot be anticipated under arbitrary contingencies.

In practical implementations, computing the SVD involves a sequence of numerical procedures. The matrix $\mathbf{S}_1$ is first reduced to an upper bidiagonal form, after which QR-based iterative methods are applied to compute the singular vectors and the diagonal matrix of singular values. Since similar numerical procedures are required for the eigendecomposition of $\tilde{\mathbf{A}}$, these aspects are described in greater detail in the following subsection.

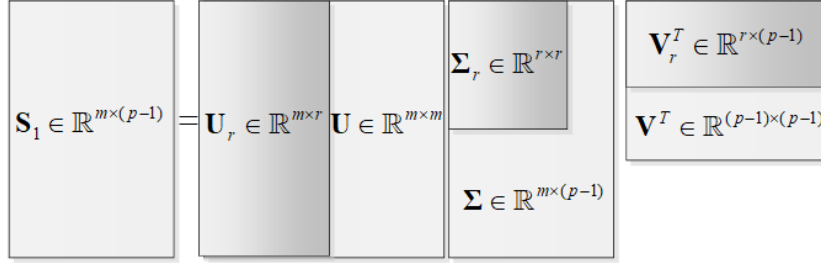


Figure 4.4: Reduction from full to compact SVD approach for the snapshot matrix S_1 .

Eigenvalue computation of the reduced DMD operator

Once the compact SVD has been computed, the reduced operator $\tilde{A}$ is constructed as in (4.19). The next step consists of computing its eigenvalues to extract the dynamic patterns of the power grid. During the early stages of this development, an alternative approach was evaluated, in which the eigenvalues of $\tilde{A}$ were estimated from its characteristic polynomial. The coefficients of the polynomial were obtained through the Leverrier–Faddeev algorithm from the successive traces of $\tilde{A}$, and the polynomial roots were estimated using the Laguerre method. This approach produced satisfactory results for low-dimensional cases (four to eight measurements). However, as the number of measurements (and hence the dimension of $\tilde{A}$) increased, the degree of the characteristic polynomial grew significantly, and root estimation became highly sensitive to small perturbations in the polynomial coefficients. For matrices of dimension $r > 10$ this approach proved unreliable. Consequently, the eigendecomposition of $\tilde{A}$ is computed instead using a QR-based algorithm, which provides a numerically stable and computationally efficient procedure for the matrices arising in the DMD method.

Since $\tilde{A}$ is in general a dense matrix, applying the QR-based algorithm directly is computationally expensive. To improve efficiency, $\tilde{A}$ is first transformed into upper Hessenberg form. A matrix is in upper Hessenberg form when all entries below the first subdiagonal are zero, that is, $h_{ij} = 0$ for $i > j + 1$. This structure preserves the eigenvalues of the original operator while substantially reducing the cost of subsequent QR iterations.

Several methods exist to obtain the Hessenberg form, including Givens rotations and the Arnoldi algorithm [150, 151]. Householder transformations are employed here due to their superior efficiency for dense matrices and their widespread adoption in numerical libraries such as LAPACK and MATLAB [152]. For any matrix $\tilde{A} \in \mathbb{R}^{r \times r}$, a sequence of $r-2$ Householder reflections $H_1, H_2, \dots, H_{r-2}$ is constructed such that [153]

$$Q = H_{r-2} \cdots H_2 H_1 \quad (4.26)$$

and the Hessenberg representation of $\tilde{A}$ is obtained by the orthogonal similarity transformation

$$\tilde{A}_H = Q \tilde{A} Q^T \quad (4.27)$$

Each reflection H_i is constructed to introduce zeros below the subdiagonal of column i and has the form

$$H_i = I - 2 \frac{\mathbf{v}_i \mathbf{v}_i^T}{\mathbf{v}_i^T \mathbf{v}_i} \quad (4.28)$$

where I is the identity matrix and the vector $\mathbf{v}_i$ is constructed as

$$\mathbf{v}_i = \mathbf{a}_i \pm \|\mathbf{a}_i\|_2 \mathbf{e}_1 \quad (4.29)$$

where $\mathbf{a}_i \in \mathbb{R}^{r-i}$ is the subcolumn formed by the entries of column i of the partially reduced matrix from row $i+1$ to row r , $\mathbf{e}_1 \in \mathbb{R}^{r-i}$ is the first canonical vector of the corresponding subspace, and the sign is chosen so that $\|\mathbf{v}_i\|_2$ is not small, which avoids catastrophic cancellation [153]. The Householder construction follows the general scheme described in [153], adapted here to the Hessenberg reduction setting in which each reflection acts on the subcolumn extending from row $i+1$ downward, so that the entry $h_{i+1,i}$ on the subdiagonal is preserved. Each $\mathbf{H}_i$ is symmetric and orthogonal, so that $\mathbf{H}_i^T = \mathbf{H}_i$ and $\mathbf{H}_i^2 = \mathbf{I}$.

The resulting Hessenberg matrix has the structure

$$\tilde{\mathbf{A}}_H = \begin{bmatrix} h_{1,1} & h_{1,2} & h_{1,3} & \cdots & h_{1,r} \\ h_{2,1} & h_{2,2} & h_{2,3} & \cdots & h_{2,r} \\ 0 & h_{3,2} & h_{3,3} & \cdots & h_{3,r} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & h_{r,r-1} & h_{r,r} \end{bmatrix} \quad (4.30)$$

Two properties of $\tilde{\mathbf{A}}_H$ are relevant for the QR iterations. First, as eigenvalues converge the active dimension of the matrix is progressively reduced (deflation), producing matrices of decreasing size. Second, even when $\tilde{\mathbf{A}}_H$ is real, some eigenvalues may appear as complex conjugate pairs, which requires the use of a shift to maintain convergence. The Wilkinson shift is used here for this purpose.

Extract the trailing 2×2 submatrix $\mathbf{\Gamma}$ of the active Hessenberg block

Wilkinson shift. At each deflation stage of the QR-based algorithm, the trailing 2×2 submatrix of the active Hessenberg block is defined as

$$\mathbf{\Gamma} = \begin{bmatrix} \tilde{a}_{r-j,r-j} & \tilde{a}_{r-j,r-j+1} \\ \tilde{a}_{r-j+1,r-j} & \tilde{a}_{r-j+1,r-j+1} \end{bmatrix} \quad (4.31)$$

where j denotes the deflation index, starting from $j = 1$ and incremented after each successful deflation. Thus, for $j = 1$, $\mathbf{\Gamma}$ corresponds to the lower-right 2×2 submatrix of the original Hessenberg matrix. As the QR iterations progress and successive eigenvalues converge, the active Hessenberg block is progressively reduced; consequently, the submatrix $\mathbf{\Gamma}$ used to compute the Wilkinson shift moves toward the upper-left portion of $\tilde{\mathbf{A}}_H$.

The Wilkinson shift ρ is defined as the eigenvalue of $\mathbf{\Gamma}$ closest to the bottom-right entry $\tilde{a}_{r-j+1,r-j+1}$. The two eigenvalues of $\mathbf{\Gamma}$ are obtained as the roots of its characteristic polynomial:

$$p_{\mathbf{\Gamma}}(\rho) = \rho^2 - (\tilde{a}_{r-j,r-j} + \tilde{a}_{r-j+1,r-j+1})\rho + (\tilde{a}_{r-j,r-j} \tilde{a}_{r-j+1,r-j+1} - \tilde{a}_{r-j,r-j+1} \tilde{a}_{r-j+1,r-j}). \quad (4.32)$$

As the QR iterations progress, the entry $\tilde{a}_{r-j+1,r-j}$ converges to zero, the submatrix $\mathbf{\Gamma}$ becomes upper triangular, and the corresponding eigenvalue appears on its diagonal. The identified eigenvalue is then deflated by removing its row and column from the active block, and the procedure is applied to the resulting submatrix to compute the next eigenvalue. This process is repeated until all eigenvalues of $\tilde{\mathbf{A}}_H$ have been obtained [153].

The resulting deflation significantly decreases the computational burden, as the matrices processed become progressively smaller. This feature is particularly advantageous for the data-driven implementation of the proposed RAS, where fast eigenvalue estimation is required to ensure real-time coordination among the RAS stages, the real-time simulation, and the physical UFLS replica.

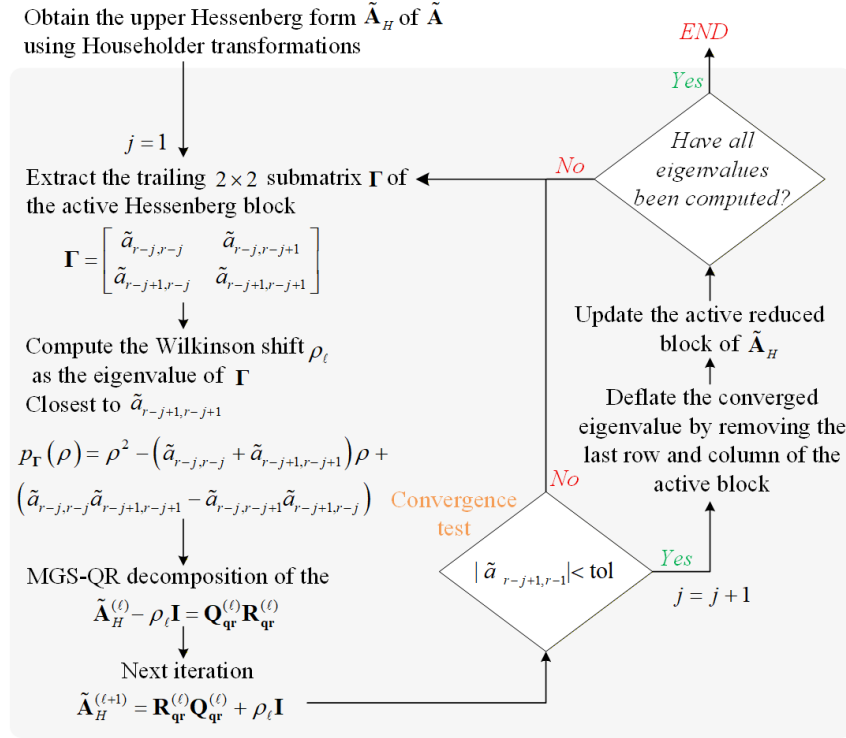


Figure 4.5: QR-based eigendecomposition of the reduced DMD operator $\tilde{\mathbf{A}}$ using Hessenberg reduction and Wilkinson shifts.

QR iteration with Wilkinson shift. The shifted QR iteration applied to the active Hessenberg block proceeds in two steps. At iteration ℓ of the QR-based algorithm, where ℓ counts successive QR factorizations applied to the active block, the shifted matrix is factored as

$$\tilde{\mathbf{A}}_H^{(\ell)} - \rho \mathbf{I} = \mathbf{Q}_{qr}^{(\ell)} \mathbf{R}_{qr}^{(\ell)} \quad (4.33)$$

and the updated Hessenberg matrix is obtained by reversing the product and restoring the shift:

$$\tilde{\mathbf{A}}_H^{(\ell+1)} = \mathbf{R}_{qr}^{(\ell)} \mathbf{Q}_{qr}^{(\ell)} + \rho \mathbf{I}. \quad (4.34)$$

Through successive iterations, $\tilde{\mathbf{A}}_H^{(\ell)}$ converges toward an upper triangular form whose diagonal entries are the eigenvalues of the original operator. In the data-driven assessment proposed in this work, the QR factorization is computed using the Modified Gram–Schmidt process (MGS), which provides improved numerical stability compared with other QR-based variants [154]. **Figure 4.5** summarizes the workflow used to compute the eigenvalues of $\tilde{\mathbf{A}}_H$ within the DMD-based assessment.

Figure 4.6 summarizes the DMD method described in this section. The data-driven assessment stage extracts measurements from the dynamic model implemented in the real-time simulator, which is connected to the physical UFLS replica where load shedding is continuously tested. The lower part of the figure shows the internal flowchart of the DMD-based data-driven assessment, highlighting its main steps. In this diagram, *householder*($\cdot$), *wilkinsonshift*($\cdot$), and *mgsqr*($\cdot$) denote the functions associated with the Householder transformation, the Wilkinson shift, and the Modified Gram–Schmidt QR factorization described in detail throughout this section.

The compact SVD and the eigendecomposition of $\tilde{\mathbf{A}}$ follow a similar internal structure, although the compact SVD does not require a Wilkinson shift because the singular values of the data matrix

are real and therefore do not require the complex shift used in the eigenvalue computation.

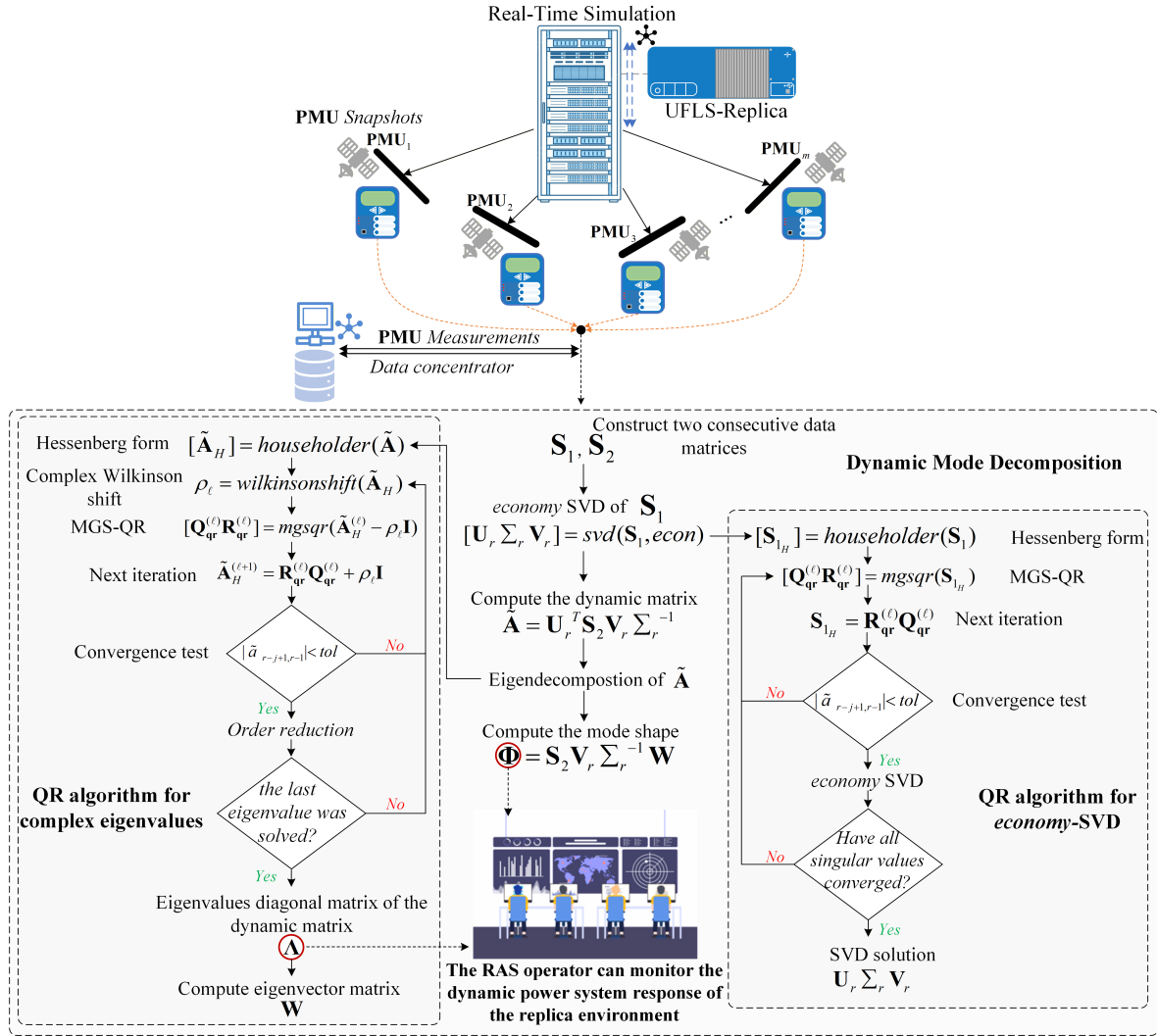


Figure 4.6: Flowchart of the DMD-based data-driven assessment within the proposed RAS framework.

Figure 4.7 presents the overall flowchart of the proposed RAS. The scheme begins with the acquisition of measurements from the physical power grid. When a steady-state operating condition is detected through the norm evaluation (green block), the measurements are transmitted to both the system-level digital twin and the data-driven assessment environment based on the UFLS physical replica. Within the system-level digital twin, the measurements are used to update the current operating point of the physical power grid.

The first stage of the proposed RAS (blue block) identifies the number of load-shedding stages of the conventional multistage UFLS required to reach the target post-contingency steady-state frequency $f_{ss}^{\text{post,ref}}$ for the n -th contingency. Once the required number of stages is estimated, a reduction strategy is applied to limit the number of tests: the amount of power associated with the last activated load-shedding stage is stored, and a random percentage of this value is added to the power assigned to the previously selected stages.

Both the n -th contingency and the associated load-shedding test are performed virtually in the UPF system-level digital twin, from which the post-contingency steady-state frequency f_{ss}^{post} is computed. This procedure is repeated through multiple iterations using a *multi-run* simulation approach. Among all the evaluated tests, the result satisfying $f_{ss}^{\text{post}} \approx f_{ss}^{\text{post,ref}}$ is selected and stored,

determining the final amount of load shedding ($LS-S$).

In parallel, in the real-time simulator the operating point is updated using the measurements received from the physical power grid (orange block). The estimated $LS-S$ amount is assigned to the first UFLS threshold of the physical replica. The remaining UFLS stages are kept enabled as backup protection, although the proposed RAS primarily evaluates the single-stage action determined by the system-level digital twin. The n -th contingency is then activated in the real-time simulator, enabling the closed-loop operation of the UFLS physical replica. In this environment, the objective is to verify that the simulated power grid remains stable and reaches $f_{ss}^{post,ref}$, while monitoring the transient response to ensure that the remaining electrical variables do not experience excessive deviations during the load-shedding event.

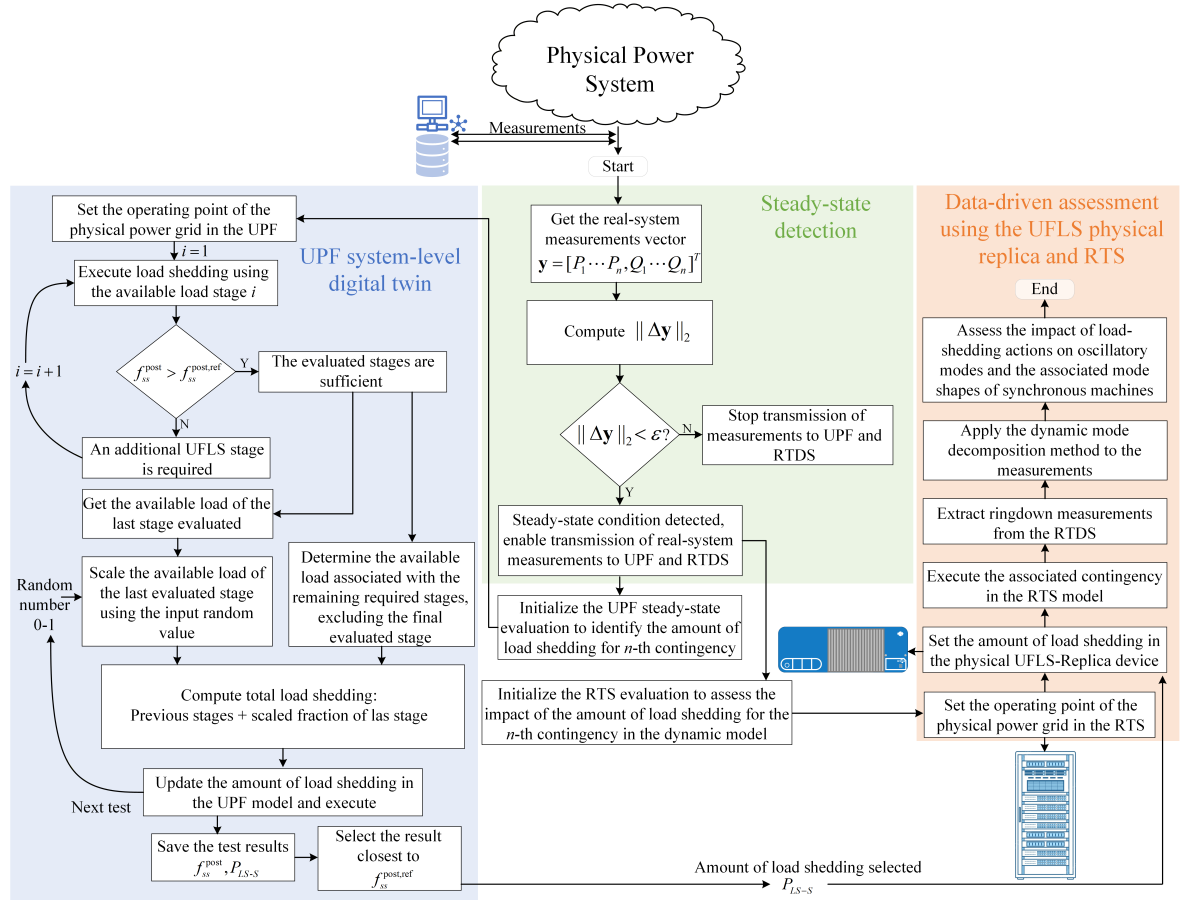


Figure 4.7: Flowchart of the DMD-based data-driven assessment within the proposed RAS framework, including compact SVD and QR-based eigendecomposition stages.

Finally, the oscillatory electromechanical behavior of the simulated power grid during the UFLS replica operation is evaluated. Ringdown measurements collected from the real-time simulation model during the first instants following the contingency are processed through the DMD-based assessment to extract the dominant dynamic patterns. The discrete-time eigenvalues are then mapped to oscillation frequencies and damping ratios, which constitute the indicators used by the proposed RAS to assess the dynamic impact of the load-shedding action. This assessment runs in parallel with the physical power grid and determines whether a single-stage load shedding is suitable under the current operating conditions, or whether a progressive load-shedding sequence should be applied to preserve stability.

With the conceptual and mathematical framework fully defined, the following section describes

the hardware-in-the-loop implementation, in which the proposed RAS is validated under realistic operating conditions.

4.4 Hardware-in-the-Loop Implementation

This section presents the hardware-in-the-loop implementation used to validate the proposed RAS under realistic operating conditions. It is organized into two subsections: the first introduces the test power grid and the problem under study, and the second describes the HIL experimental setup, including the real-time simulation platform, hardware devices, and communication architecture.

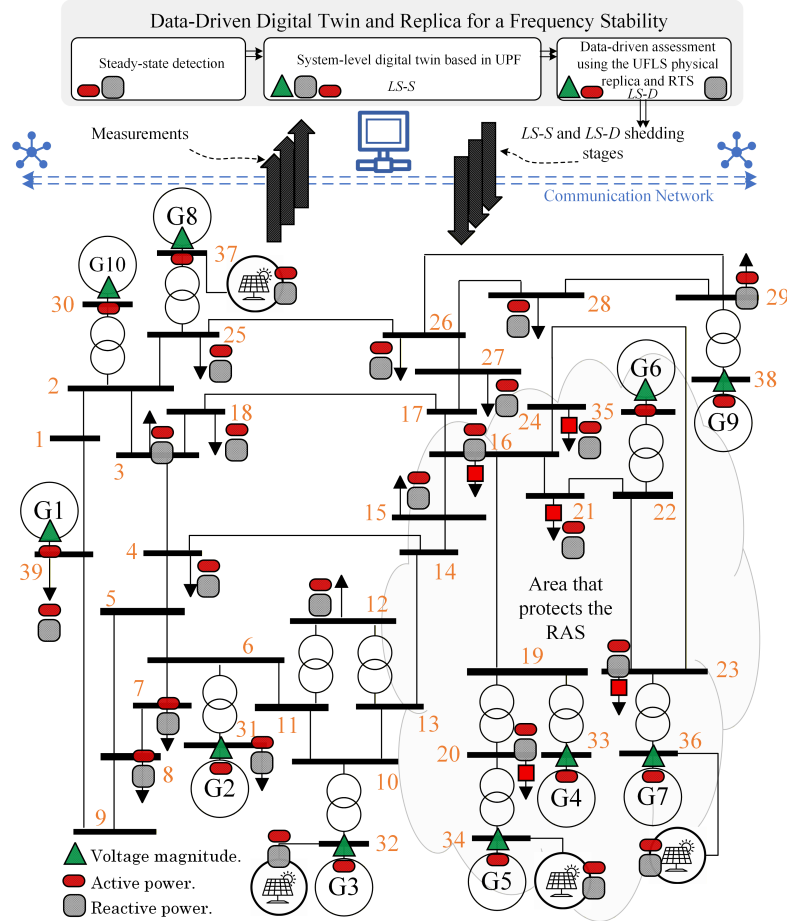


Figure 4.8: IEEE 39-bus test system with measurement points and protected area.

Test power grid description and problem definition

As in Chapter 3, the IEEE 39-bus New England test system is used to evaluate the performance of the proposed RAS. In addition to the voltage stability issues addressed in Chapter 3, this test system can also exhibit frequency stability issues under certain operating conditions and specific contingencies, which makes it a suitable platform for validating the proposed RAS. Furthermore, using the same benchmark allows demonstrating that a structural approach analogous to the one developed for the voltage stability RAS can be followed, highlighting the potential of this methodology to be generalized for addressing different stability problems in power grids.

Figure 4.8 illustrates the topology of the system, which is identical to the one used for the voltage stability RAS. However, to reflect a behavior more representative of modern power grids, photo-

voltaic power plants are incorporated at buses 32, 34, 36, and 37. As a result, both the inertial support and the active power reserve associated with the primary frequency control of the remaining synchronous machines are reduced. Additionally, the equivalent inertia of the synchronous machines was reduced in order to obtain a lower-inertia power system, thereby degrading the system dynamic response.

Under these operating conditions, contingencies involving generation loss, particularly the loss of synchronous machines, can drive the power grid frequency to considerably low f_{ss}^{post} values. In such scenarios, the primary and secondary regulation controls may not be able to restore the frequency to its nominal value, especially if the remaining synchronous machines operate close to their generation limits. Therefore, the RAS is designed with the objective of achieving the target post-contingency steady-state frequency $f_{ss}^{\text{post,ref}} = 59.5$ Hz, as established in [119].

The proposed RAS is designed to protect the area highlighted in gray. Accordingly, it only considers generation contingencies occurring within this zone, and the corresponding load-shedding actions are also restricted to the same zone. This configuration follows the PRC guidelines, which establish that under-frequency load shedding should be implemented within the affected region rather than in neighboring areas. Based on this criterion, the RAS is configured to perform load shedding at buses 16, 20, 21, 22, and 24. Although the proposed RAS focuses on this specific area, the same operational methodology can be extended to other areas of the power grid.

Figure 4.8 also indicates the measurement points obtained from the power grid, along with the type of variable collected at each location, including voltage magnitude and active or reactive power. These measurements constitute the input vector for the steady-state detection stage. Once processed, this information is forwarded to the system-level digital twin, the data-driven assessment stage, and the UFLS replica.

After defining the characteristics of the test system, the next subsection describes the hardware-in-the-loop validation platform used to deploy and assess the proposed RAS.

Hardware-in-the-loop validation platform

The validation platform consists of three main elements:

- **Emulated physical power grid in RTDS:** Power-system operation is governed by strict security and reliability constraints, which limits the possibility of performing direct tests during the development of RAS schemes and digital twins. For this reason, real-time simulators are commonly used to emulate the behavior of the physical power grid, including the measurement and control points that would exist in an actual implementation. In practice, the opportunity to directly link a digital twin and a RAS replica with the physical power grid would occur only during commissioning, and even then under strict operational and security constraints. In this validation platform, the IEEE 39-bus New England system is implemented in an RTDS simulator to emulate the physical power grid.
- **Real-time dynamic validation model:** To provide a controlled testing environment for the UFLS replica and to evaluate the dynamic response of the power grid, a real-time dynamic model of the IEEE 39-bus New England system is also implemented in RTDS. This model includes synchronous machines, their associated control systems, transmission lines, and load models, following a structure similar to that used in Chapter 3. However, in this chapter the load representation is extended to include frequency-dependent behavior, which is relevant for frequency-stability studies [132]. Regarding the photovoltaic plants, an averaged representation based on controlled current sources is adopted, consistent with generic photovoltaic plant modeling approaches used for electromechanical and real-time simulation studies [155,

156]. To provide a more realistic validation, the results section includes tests performed under different parametric variations.

- **Industrial-grade controllers:** SEL-3555 real-time automation controllers are employed as key components of the proposed RAS. These controllers are used across several stages of the operational methodology, including steady-state detection, communication between the system-level digital twin and the real-time simulation environment, multi-run evaluation, UFLS replica operation, and DMD-based data-driven assessment.

Figure 4.9 illustrates the flowchart of the HIL validation platform. The information flow originates from the RTDS-based emulation of the physical power grid. Within this simulator, the communication interface is configured to transmit analog signals corresponding to the measurement points shown in Figure 4.8, as well as the breaker status of the synchronous machines located in the protected area. These signals are transmitted using DNP3 and IEC 61850 GOOSE protocols, respectively.

The information is received by *RTAC-A*, where the measurement vector is constructed and the steady-state detection criterion is evaluated over a 3-second time window. In this way, a steady-state condition is detected when the variation of the measurement vector remains below the predefined threshold during the observation interval. Additionally, the UFLS scheme associated with the emulated physical power grid and the UFLS replica coexist within *RTAC-A*. However, they operate independently, with separate procedures, input signals, and tripping commands, thereby preventing interference between the physical-grid protection logic and the replica-based validation process.

In addition, *RTAC-A* acts as the communication interface among the devices that compose the proposed RAS. Once a steady-state condition is detected, *RTAC-A* sends the operating point of the emulated physical power grid to *RTAC-B* through the NGVL protocol every 10 ms. *RTAC-B* uses this information to automatically update the operating point of the system-level digital twin, which represents the steady-state characteristics of the 39-bus system. In this way, the digital twin is initialized under the same operating conditions as the emulated physical power grid.

Based on this operating point, *RTAC-B* applies the *multi-run* evaluation approach to assess the n -th contingency and determine the static load-shedding amount, $LS-S$, required to achieve the target post-contingency steady-state frequency $f_{ss}^{\text{post,ref}}$. Once identified, $LS-S$ is sent back to *RTAC-A* through the NGVL protocol, where it is subsequently used in the evaluation stage of the UFLS physical replica.

Simultaneously, when *RTAC-A* detects a steady-state condition, it sends the operating point of the emulated physical power grid to the RTDS dynamic validation model through the DNP3 protocol. This ensures that the real-time dynamic model starts from the same initial conditions as the emulated physical power grid, enabling the assessment of the n -th contingency and the corresponding load-shedding amount $LS-S$ within a representative dynamic environment.

In this configuration, the RTDS dynamic model interacts exclusively with the UFLS replica embedded in *RTAC-A*. Consequently, *RTAC-A* receives the frequency measurements of the buses associated with the protected area through the DNP3 protocol, as monitored from the dynamic model implemented in RTDS. To automate the evaluation procedure, a Python script integrated into the RTDS validation environment triggers the n -th contingency and assesses the resulting dynamic response for the current $LS-S$ value. The UFLS replica then responds to the simulated dynamics by applying the load-shedding action as a single-stage shedding command assigned to the first threshold of the conventional UFLS scheme.

The transient response is subsequently analyzed to verify that the frequency evolution is acceptable and that other electrical variables, such as voltage magnitudes, remain within permissible limits. If no violations are detected and the dynamic response is considered acceptable, $LS-S$ is retained as

the final load-shedding action. Otherwise, an additional dynamic load-shedding component, denoted as $LS-D$, is computed. In that case, the final load-shedding action is given by the combination of the static and dynamic components, $LS-S+LS-D$.

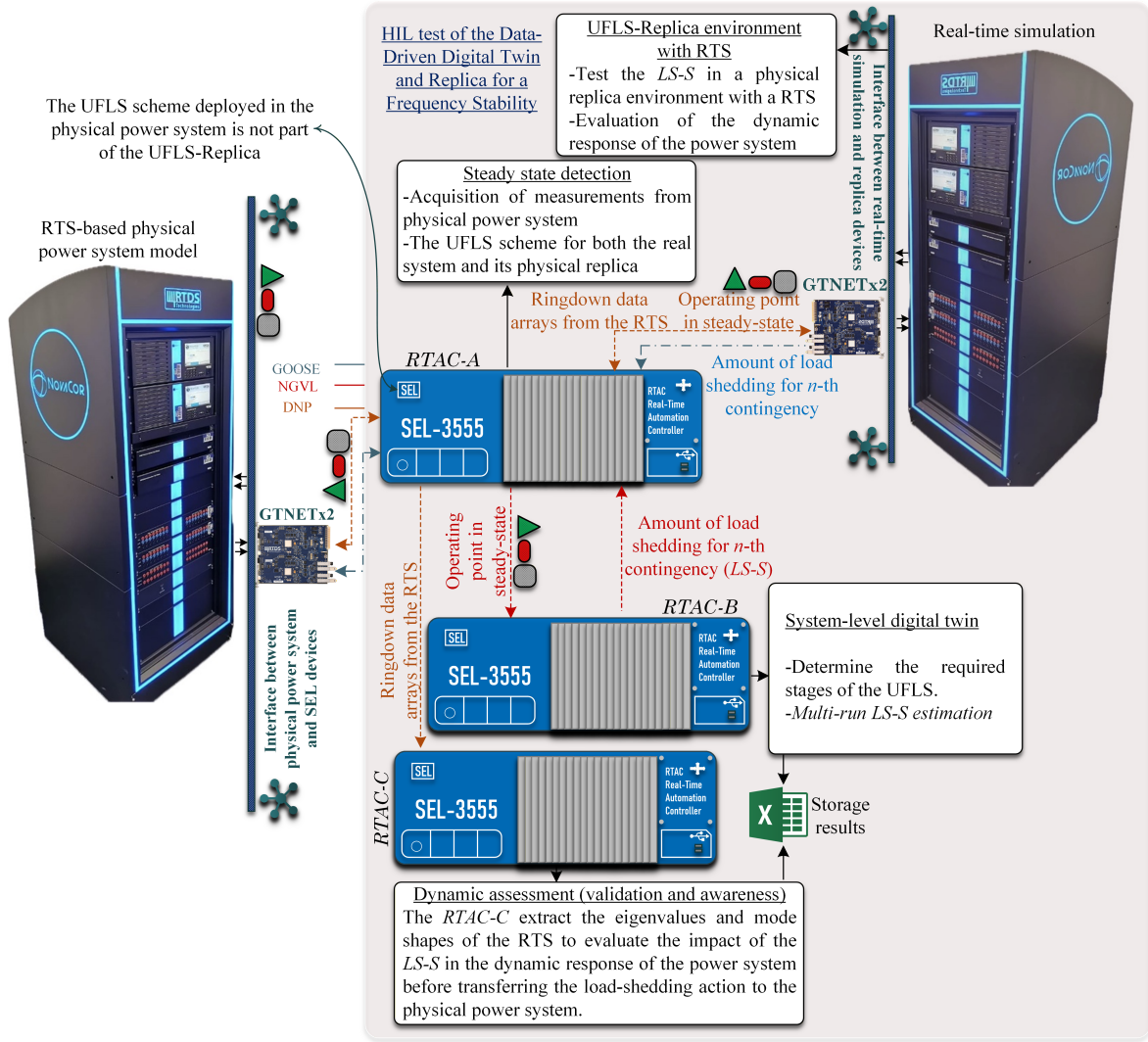


Figure 4.9: Proposed UFLS-RAS architecture integrating the system-level digital twin, UFLS-Replica, and DMD-based dynamic assessment.

Finally, the selected load-shedding action is transmitted to RTAC-A and configured in the UFLS scheme associated with the emulated physical power grid. The scheme remains armed and ready to operate when the n -th contingency occurs and the corresponding frequency threshold violation is detected.

On the other hand, the dynamic model implemented in RTDS sends synchronized dynamic measurements to RTAC-C. The measurements are transmitted via the PMU protocol at a reporting rate of 10 samples per second. These measurements may include active power, frequency, and rotor-speed-related signals available within the real-time simulation environment. RTAC-C embeds the DMD-based data-driven assessment method, including the numerical algorithms required for its solution, such as compact SVD, Householder transformations, Wilkinson shifts, and QR-based eigendecomposition.

Using these measurements, RTAC-C performs a data-driven assessment of the dynamic behavior of the power grid represented in RTDS, enabling the extraction of dominant oscillatory modes

and their corresponding spatial mode shapes. This information provides deeper insight into the dynamic characteristics of the power grid, which is typically not available in conventional RAS implementations. Based on these results, the proposed RAS can make more informed decisions regarding load-shedding actions and anticipate their potential impact on the dynamic response of the system.

Finally, both the information obtained from the data-driven assessment and the results of the evaluations performed in the system-level digital twin are stored in CSV files. This allows the RAS operator to access a record of the ongoing assessments and better understand the decision-making process carried out by the proposed RAS. Table 4.1 summarizes the communication delays associated with the data exchange paths between the devices, as well as the processing times required for each task executed by the RTAC industrial-grade controllers.

Table 4.1: Processing times associated with the HIL validation platform

Communication path and device	Protocol	Time
Physical system GTNETx2 $\rightarrow$ RTAC-A (Measurements of the system)	DNP3	100 ms
Physical system GTNETx2 $\leftrightarrow$ RTAC-A (Breaker status and trip signals)	GOOSE	4 ms
RTAC-A (Steady-state detection)	-	100 ms
RTAC-A (UFLS physical system)	-	100 ms
RTAC-A (UFLS-Replica)	-	100 ms
RTAC-A $\rightarrow$ RTAC-B (Operating point)	NGVL	10 ms
RTAC-B (Digital twin and Multi-run)	-	2.974 s
RTAC-B $\rightarrow$ RTAC-A (Amount LS-S)	NGVL	10 ms
Replica system GTNETx2 $\rightarrow$ RTAC-A (Measurements of the system)	PMU	100 ms
Replica system GTNETx2 $\leftrightarrow$ RTAC-A (Breaker status and trip signals)	GOOSE	4 ms
RTAC-A $\rightarrow$ RTAC-C (Ringdown data)	PMU	100 ms
RTAC-C (Data-driven assessment)	-	500 ms

With the HIL validation platform fully implemented and configured, a testing environment is available to evaluate the performance of the proposed RAS under realistic operating conditions. The use of industrial-grade controllers in this validation framework enables the assessment of the practical feasibility of deploying this type of RAS in real power grids, providing insight into how close such next-generation RAS schemes are to practical implementation.

The following section presents the simulation results, highlighting the capability of the proposed RAS to maintain frequency stability within the protected area.

4.5 Results of the HIL Implementation

This section presents the validation and performance assessment of the proposed RAS using the developed HIL platform. The results are organized into three subsections. The first subsection validates the system-level digital twin embedded in RTAC-B, demonstrating its capability to reproduce the steady-state characteristics of the physical power grid when implemented in an industrial-grade controller. The second subsection validates the DMD-based data-driven assessment embedded in RTAC-C by comparing its results against the small-signal analysis obtained from DigSILENT PowerFactory. Finally, the third subsection evaluates the overall behavior of the proposed RAS in the HIL platform, demonstrating its ability to maintain the power grid within acceptable operating limits and to improve its performance compared with a conventional RAS.

Digital Twin Validation

This subsection presents the validation of the system-level digital twin implemented in RTAC-B. Table 4.2 summarizes the control-mode configuration of the generation units represented in the digital

Table 4.2: Modeling assumptions for generation unit control modes in the digital twin

Bus Number	Type of Generation	Control Mode	Droop (p.u.)
10	PV	Constant Power	–
20	PV	Constant Power	–
23	PV	Constant Power	–
25	PV	Constant Power	–
30	SM	Droop	0.09
31	SM	Droop	0.09
32	SM	Droop	0.09
33	SM	Droop	0.09
34	SM	Droop	0.09
35	SM	Droop	0.09
36	SM	Droop	0.09
37	SM	Droop	0.09
38	SM	Droop	0.09
39	SM	Constant Power	–

twin. Synchronous machines are modeled under droop control, whereas photovoltaic plants operate in constant-power mode, meaning that they do not participate in primary frequency regulation within the proposed UPF formulation. To verify the correct implementation of the digital twin, its steady-state operating point is compared against that of the physical power grid modeled in RTDS.

First, the equilibrium condition of the physical system is established in RTDS. Subsequently, the digital twin is automatically adjusted to reproduce the same operating conditions. The comparison is presented in Table 4.3, which includes bus voltage magnitudes, active and reactive power generation from synchronous machines and photovoltaic plants, and active and reactive power consumption at load buses. The results show a high level of agreement between both systems, thereby validating the capability of the system-level digital twin to accurately reproduce the steady-state operating point of the physical power grid. In particular, the maximum voltage magnitude deviation between the digital twin and RTDS is below 0.002 p.u., while the active-power deviations remain negligible for all generation and load buses.

Finally, for validation purposes, Figure 4.10 presents a comparison between the response of the system-level digital twin implemented in RTAC-B and the RTDS following the simultaneous loss of generation from units G6 and G7. The agreement between both final values shows that the system-level digital twin can provide, in a few algebraic iterations, the same post-contingency steady-state frequency that the RTDS dynamic model reaches only after the electromechanical transient has sufficiently settled. These units are connected to buses 37 and 36, respectively, as shown in Figure 4.8. In both environments, a 555 MW load-shedding action is applied in the area of interest to emulate the action of a UFLS scheme. In the RTDS implementation, the UFLS action is triggered when the frequency reaches 59.3 Hz, whereas in the system-level digital twin the load-shedding action is evaluated directly from the post-contingency steady-state solution without explicitly simulating the transient frequency evolution.

The objective of this comparison is to verify that the digital twin accurately reproduces the steady-state behavior of the power grid represented in RTDS, particularly in terms of post-contingency frequency estimation and load-shedding requirements. The results show that the system-level digital twin accurately characterizes the post-contingency steady-state frequency, f_{ss}^{post} , using the RTDS response as a reference. In particular, the digital twin captures the aggregated steady-state effect of primary frequency regulation and the associated UFLS action without reproducing the full electromechanical transient response during the initial seconds of the event. This enables direct esti-

Table 4.3: Power-flow comparison between the digital twin and the physical power grid modeled in RTDS under the base case

Bus Number	Voltage (p.u.)		Active Power Generation (MW)		Reactive Power Generation (Mvar)		Active Power Load (MW)		Reactive Power Load (Mvar)	
	DT	RTDS	DT	RTDS	DT	RTDS	DT	RTDS	DT	RTDS
1	1.0367	1.0369								
2	1.0180	1.0183								
3	0.9837	0.9835					371.40	371.31	2.74	2.76
4	0.9452	0.9443					577.00	577.01	208.85	212.34
5	0.9456	0.9447								
6	0.9475	0.9466					10.10	10.11	4.97	5.05
7	0.9375	0.9363					269.66	269.67	95.06	96.88
8	0.9379	0.9366					602.06	602.07	198.56	202.99
9	1.0034	1.0029								
10	0.9577	0.9559	405	405	0	0				
11	0.9527	0.9519								
12	0.9303	0.9290					8.65	8.66	99.59	101.72
13	0.9546	0.9538								
14	0.9530	0.9522								
15	0.9599	0.9593					368.89	368.90	174.25	176.38
16	0.9813	0.9809					379.03	379.04	37.00	37.21
17	0.9846	0.9843								
18	0.9825	0.9822					182.16	182.17	34.40	34.59
19	0.9833	0.9832								
20	0.9809	0.9808	270	270	0	0	720.10	720.11	117.42	118.10
21	0.9891	0.9889					315.86	315.87	132.14	132.57
22	1.0193	1.0192								
23	1.0194	1.0193	370	370	0	0	286.18	286.19	98.39	97.82
24	0.9911	0.9901					355.74	355.77	-105.99	-106.28
25	1.0238	1.0230	405	405	0	0	258.99	259.00	54.96	54.57
26	1.0099	1.0097					160.33	160.34	19.66	19.61
27	0.9905	0.9902					324.04	324.05	86.81	87.06
28	1.0138	1.0137					237.25	237.26	31.91	31.78
29	1.0169	1.0168					326.32	326.33	31.11	30.96
30	1.0475	1.0475	540.03	540.00	195.44	193.69				
31	0.9820	0.9820	574.90	574.97	179.68	183.50				
32	0.9831	0.9831	265.00	265.00	132.26	135.91				
33	0.9912	0.9912	670.03	670.00	54.20	55.17				
34	1.0050	1.0050	238.01	238.00	127.28	128.03				
35	1.0493	1.0493	675.02	675.00	249.94	250.81				
36	1.0635	1.0635	205.01	205.00	173.48	173.86				
37	1.0278	1.0278	183.00	183.00	16.54	19.91				
38	1.0265	1.0265	840.04	840.00	72.45	72.55				
39	1.0300	1.0300	1400.00	1400.00	265.46	261.84				

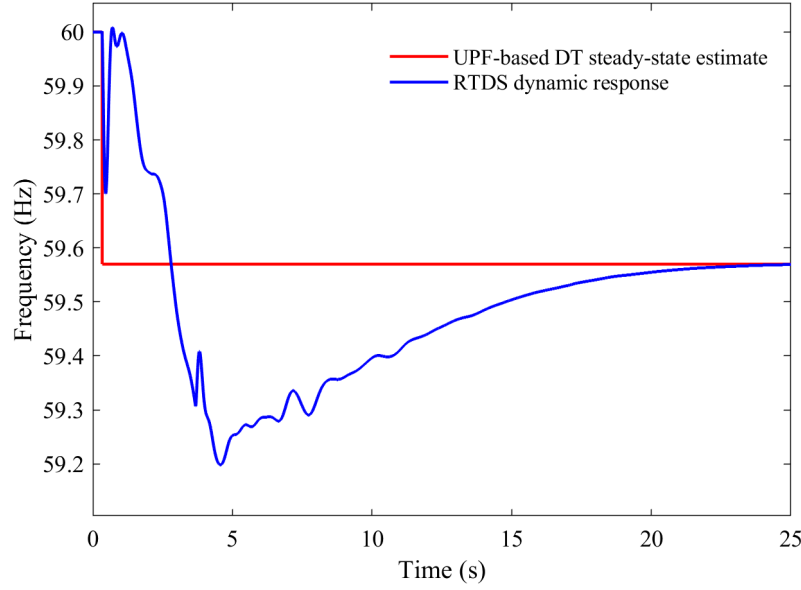


Figure 4.10: Steady-state frequency validation of the power-flow-based digital twin with primary frequency regulation against the RTDS dynamic response. The digital twin computes the post-contingency steady-state frequency directly from the UPF formulation, without numerical time-domain integration.

mation of the steady-state frequency without waiting for the system to fully settle in the dynamic simulation. Therefore, the system-level digital twin implemented in *RTAC-B* is validated as a reliable tool and can be effectively used within the proposed RAS framework.

Dynamic Mode Decomposition Validation

This subsection validates the modal information obtained from the DMD-based data-driven assessment by benchmarking it against results from DIgSILENT PowerFactory, which is used as a model-based reference [157]. The New England 39-bus system is implemented in DIgSILENT PowerFactory, where modal characteristics are computed using its Modal Analysis tool under a given operating condition. These results are then used as reference values for comparison.

To excite the electromechanical modes of the power system, a three-phase fault is applied at the midpoint of line 14–15 and cleared after one network cycle. The resulting dynamic response is simulated in DIgSILENT PowerFactory, and the corresponding time-series data are exported in CSV format. These measurements are subsequently imported into *RTAC-C*, where they are used as input for the DMD-based data-driven assessment. The DMD method is applied using a 6-second observation window and a sampling rate of 10 samples per second. This procedure enables a consistent comparison between the data-driven and model-based approaches for modal analysis.

Table 4.4: Comparison between DIgSILENT PowerFactory small-signal analysis and DMD-based modal identification

Mode	Small-Signal DIgSILENT (Hz)	DMD in <i>RTAC-C</i> (Hz)	Error (%)
1	0.1344	0.1289	4.1
2	0.2748	0.3461	25.9
3	0.6386	0.6427	0.6
4	0.9792	0.9345	4.6
5	1.0529	1.0392	1.3
6	1.1101	1.1098	0.03
7	1.1964	1.2022	0.5
8	1.4229	1.4670	3.1

Table 4.4 presents a comparison of the most relevant oscillatory modes obtained from the small-signal analysis in DIgSILENT PowerFactory and from the DMD-based data-driven assessment implemented in RTAC-C. Overall, the DMD approach identifies most of the relevant modes with acceptable accuracy. However, mode 2 exhibits a larger frequency deviation, indicating that not all modes are equally observable from the selected measurement set and excitation event.

The largest discrepancy is observed for mode 2. This behavior can be attributed to the sensitivity of data-driven modal identification to modes with low excitation energy, weak observability, or closely spaced frequency content [158]. Despite this limitation, the modes with higher relevance for the observed dynamic response are consistently captured. These results support the suitability of the DMD-based approach for practical modal analysis within the proposed RAS framework.

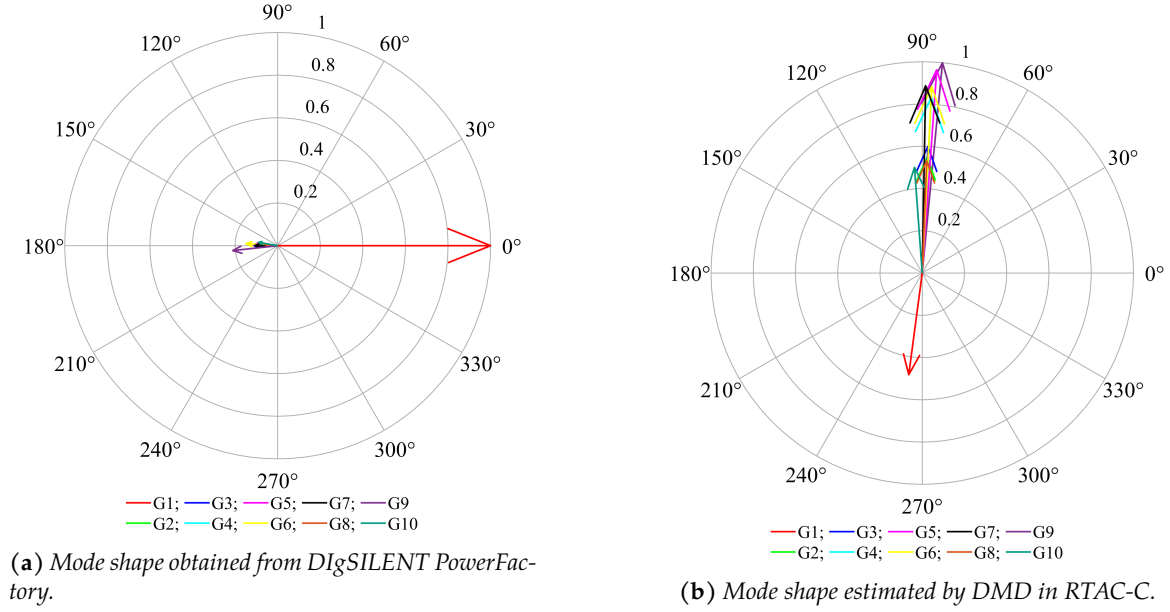


Figure 4.11: Mode-shape comparison for mode 3 between DIgSILENT PowerFactory and DMD implemented in RTAC-C.

A comparison of the mode shapes obtained from DIgSILENT PowerFactory and from the DMD-based data-driven assessment implemented in RTAC-C is also performed. Before comparing mode shapes, both DIgSILENT and DMD-based mode vectors are normalized with respect to their maximum magnitude and phase-aligned using the dominant generator as reference. This normalization is necessary because modal vectors are defined up to an arbitrary complex scaling factor.

Figure 4.11 shows the normalized mode shape corresponding to mode 3. The reference results obtained from DIgSILENT PowerFactory indicate that generator G1 exhibits the highest participation in this mode, while the remaining machines present lower amplitudes and are approximately 180° out of phase with respect to G1. The DMD-based results capture a consistent phase relationship, also showing an approximate 180° phase shift between G1 and the rest of the generators. However, differences are observed in the relative magnitudes, since some machines exhibit higher amplitudes in the DMD estimation than in the model-based reference. It is important to note that the mode shapes obtained from DIgSILENT PowerFactory and the DMD implementation may differ by a global phase rotation and complex conjugation due to differences in the eigenvector and time-domain conventions adopted by each method. Therefore, the comparison focuses on the relative modal participation and coherence among synchronous machines rather than on the absolute angular orientation of the phasors.

This discrepancy is mainly attributed to the differences between both approaches. The small-

signal analysis relies on a linearized state-space model with full model observability, whereas DMD is a data-driven technique whose results depend on the excitation event, operating condition, measurement set, and observation window. Despite these magnitude differences, the DMD approach successfully captures the underlying physical behavior of the power grid, particularly the relative phase relationships between generators, which are critical for identifying coherent groups and inter-area or local oscillations.

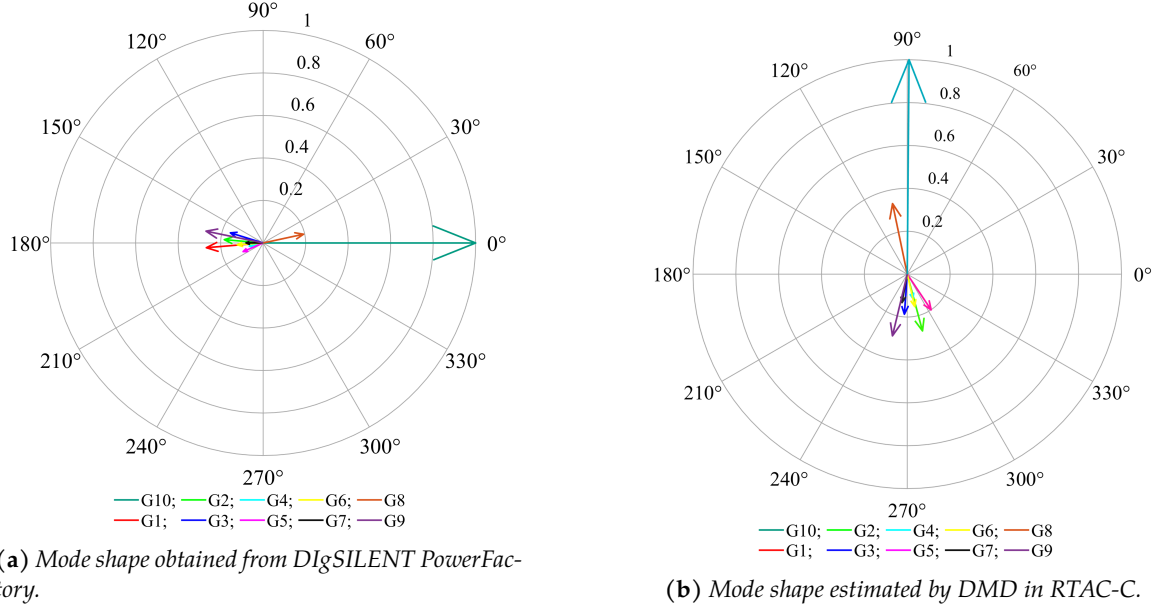


Figure 4.12: Mode-shape comparison for mode 6 between DIgSILENT PowerFactory and DMD implemented in RTAC-C.

Finally, Figure 4.12 presents the comparison of the mode shape corresponding to mode 6. Both approaches exhibit a consistent pattern, identifying generator G10 as the dominant participant, while the remaining machines show lower amplitudes and are approximately 180° out of phase with respect to G10.

In addition, generator G8 exhibits a phase response closer to G10 in both methods, suggesting a degree of coherent behavior between these units. This strong agreement in the relative phase relationships and dominant participation reinforces the accuracy of the data-driven assessment implemented in the RTAC-C, further validating its capability to capture the underlying electromechanical dynamics when benchmarked against DIgSILENT.

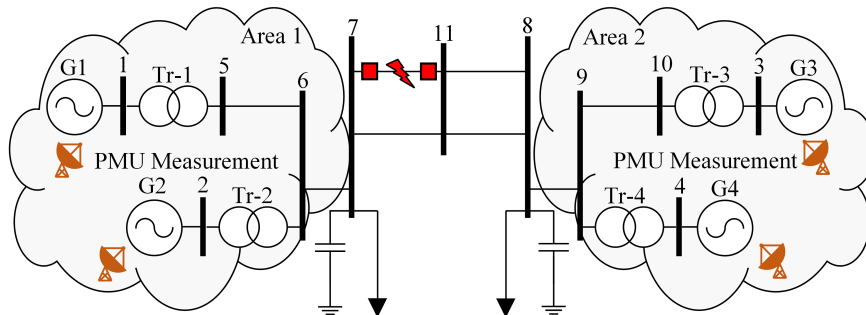


Figure 4.13: Kundur two-area power system.

On the other hand, data-driven modal analysis methods such as DMD can be sensitive to measurement noise, which may affect the modal information used by the proposed RAS. To evaluate

this impact, validation tests are conducted using the RTDS-based physical replica and *RTAC-C*, introducing white Gaussian noise into the signals obtained from RTDS.

To better isolate and assess the effect of noise on the estimated oscillatory modes, a small test power system is considered. Specifically, the well-known two-area, 12-bus Kundur system is used, as it is widely adopted for the analysis of electromechanical oscillations. The power system is shown in Figure 4.13.

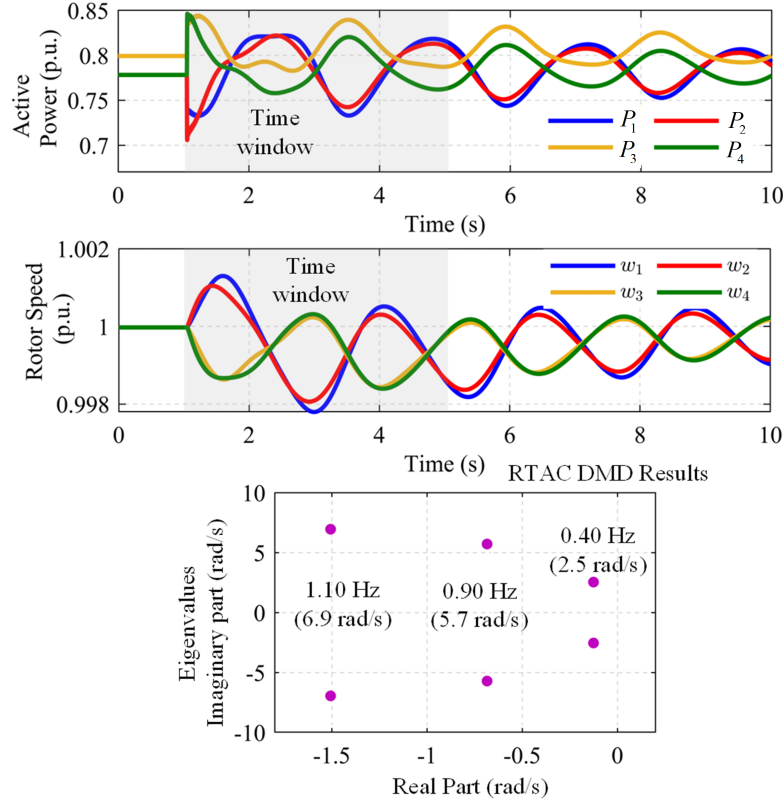


Figure 4.14: Data-driven assessment results obtained in the RTAC from active power and rotor speed measurements from generators 1–4 of the Kundur two-area system.

To excite the oscillatory modes of the power system, line 7–11 is tripped from both ends. Figure 4.14 shows the active power and rotor speed responses of generators 1–4, which are obtained from the RTDS and transmitted to the *RTAC-C* via a PMU protocol at a sampling rate of 10 samples per second with a time window of 4 seconds. As a first step, the signals are processed without added noise in order to establish a reference set of oscillatory modes. Under these conditions, the data-driven assessment implemented in the *RTAC-C* identifies three modes at 0.4024 Hz, 0.9008 Hz, and 1.1066 Hz, which are used as reference for comparison.

Subsequently, the same contingency is repeated; however, Gaussian white noise is added to the signals of synchronous machines 1–4, corresponding to a signal-to-noise ratio (SNR) of 44.35 dB, as shown in Figure 4.15. These noisy measurements are processed by the *RTAC-C* to perform the data-driven assessment.

Table 4.5 summarizes the results, including additional evaluations with increased sampling rates of 20, 30, and 60 samples per second. For a sampling rate of 10 samples per second, the identified oscillatory modes exhibit slight deviations due to the injected noise, with Mode 2 showing the largest variation compared to the noise-free case. As the sampling rate increases, a larger number of noise-contaminated samples is incorporated into the data matrices. Under the compact-SVD imple-

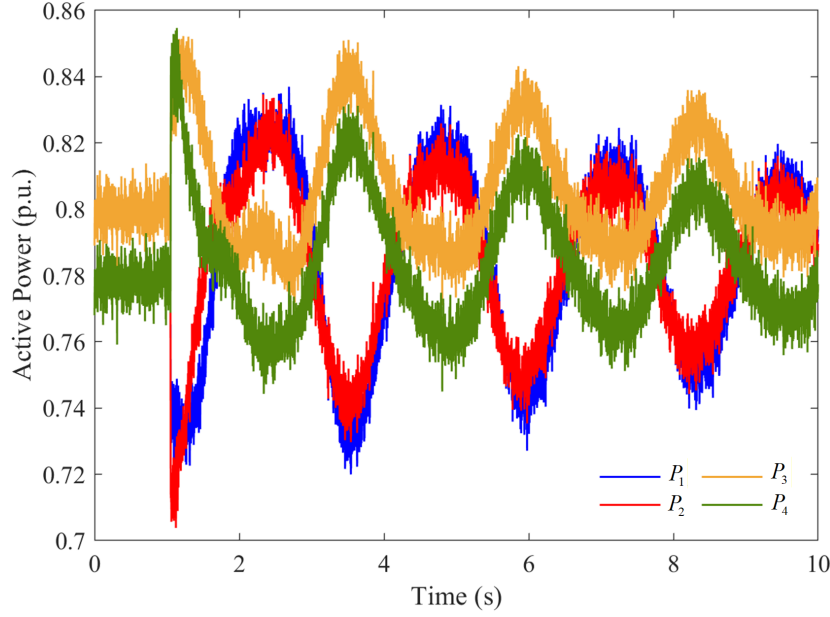


Figure 4.15: Active power measurements from generators 1–4 of the Kundur two-area system under noisy conditions with a SNR of 44.35 dB, used to evaluate the robustness of the DMD-based modal assessment.

mentation, without additional modal truncation or denoising, this can affect the conditioning of the DMD estimation and increase the sensitivity of low-energy modes. Among them, Mode 2 remains the most sensitive, which is consistent with its lower energy content relative to the other modes.

Table 4.5: Impact of measurement noise (SNR = 44.35 dB) on data-driven modal identification

Sampling rate (s^{-1})	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)
10	0.4016	0.7908	1.1275
20	0.3945	0.7536	1.1121
30	0.3989	0.7416	1.1017
60	0.3963	0.7350	1.0954

It is worth noting that the noise level considered in this analysis is conservative and not typically observed in practical power system measurements, It is worth noting that the noise levels considered in this analysis are intentionally conservative with respect to typical high-quality synchronized measurements used in transmission-level monitoring systems.

Finally, an additional evaluation is conducted using signals with an SNR of 58 dB, as shown in [Figure 4.16](#). Although this still represents a conservative scenario, it allows assessing the capability of the data-driven assessment to accurately estimate oscillatory modes, particularly the dominant ones, which are of primary interest for the proposed RAS and control center.

[Table 4.6](#) summarizes the results obtained by the RTAC-C for different sampling rates (10, 20, 30, 60, and 120 samples per second) and varying observation time windows. The results indicate that increasing the observation window has a limited impact on the estimated modal frequencies. In contrast, as the sampling rate increases, the effect of noise on the DMD-based estimation becomes more noticeable.

Despite this, the dominant modes (Modes 1 and 3) are consistently identified with small deviations in their estimated frequencies. Conversely, the mode with lower energy (Mode 2) exhibits higher sensitivity to noise, with its estimation degrading as the sampling rate increases. It is important to note that, given the typical range of electromechanical oscillations in power systems (0.3–2

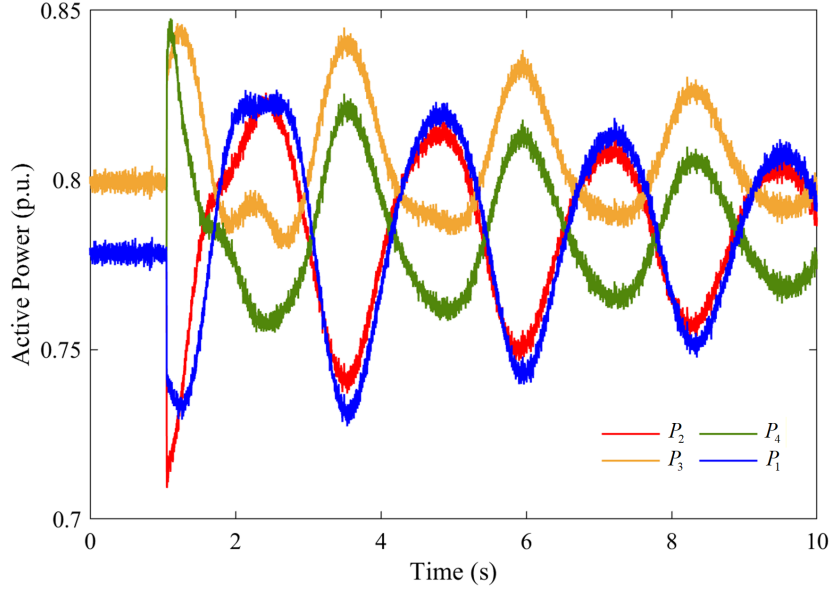


Figure 4.16: Active power measurements from generators 1–4 of the Kundur two-area system under moderate-noise-conditions with a SNR of 58 dB, used to evaluate the robustness of the DMD-based modal assessment.

Hz), high sampling rates are not required in practice. Sampling rates around 10 samples per second are generally sufficient to capture these dynamics, while also providing an inherent filtering effect that improves the observability of the dominant modes.

Table 4.6: Impact of measurement noise (SNR = 58 dB) on data-driven modal identification

Sampling rate (s ⁻¹)	Mode	Window time				
		4 s	5 s	6 s	7 s	8 s
10	1	0.4024	0.4041	0.4073	0.4057	0.4074
	2	0.9008	0.8892	0.8549	0.8557	0.8447
	3	1.1066	1.1157	1.1167	1.1166	1.1112
20	1	0.4010	0.4029	0.4069	0.4062	0.4067
	2	0.8175	0.7924	0.7868	0.7807	0.7857
	3	1.1143	1.1211	1.1212	1.1160	1.1067
30	1	0.4000	0.4029	0.4060	0.4057	0.4068
	2	0.7839	0.7730	0.7699	0.7670	0.7543
	3	1.1161	1.1156	1.1190	1.1189	1.1010
60	1	0.3998	0.4013	0.4046	0.4051	0.4065
	2	0.7460	0.7549	0.7475	0.7436	0.7471
	3	1.1051	1.1162	1.1045	1.1098	1.1049
120	1	0.3998	0.4017	0.4051	0.4049	0.4068
	2	0.7460	0.7419	0.7454	0.7388	0.7318
	3	1.1210	1.1160	1.1190	1.1156	1.1010

Although this analysis is conducted using measurements from the physical replica, it is directly relevant to the proposed RAS, as the RTAC-C can be switched to acquire measurements from the physical power system, enabling real-time monitoring and modal estimation during contingencies.

In this context, these results complete the validation of the data-driven assessment development in the industrial-grade controller RTAC-C, demonstrating a performance level suitable for its integration into the full operation of the proposed RAS.

Performance Results of the Proposed UFLS-RAS

This subsection presents the performance results of the proposed UFLS-RAS. As defined in the proposed framework, this UFLS-oriented remedial action scheme takes a conventional multistage UFLS scheme as a reference and uses its load-shedding resources, while adapting the amount of load shedding according to the contingencies and operating conditions considered within the RAS design. In this context, Table 4.7 summarizes the operating parameters of the conventional UFLS scheme.

Table 4.7: Operating parameters of the conventional UFLS scheme

Stage	Operating Parameters		
	Frequency Threshold (Hz)	Active Power (%)	Total Active Power (MW)
1	59.3	8.3%	180
2	59.1	8.3%	180
3	58.9	8.3%	180
4	58.7	8.3%	180
5	58.5	8.3%	180
6	58.3	8.3%	180

To evaluate the performance of the proposed UFLS-RAS, three representative operating scenarios are considered:

- **Base Case:** This scenario corresponds to the nominal operating point defined in Table 4.3 and is used as the reference condition of the power system.
- **Case 1:** The power system operates under the base-case conditions; however, the load-shedding resources associated with stage 2 of the UFLS scheme are partially unavailable. Specifically, only 110 MW of the original 180 MW are accessible. This scenario is designed to demonstrate the capability of the proposed UFLS-RAS to handle limited resource availability by reallocating load-shedding actions across other available stages, supported by the system-level digital twin.
- **Case 2:** This scenario represents a modified operating condition in which the load at bus 21 is increased from 315 MW to 390 MW, while the generation of units G4 and G5 is adjusted to 695 MW and 295 MW, respectively. This operating-point variation is considered to evaluate the adaptability of the proposed UFLS-RAS to changing system conditions, requiring the scheme to adjust its operating parameters accordingly.

In addition, the contingencies evaluated by the proposed UFLS-RAS are defined as follows:

- **C1** ($N - 1$): Disconnection of synchronous generator G6.
- **C2** ($N - 2$): Simultaneous disconnection of synchronous generators G6 and G7.

For clarity, the results are presented on a per-contingency basis. Within each contingency, the performance of the proposed UFLS-RAS is evaluated for the Base Case, Case 1, and Case 2.

Contingency C1

An important parameter in the proposed UFLS-RAS is the number of simulations performed within the *multi-run* approach of the system-level digital twin, which is used to estimate the required load shedding for each contingency. To this end, a sensitivity analysis is conducted by varying the number of runs, with the objective of evaluating the computational performance of the industrial-grade controller *RTAC-B*.

Table 4.8: Execution time of the multi-run approach implemented in RTAC-B

Number of Runs	Total Execution Time (s)
50	2.974
100	5.972
200	11.971
300	17.974
400	23.975
500	30.027
600	35.975
700	41.974
800	47.973
900	53.975
1000	59.974
1050	62.972

Table 4.8 summarizes the execution time of the *multi-run* approach implemented in RTAC-B for a range of 50 to 1050 runs. The maximum execution time is approximately one minute for 1050 runs. Although increasing the number of runs improves the resolution of the estimated load-shedding amount, such precision is not strictly required due to the discrete nature of load-shedding resources in practical power systems. Therefore, 50 runs are selected as a suitable trade-off between computational efficiency and estimation accuracy for the proposed UFLS-RAS.

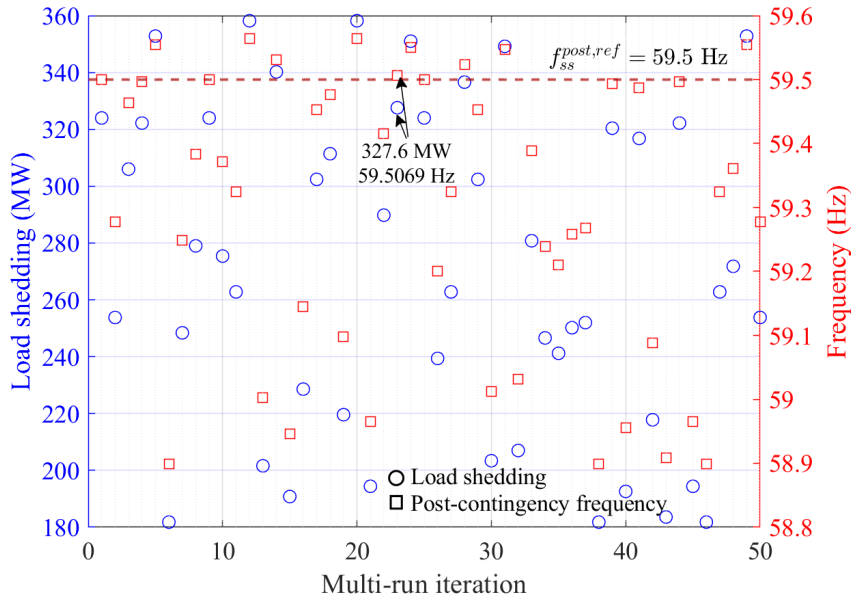


Figure 4.17: Multi-run evaluation performed by RTAC-B for contingency C1 under base case. Each test corresponds to a randomly generated load-shedding candidate evaluated through the power-flow-based digital twin with primary frequency regulation; the selected candidate corresponds to 327.6 MW

For contingency C1 under the base case, the proposed UFLS-RAS, supported by the system-level digital twin implemented in RTAC-B, determines that the first stage of the conventional UFLS scheme, corresponding to 180 MW, is insufficient to restore the post-contingency steady-state frequency to the reference value $f_{ss}^{post,ref} = 59.5 \text{ Hz}$. Consequently, the UFLS-RAS identifies that stages 1 and 2 of the UFLS scheme are required.

Based on this initial assessment, the *multi-run* approach is employed to refine the total amount of load shedding. Figure 4.17 illustrates the 50 simulations performed. Several evaluated cases result

in a post-contingency steady-state frequency f_{ss}^{post} below the reference value $f_{ss}^{\text{post,ref}}$, while a subset satisfies the frequency requirement. Accordingly, the system-level digital twin selects the minimum load-shedding value that ensures $f_{ss}^{\text{post}} \geq f_{ss}^{\text{post,ref}}$, resulting in a final load-shedding amount of 327.6 MW.

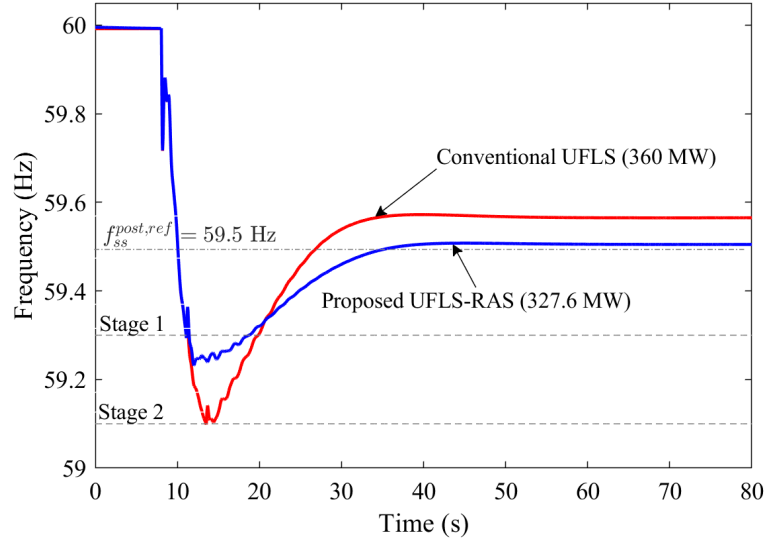


Figure 4.18: Frequency response at bus 21 under contingency C1 for the base case, comparing the conventional UFLS scheme and the proposed UFLS-RAS. The proposed UFLS-RAS reaches a post-contingency steady-state frequency closer to $f_{ss}^{\text{post,ref}}$ while requiring less load shedding than the conventional scheme.

Subsequently, the load-shedding amount estimated by the system-level digital twin is validated in the physical replica environment. Figure 4.18 compares the system frequency response under the conventional UFLS scheme and the proposed UFLS-RAS, physically implemented through the UFLS-Replica. Following contingency C1, the conventional UFLS scheme triggers stages 1 and 2, resulting in a total load shedding of 360 MW. This action restores the steady-state frequency to a value above 59.5 Hz. Although the frequency requirement is satisfied, this approach leads to over-shedding, since a lower amount of load shedding would be sufficient to meet the frequency constraint. In this work, the term UFLS-Replica refers to the physical and real-time-simulation-based environment in which the UFLS logic is deployed and dynamically evaluated prior to its application to the physical power grid.

In contrast, the response obtained with the proposed UFLS-RAS, which sheds 327.6 MW through the UFLS-Replica, achieves a steady-state frequency close to 59.5 Hz, in agreement with the estimation provided by the system-level digital twin. Moreover, since the UFLS-Replica executes the load shedding at the first frequency threshold, the system exhibits an improved transient frequency response, characterized by a higher frequency nadir. This approach mitigates superfluous load shedding and exhibits enhanced frequency stability characteristics relative to the conventional UFLS scheme.

Subsequently, the proposed UFLS-RAS is evaluated under Case 1, where the load-shedding capacity of stage 2 is partially reduced. Under this condition, the load available from stages 1 and 2 is 290 MW, which is lower than the amount estimated by the system-level digital twin to reach the target post-contingency steady-state frequency. Consequently, the proposed UFLS-RAS uses an additional fraction of the load assigned to stage 3 to compensate for the reduced availability of stage 2.

Based on the *multi-run* approach results illustrated in Figure 4.19, the proposed UFLS-RAS estimates that a total load shedding of 325 MW is sufficient to achieve a steady-state frequency close to 59.5 Hz. Therefore, this value is selected by the system-level digital twin.

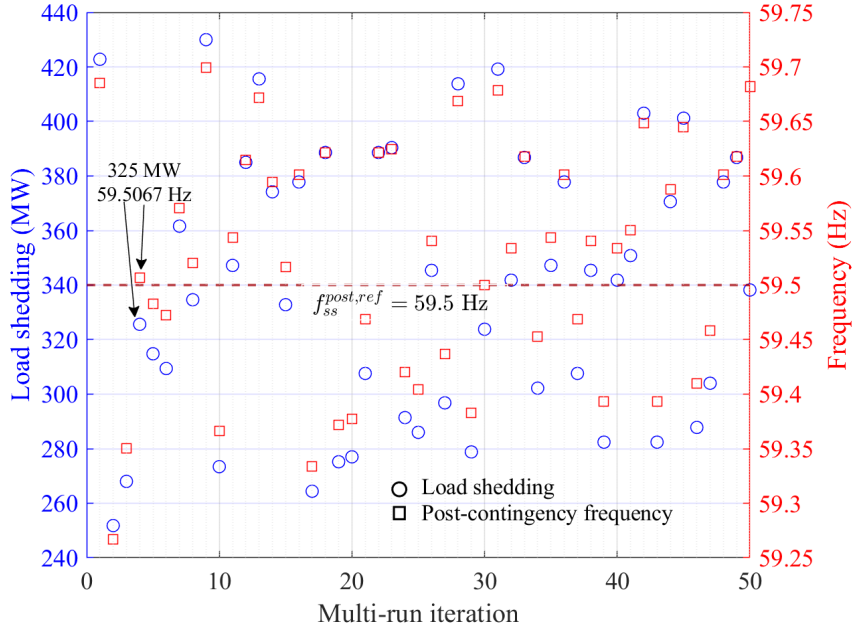


Figure 4.19: Multi-run evaluation performed by RTAC-B for contingency C1 under Case 1. Each test corresponds to a randomly generated load-shedding candidate evaluated through the power-flow-based digital twin with primary frequency regulation; the selected candidate corresponds to 325 MW.

The scenario is then validated in the physical replica environment by comparing the system frequency response under the conventional UFLS scheme and the proposed UFLS-RAS. Figure 4.20 shows that the frequency deviation caused by contingency C1 is not severe enough to trigger additional UFLS stages in the conventional scheme. However, due to the limited load-shedding capacity of stage 2, the conventional UFLS scheme is unable to restore the frequency to the desired level, leaving the system at a lower steady-state frequency.

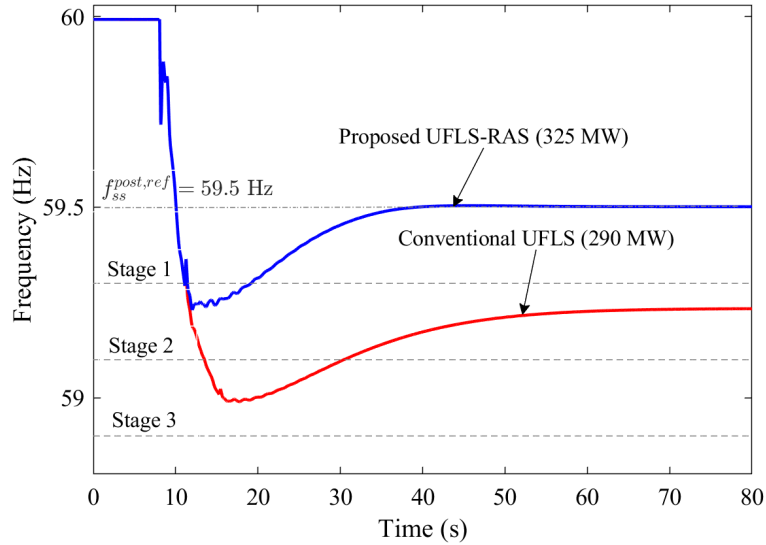


Figure 4.20: Frequency response at bus 21 under contingency C1 for Case 1, comparing the conventional UFLS scheme and the proposed UFLS-RAS. Due to the load-shedding limitation imposed in Case 1, the conventional UFLS scheme is unable to restore the post-contingency steady-state frequency to the target value, whereas the proposed UFLS-RAS identifies an alternative load-shedding action capable of recovering $f_{ss}^{post,ref} = 59.5$ Hz.

In contrast, when the proposed UFLS-RAS is deployed through the UFLS-Replica, it updates the

required load-shedding amount by identifying the reduced availability in stage 2 and reallocating the required shedding through available load from subsequent stages, in this case stage 3. As a result, the proposed UFLS-RAS successfully restores the system frequency to the target value of 59.5 Hz.

These results demonstrate that the proposed UFLS-RAS improves the system frequency response and exhibits adaptability to limitations in the availability of load-shedding resources across UFLS stages.

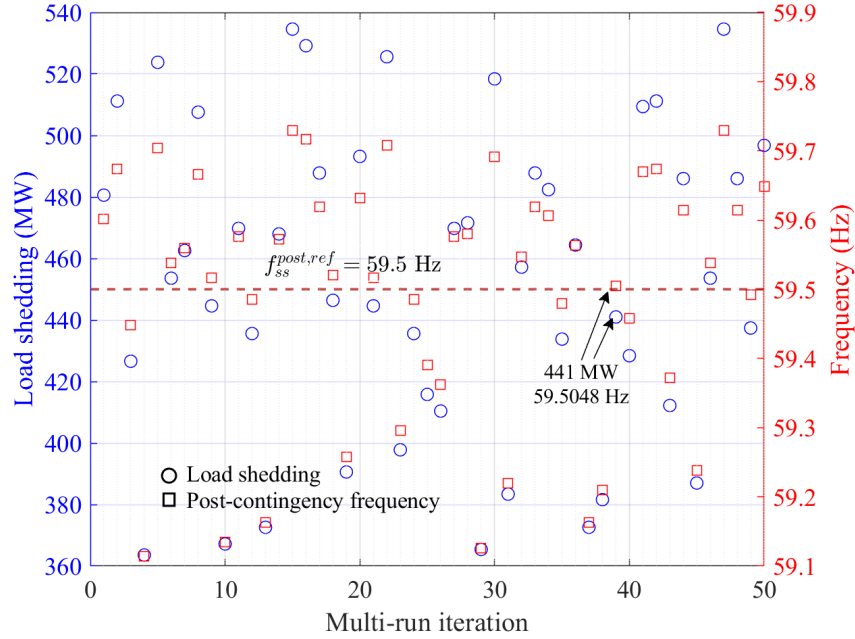


Figure 4.21: Multi-run evaluation performed by RTAC-B for contingency C1 under Case 2. Each test corresponds to a randomly generated load-shedding candidate evaluated through the power-flow-based digital twin with primary frequency regulation; the selected candidate corresponds to 441 MW.

For contingency C1 under Case 2, where the operating point of the physical power grid is modified, the proposed UFLS-RAS adapts to the new system conditions and determines that a third load-shedding stage is required. Through the *multi-run* approach, it estimates a total load shedding of 441 MW, resulting in a steady-state frequency of 59.5048 Hz, as shown in Figure 4.21.

Figure 4.22 compares the power system response under the conventional UFLS scheme and the proposed UFLS-RAS. The results show that the frequency deviation caused by C1 triggers only two stages of the conventional UFLS scheme, leading to a load shedding of 360 MW. However, this action is insufficient to restore the frequency to the desired threshold, leaving the post-contingency steady-state frequency slightly below the target value.

In contrast, the adaptive operation of the proposed UFLS-RAS enables the adjustment of the load shedding to the required level, successfully restoring the system frequency to the desired value. Additionally, the UFLS-Replica exhibits improved dynamic performance during the transient response. These results further demonstrate the capability of the proposed UFLS-RAS to adapt to changing operating conditions, whereas the static nature of the conventional UFLS may result in operation outside acceptable frequency limits.

Within the proposed UFLS-RAS, the replica acts as a dynamic validation and awareness layer between the system-level digital twin and the physical load-shedding action. While the digital twin estimates the required load shedding from a steady-state perspective, the replica evaluates the associated dynamic behavior, allowing the assessment of frequency performance, electromechanical

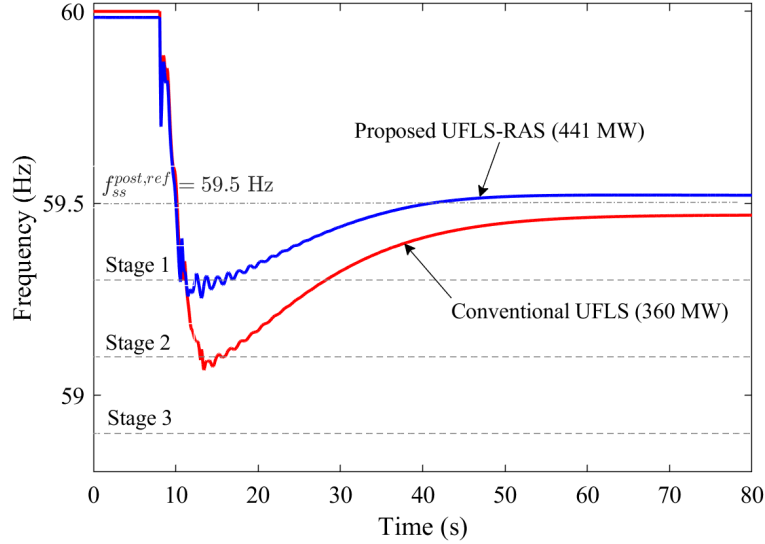


Figure 4.22: Frequency response at bus 21 under contingency C1 for Case 2, comparing the conventional UFLS scheme and the proposed UFLS-RAS. Due to the load-shedding limitations imposed in Case 2, the conventional UFLS scheme is unable to restore the post-contingency steady-state frequency to the target value, whereas the proposed UFLS-RAS identifies an alternative load-shedding action capable of recovering $f_{ss}^{post,ref}$.

oscillations, and stability-related effects before the action is transferred to the physical UFLS scheme.

Table 4.9 provides a summary of the load-shedding actions for both the conventional UFLS scheme and the proposed UFLS-RAS under contingency C1, detailing the number of activated stages and the corresponding load contribution from the final stage.

Table 4.9: Comparison of UFLS performance for contingency C1 under different cases

Case	Scheme	Total Load Shed (MW)	Number of Stages Activated	Load Taken from Final Stage (MW)
Base Case	Conventional UFLS	360	2	–
Base Case	Proposed UFLS-RAS	327.6	2	147.6
Case 1	Conventional UFLS	290	2	–
Case 1	Proposed UFLS-RAS	325	3	35
Case 2	Conventional UFLS	360	2	–
Case 2	Proposed UFLS-RAS	441	3	81

So far, the results have shown that the proposed UFLS-RAS has a positive impact on both the steady-state and dynamic frequency response of the system. However, it is also important to assess its impact on other system variables.

In this context, Figure 4.23 illustrates the rotor speed responses of several synchronous machines that remain connected during contingency C1 under the base case, comparing the operation of the conventional UFLS scheme and the proposed UFLS-RAS. Although both responses remain stable, the rotor-speed oscillation amplitudes are slightly higher when the proposed UFLS-RAS is applied.

This behavior is primarily attributed to the operating strategy of each scheme. The proposed UFLS-RAS performs load shedding in a single stage, representing a more abrupt intervention that may induce stronger perturbations in other system variables. In contrast, the conventional UFLS scheme distributes the load-shedding action across multiple stages, leading to a more gradual system response. Therefore, a more detailed assessment of the system dynamic behavior is carried out

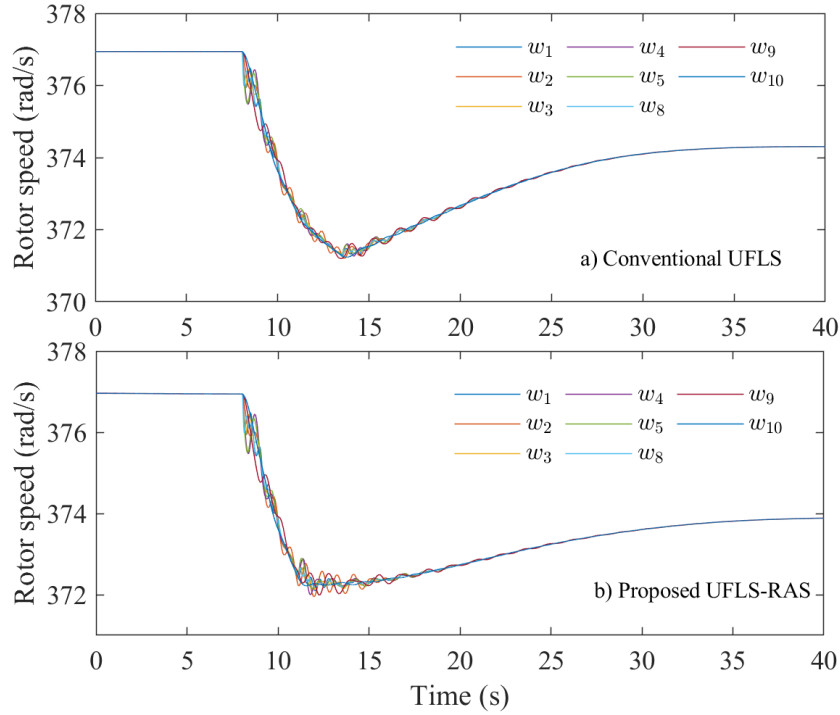


Figure 4.23: Comparison of the synchronous-generator rotor-speed responses under contingency C1 for the base case using the conventional UFLS scheme and the proposed UFLS-RAS.

using the data-driven assessment implemented in *RTAC-C* during the C1 event.

Table 4.10 shows the results of the data-driven assessment implemented in *RTAC-C*. First, the power system is protected using the conventional UFLS scheme and subsequently using the proposed UFLS-RAS. In both cases, the table reports the continuous-time eigenvalues estimated by DMD and the corresponding oscillation frequencies. The results are computed over a 6-second time window following the contingency onset, with a sampling rate of 10 samples per second.

Overall, both local and inter-area oscillation modes are observed under the operation of the two schemes. However, when the proposed UFLS-RAS is in operation, some modes exhibit real parts closer to the imaginary axis, indicating lower damping compared with the conventional UFLS scheme.

Table 4.10: Data-driven assessment for C1 under the base case: continuous-time eigenvalues and frequencies

Mode	Conventional UFLS		Proposed UFLS-RAS	
	Eigenvalue	Frequency (Hz)	Eigenvalue	Frequency (Hz)
1	$-4.3893 \pm j11.9207$	1.8972	$-0.7796 \pm j11.1145$	1.7689
2	$-1.2229 \pm j11.8876$	1.8920	$-2.0137 \pm j7.7062$	1.2265
3	$-1.5475 \pm j7.1580$	1.1392	$-0.5652 \pm j4.8468$	0.7714
4	$-1.1478 \pm j3.1816$	0.5064	$-0.1641 \pm j2.7809$	0.4426
5	$-0.2191 \pm j3.0977$	0.4930	$-1.5887 \pm j2.3527$	0.3744
6	$-0.5919 \pm j1.1934$	0.1899	$-0.4488 \pm j0.8218$	0.1308

This behavior is consistent with the rotor speed responses shown in Figure 4.23 and is attributed to the single-stage load-shedding methodology. Although this approach has demonstrated strong performance in terms of frequency response, it may also introduce dynamic risks. Specifically, disconnecting a large amount of load in a single stage can excite poorly damped or even unstable oscillation modes. Even though instability is not observed in this case, the analysis highlights the

importance of having detailed dynamic information about the power system to support informed operational and design decisions.

Finally, within the data-driven assessment stage implemented in *RTAC-C*, Figure 4.24 illustrates a comparison of the mode shape corresponding to mode 4 under the operation of the conventional UFLS scheme and the proposed UFLS-RAS. For this oscillation mode, under the conventional UFLS scheme, the synchronous machines with the highest participation are generators G7 and G9, while the remaining machines exhibit a similar level of participation. In contrast, when the proposed UFLS-RAS is in operation, characterized by single-stage load shedding, generators G7 and G9 continue to exhibit large amplitudes in this mode. Additionally, the participation of other machines, such as G2, becomes more pronounced. Conventional UFLS (360 MW) Proposed UFLS-RAS (327.6 MW) $f_{ss}^{\text{post,ref}} = 59.5 \text{ Hz}$

This behavior indicates that single-stage load shedding can lead to a redistribution of modal participation, causing additional synchronous machines to contribute significantly to the dominant oscillation modes of the power system, which may pose a risk to system stability.

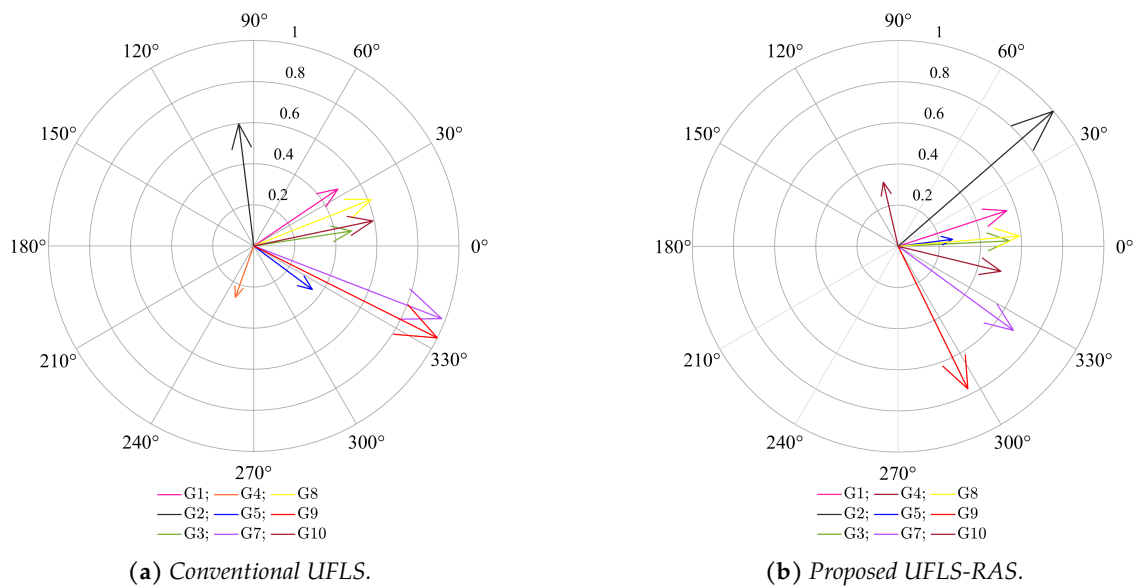


Figure 4.24: Mode-shape comparison between the conventional UFLS scheme and the proposed UFLS-RAS for mode 4 under C1 in the base case.

Conventional RAS schemes typically lack access to this type of information during continuous operation and are therefore unable to assess how their load-shedding actions may influence other system variables. This limitation highlights the advantage of the proposed UFLS-RAS methodology, which leverages data-driven insights to enable informed decision-making with awareness of its actual impact on the power system.

Contingency C2

Similarly, to evaluate the performance of the proposed UFLS-RAS under contingency C2, 50 simulations are conducted as part of the *multi-run* approach implemented in the system-level digital twin. Contingency C2 corresponds to the simultaneous loss of two generation units, representing a more severe disturbance than C1. Consequently, a higher amount of load shedding is required.

For the base case, the system-level digital twin determines that the fourth stage of the conventional UFLS scheme must be considered. Based on the *multi-run* simulations shown in Figure 4.25, the UFLS-RAS estimates that disconnecting 567 MW of load leads the system to a post-contingency

steady-state frequency of 59.5055 Hz.

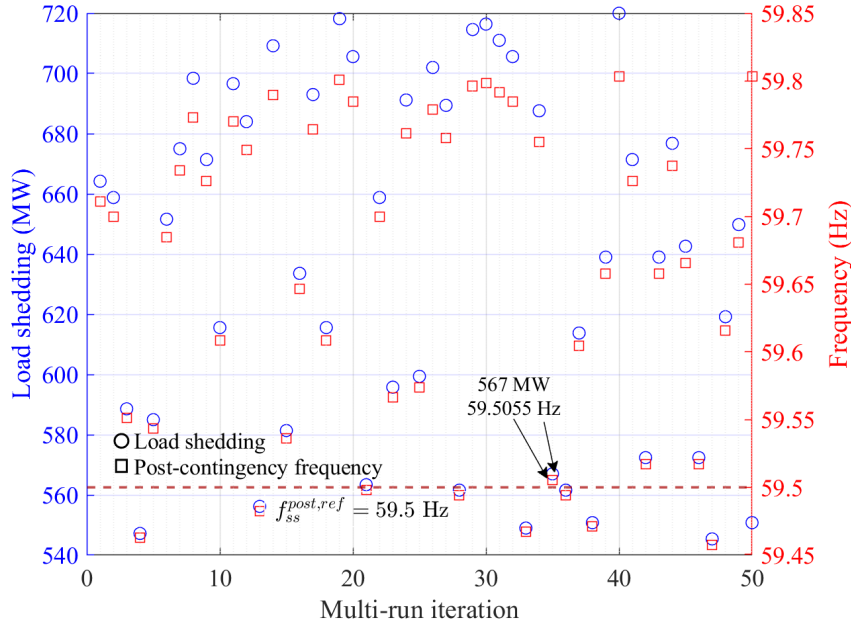


Figure 4.25: Multi-run evaluation performed by RTAC-B for contingency C2 under base case. Each test corresponds to a randomly generated load-shedding candidate evaluated through the power-flow-based digital twin with primary frequency regulation; the selected candidate corresponds to 567 MW.

Figure 4.26 illustrates the system frequency response under the operation of the conventional UFLS scheme and the proposed UFLS-RAS. Under the conventional UFLS scheme, the frequency deviation triggers three UFLS stages, resulting in a total load shedding of 540 MW. Although this action enables frequency recovery, the system does not reach the desired steady-state value and exhibits a less effective dynamic response.

In contrast, when the proposed UFLS-RAS is deployed, it sheds the amount estimated by the system-level digital twin, that is, 567 MW. This action is equivalent to disconnecting three full UFLS stages plus a portion of the fourth stage, thereby providing a finer and more precise load-shedding strategy. As a result, the system frequency reaches and slightly exceeds the desired target value.

Overall, despite the higher severity of the $N - 2$ contingency, the proposed UFLS-RAS provides an improved system response, achieving better steady-state frequency values and a more favorable dynamic behavior compared with the conventional UFLS scheme. These results demonstrate that the proposed UFLS-RAS is capable of adaptively adjusting the amount of load shedding according to the severity of the disturbance, effectively handling both $N - 1$ and $N - 2$ contingencies.

Figure 4.27 shows the simulations performed using the *multi-run* approach within the system-level digital twin for Case 1, in which the available load-shedding capacity of stage 2 is limited to 110 MW from the original 180 MW. Under this condition, the proposed UFLS-RAS estimates that a total load shedding of 564.8 MW is required to achieve a steady-state frequency of 59.501 Hz. This amount involves the disconnection of three full UFLS stages and an additional 24.8 MW from the fourth stage.

Figure 4.28 presents a comparison of the system frequency response under the conventional UFLS scheme and the proposed UFLS-RAS. In the case of the conventional UFLS scheme, a lower amount of active power is shed, 470 MW, due to the limited availability of load in stage 2. As a result, the scheme is unable to restore the system frequency to the desired value. Moreover, the frequency deviation caused by contingency C2 is not severe enough to trigger the fourth UFLS stage, which causes the frequency to settle at undesirably low levels.

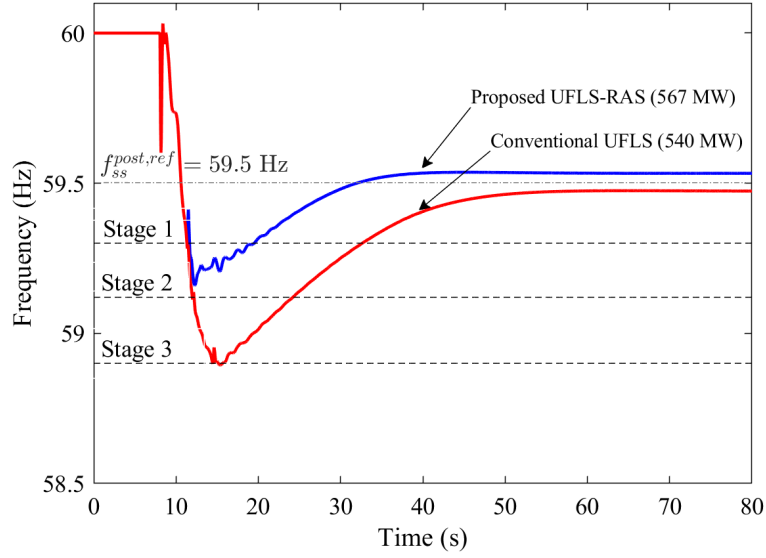


Figure 4.26: Frequency response at bus 21 under contingency C2 for base case, comparing the conventional UFLS scheme and the proposed UFLS-RAS. The conventional UFLS scheme is unable to restore the post-contingency steady-state frequency to the target value, whereas the proposed UFLS-RAS identifies an alternative load-shedding action capable of recovering $f_{ss}^{post,ref} = 59.5$ Hz.

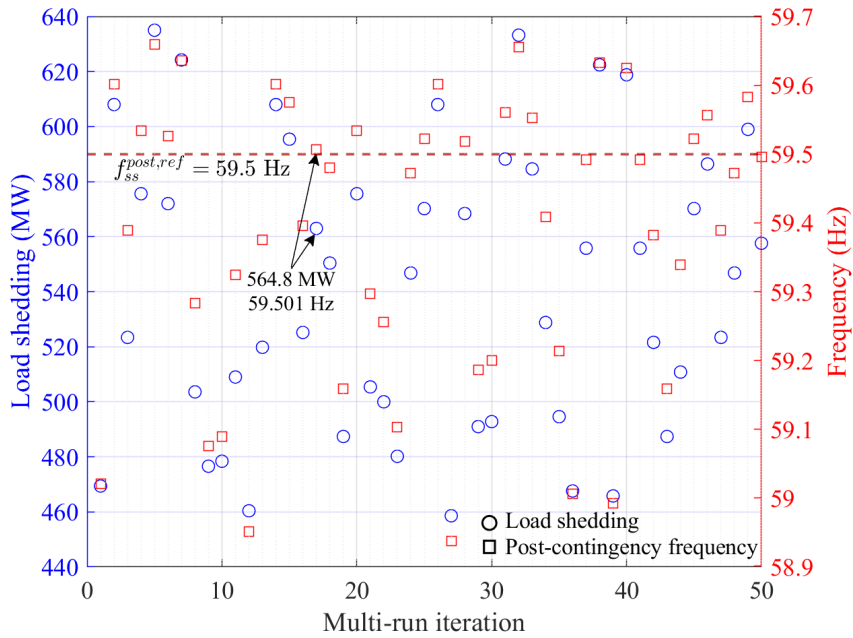


Figure 4.27: Multi-run evaluation performed by RTAC-B for contingency C2 under Case 1. Each test corresponds to a randomly generated load-shedding candidate evaluated through the power-flow-based digital twin with primary frequency regulation; the selected candidate corresponds to 564.8 MW.

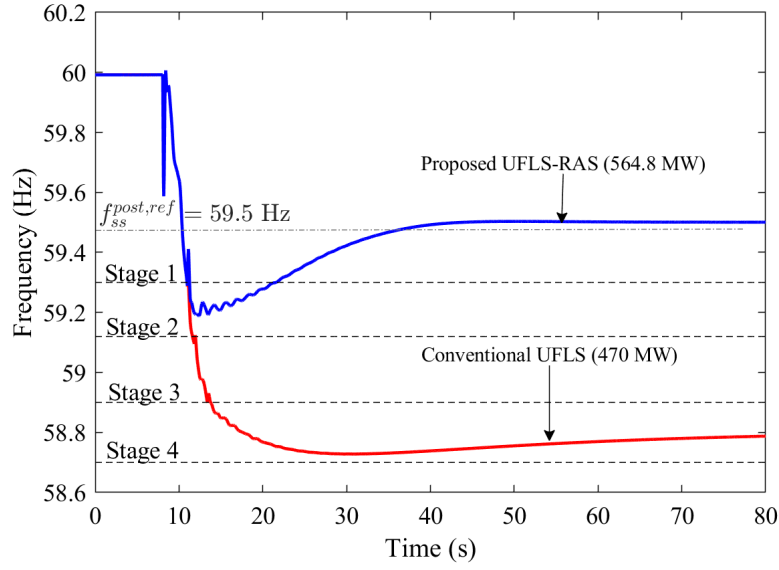


Figure 4.28: Frequency response at bus 21 under contingency C2 for Case 1, comparing the conventional UFLS scheme and the proposed UFLS-RAS. Due to the load-shedding limitation imposed in Case 1, the conventional UFLS scheme is unable to restore the post-contingency steady-state frequency to the target value, whereas the proposed UFLS-RAS identifies an alternative load-shedding action capable of recovering $f_{ss}^{post,ref} = 59.5$ Hz.

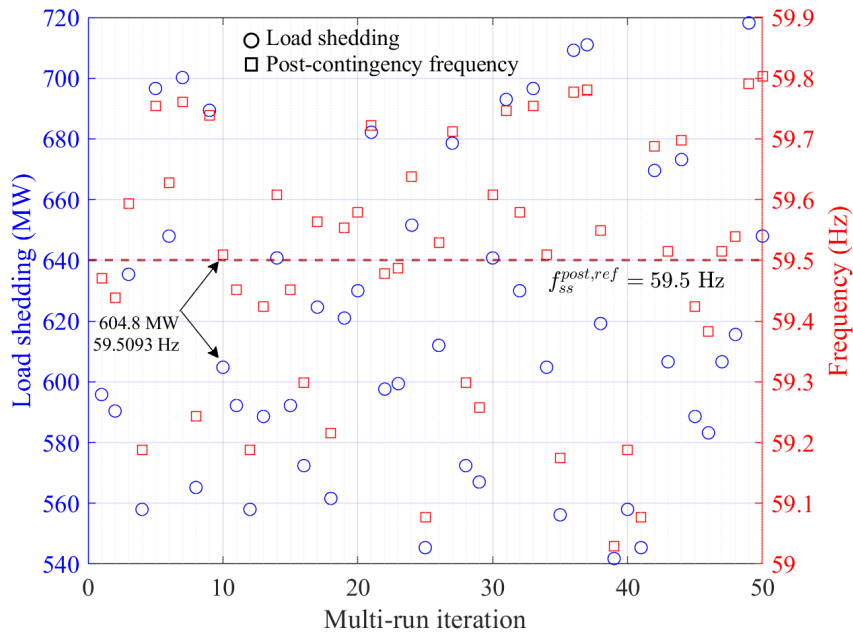


Figure 4.29: Multi-run evaluation performed by RTAC-B for contingency C2 under Case 2. Each test corresponds to a randomly generated load-shedding candidate evaluated through the power-flow-based digital twin with primary frequency regulation; the selected candidate corresponds to 604.8 MW.

In contrast, the proposed UFLS-RAS disconnects the 564.8 MW estimated by the system-level digital twin, overcoming the limitations of the conventional scheme. Consequently, the system achieves improved steady-state frequency values, along with a more favorable dynamic response.

Finally, the performance of the proposed UFLS-RAS is evaluated for Case 2, which corresponds to a change in the operating point of the power grid. Figure 4.29 presents the simulations carried out using the *multi-run* approach. For this operating condition and contingency C2, the UFLS-RAS estimates that 604.8 MW of load must be shed for the system to reach a steady-state frequency of 59.5093 Hz. Therefore, this value is assigned to the UFLS-Replica for the subsequent tests.

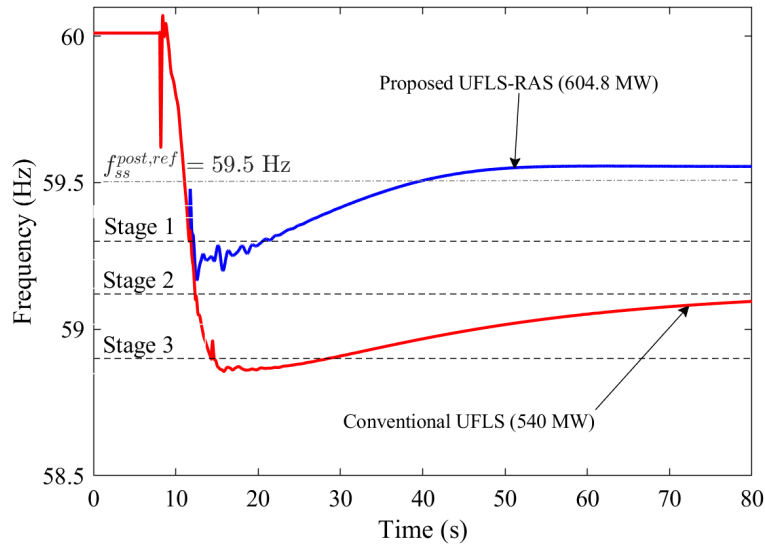


Figure 4.30: Frequency response at bus 21 under contingency C2 for Case 2, comparing the conventional UFLS scheme and the proposed UFLS-RAS. The conventional UFLS scheme is unable to restore the post-contingency steady-state frequency to the target value, whereas the proposed UFLS-RAS identifies an alternative load-shedding action capable of recovering $f_{ss}^{post,ref} = 59.5$ Hz.

Table 4.11: Comparison of UFLS performance for contingency C2 under different cases

Case	Scheme	Total Load Shed (MW)	Number of Stages Activated	Load Taken from Final Stage (MW)
Base Case	Conventional UFLS	540	3	–
Base Case	Proposed UFLS-RAS	567	4	27
Case 1	Conventional UFLS	470	3	–
Case 1	Proposed UFLS-RAS	564.8	4	94.8
Case 2	Conventional UFLS	540	3	–
Case 2	Proposed UFLS-RAS	604.8	4	64.8

Figure 4.30 presents a comparison of the system frequency response under the conventional UFLS scheme and the proposed UFLS-RAS. The conventional UFLS scheme activates only three stages, resulting in a total load shedding of 540 MW. In contrast, the proposed UFLS-RAS disconnects three full stages and a portion of the fourth stage, corresponding to 604.8 MW as estimated by the system-level digital twin.

This additional and more precise load shedding enables the system frequency to reach and slightly exceed the desired target value. Furthermore, the proposed UFLS-RAS exhibits superior dynamic frequency performance during the transient following contingency C2. Table 4.11 provides

a general summary of the load-shedding amounts implemented by both the conventional UFLS scheme and the proposed UFLS-RAS across the three evaluated cases under contingency C2.

The results presented so far indicate that the proposed UFLS-RAS can support $N - 2$ contingencies, exhibiting satisfactory performance by maintaining the system frequency within the design limits. In addition, through its data-driven assessment stage, the UFLS-RAS is able to evaluate the impact of its actions on the electromechanical oscillation modes of the power system.

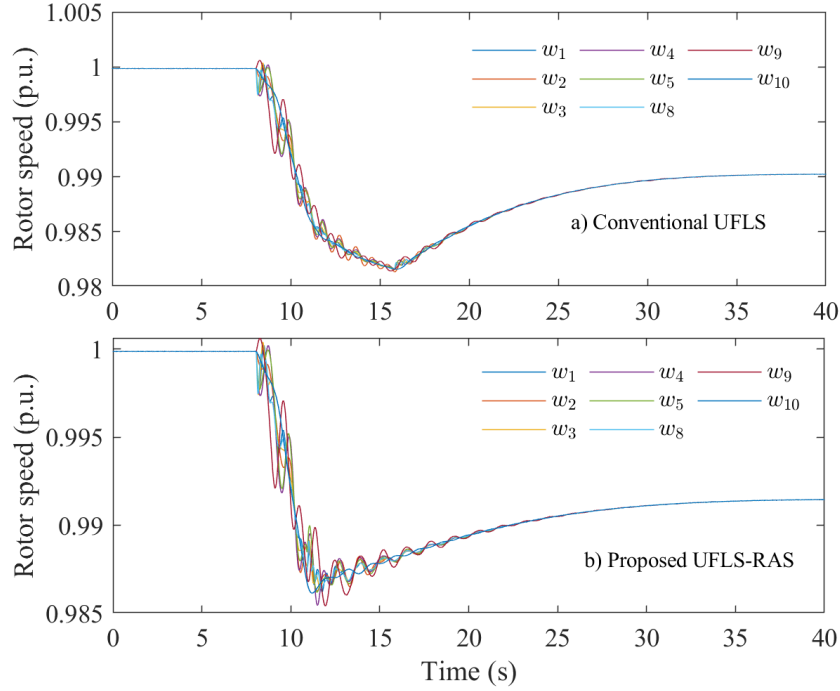


Figure 4.31: Comparison of rotor speed response under C2 for the base case using the conventional UFLS scheme and the proposed UFLS-RAS.

Figure 4.31 illustrates the rotor speed responses of the synchronous machines in the test system under contingency C2 for the base case. Stable behavior is observed under both schemes. However, when load shedding is executed in a single stage, as in the proposed UFLS-RAS, the rotor speeds exhibit higher-amplitude oscillations with lower damping. Although these oscillations remain stable, it is important for the proposed UFLS-RAS to be aware of the impact of its load-shedding actions on the electromechanical modes of the power system. Under certain operating conditions, such oscillation modes could become unstable, potentially leading to a detrimental rather than beneficial effect on system performance.

Table 4.12: Data-driven assessment for C2 under the base case: continuous-time eigenvalues and frequencies

Mode	Conventional UFLS		Proposed UFLS-RAS	
	Eigenvalue	Frequency (Hz)	Eigenvalue	Frequency (Hz)
1	$-1.4954 \pm j10.3251$	1.6433	$-0.8222 \pm j14.1584$	2.2534
2	$-0.0423 \pm j6.6871$	1.0643	$-0.0164 \pm j6.4128$	1.0206
3	$-0.4262 \pm j5.7951$	0.9223	$-0.6099 \pm j5.7916$	0.9218
4	$-1.3938 \pm j3.1366$	0.4992	$-0.3184 \pm j4.1684$	0.6634
5	$-0.3530 \pm j0.8226$	0.1309	$-0.2438 \pm j1.3166$	0.2095
6	$-0.2776 \pm j1.7218$	0.2740	$-0.2140 \pm j0.7671$	0.1221

In this context, Table 4.12 presents the results of the data-driven assessment performed by RTAC-C, comparing the continuous-time eigenvalues and oscillation frequencies under the conventional

UFLS scheme and the proposed UFLS-RAS. Overall, when the proposed UFLS-RAS is in operation, several modes exhibit lower damping, as indicated by real parts closer to the imaginary axis. This is reflected in the higher-amplitude, lower-damped oscillations observed in the rotor speed responses shown in Figure 4.31. These results indicate that single-stage load shedding constitutes a more severe disturbance to the power system, potentially leading to the emergence of poorly damped oscillation modes.

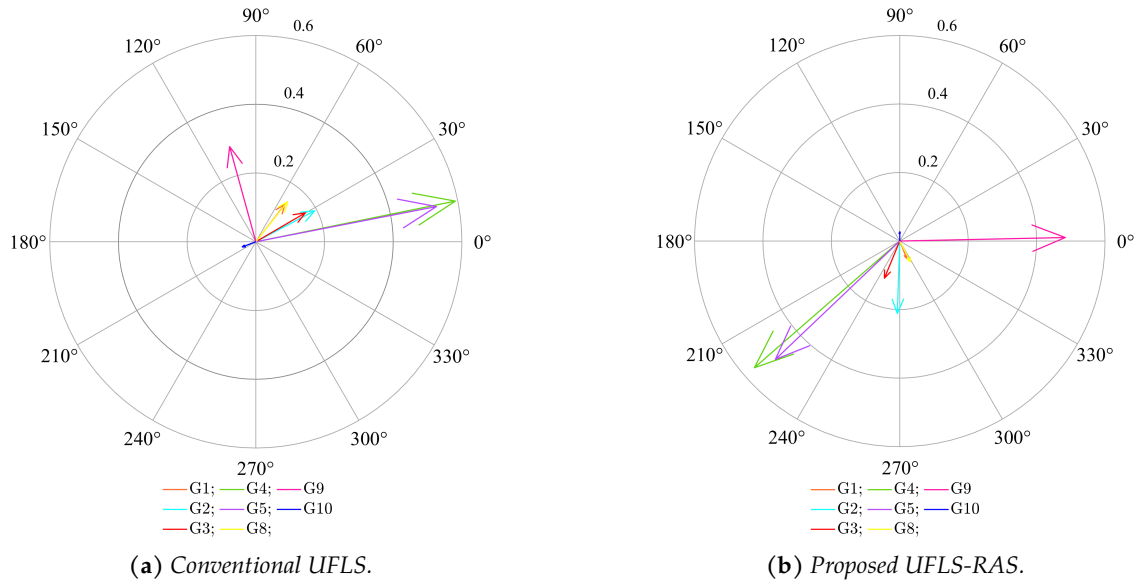


Figure 4.32: Mode-shape comparison between the conventional UFLS scheme and the proposed UFLS-RAS for mode 3 under C2 in the base case.

Finally, based on the information obtained from the data-driven assessment implemented in RTAC-C, Figure 4.32 illustrates the mode shape associated with mode 3 under the operation of the conventional UFLS scheme and the proposed UFLS-RAS. In the case of the conventional UFLS scheme, synchronous machines G4 and G5 exhibit the highest participation in this oscillatory mode, as they are electrically close to contingency C2, while the remaining machines show comparatively lower modal contributions.

In contrast, under the operation of the proposed UFLS-RAS, although G4 and G5 remain dominant, a significant increase in the participation of machine G9 is observed, indicating a broader redistribution of the system oscillatory dynamics. This behavior highlights that the proposed UFLS-RAS may lead to reduced damping and increased oscillation amplitudes, involving a larger number of synchronous machines in the electromechanical modes.

Although the analyzed modes remain stable, the proposed UFLS-RAS provides a more informed operating framework than the conventional UFLS scheme by incorporating the capability to assess the impact of its control actions on both frequency response and electromechanical modes. This feature supports the identification and avoidance of undesirable operating conditions, while enhancing situational awareness and real-time decision-making within the proposed UFLS-RAS framework performance.

The simulation results obtained in the UFLS-Replica can also be used as a dynamic validation stage for the load-shedding action estimated by the system-level digital twin. In particular, before transferring the selected action to the physical UFLS scheme, the replica environment allows verifying whether the proposed load shedding preserves the stability of the power system after the abrupt disconnection of load. If the dynamic response indicates poorly damped oscillations, excessive deviations, or potential instability, the same framework provides the information required to

modify the shedding strategy. For instance, the load-shedding action could be redistributed over more than one stage to avoid disconnecting a large amount of load at once, or the total amount of load shedding could be reduced if the dynamic validation shows that the original action is too severe. Although this automatic corrective logic is not implemented in the results presented in this thesis, the proposed UFLS-RAS is prepared to support this functionality through the interaction between the system-level digital twin, the UFLS-Replica, and the DMD-based data-driven assessment.

Parametric Sensitivity Analysis of the Proposed UFLS-RAS

Although the operational methodology of the proposed UFLS-RAS is inherently adaptive, its dynamic adjustment relies on model-based estimations. In particular, the framework depends on two main models: the power flow with primary frequency regulation used within the system-level digital twin, and the dynamic model implemented in the real-time simulator within the replica environment. While these models are calibrated to represent the physical behavior of the real system, discrepancies between modeled and actual system conditions are inevitable.

In practice, model parameters are intended to reflect field conditions; however, uncertainties and deviations may persist. Variations in some parameters may have a negligible impact, whereas others can significantly influence the performance of the proposed UFLS-RAS. In this regard, the governor droop gains of synchronous machines are among the most critical parameters, since deviations in their values directly affect the estimation of the required load shedding.

From an operational perspective, generation companies are required to provide dynamic models of their units, including control parameters such as droop gains. However, these values are typically provided as nominal settings and may be adjusted during real-time operation. Although such modifications should be reported to control centers, this is not always enforced, and updates are not consistently reflected in system models. This issue can also propagate to the system-level digital twin and to the associated real-time replica, where parameter inconsistencies may arise.

Therefore, this section presents a sensitivity analysis to variations in the droop gains of synchronous machines to evaluate their impact on the performance of the proposed UFLS-RAS. This analysis provides insight into the robustness of the proposed scheme under modeling uncertainties and highlights potential actions to mitigate their effects.

Table 4.13: Droop gain variation ranges for sensitivity analysis

Variation	Minimum Droop (p.u.)	Reference Droop (p.u.)	Maximum Droop (p.u.)
±1%	0.08910	0.09000	0.09090
±3%	0.08730	0.09000	0.09270
±5%	0.08550	0.09000	0.09450
±7%	0.08370	0.09000	0.09630
±9%	0.08190	0.09000	0.09810

Table 4.13 summarizes the parametric variation ranges considered in this analysis. As a baseline condition, all synchronous machines in the power system operate with a droop gain of 0.09 p.u., which is adopted as the reference value. From this base case, parametric variations are introduced only in synchronous machines G3, G4, and G10, selecting one representative unit per system area.

It is important to emphasize that these parametric variations are applied exclusively to the RTDS model that represents the physical power system. In contrast, the system-level digital twin and the RTDS model associated with the replica environment retain the nominal droop values. Therefore, this analysis evaluates the effect of a parameter mismatch between the physical system representa-

tion and the models used by the proposed UFLS-RAS.

This approach avoids the simultaneous application of multiple parametric perturbations, which would lead to a poorly tuned model that does not accurately represent the expected behavior of a real system. Instead, the objective is to assess the impact of plausible parameter deviations on an otherwise properly calibrated model.

Although Table 4.13 presents both positive and negative variation ranges, the tests reported in this section focus on positive droop-parameter increments of 1%, 3%, 5%, 7%, and 9% with respect to the nominal value. This represents a conservative scenario, since increasing the droop parameter reduces the effective primary-frequency regulation gain and, consequently, the active-power contribution of synchronous machines in response to frequency deviations. As a result, a reduced active-power response leads to larger frequency deviations, which may require higher levels of load shedding to maintain the desired post-contingency frequency.

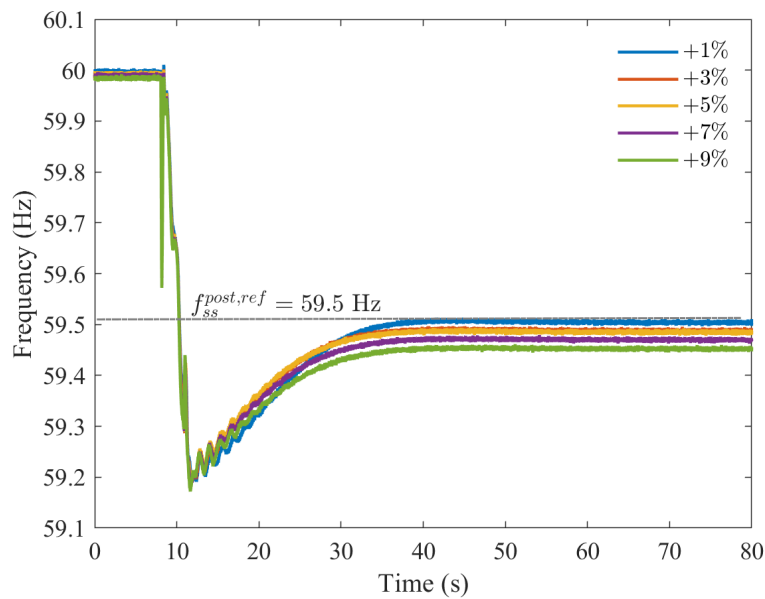


Figure 4.33: Frequency response at bus 21 under contingency C2 for the base case considering droop-parameter increments of 1%, 3%, 5%, 7%, and 9% with respect to the nominal values of the synchronous-machine droop parameters.

Figure 4.33 shows the frequency response at bus 21 following contingency C2 under the base-case operating condition. In this scenario, the proposed UFLS-RAS performs a load shedding of 567 MW, targeting a post-contingency steady-state frequency of $f_{ss}^{post,ref} = 59.5$ Hz. This value is used as the reference by the system-level digital twin and its *multi-run* approach implemented in RTAC-B.

The results show that a 1% positive increment in the droop parameters with respect to their nominal values does not significantly affect system performance, as the desired post-contingency frequency is still reached after the contingency with the prescribed load-shedding action. However, for positive droop-parameter increments of 3% and above, the frequency deviation increases noticeably, and the system fails to reach the target value. This suggests that, under such parameter mismatch conditions, the load-shedding amount estimated with nominal droop values may no longer be sufficient to achieve the desired post-contingency steady-state frequency. As the droop-parameter increment increases, the post-contingency steady-state frequency progressively departs from the target value due to the reduction in the effective primary-frequency regulation gain.

To mitigate the impact of positive droop-parameter increments in synchronous machines, an increase in the post-contingency steady-state frequency target is evaluated. Specifically, the reference

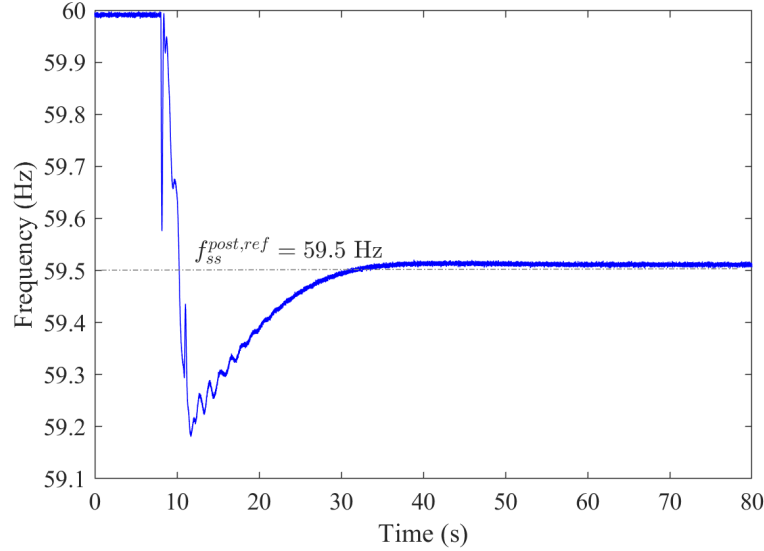


Figure 4.34: Frequency response under contingency C2 for the base case with a 9% positive droop-parameter increment and an updated post-contingency frequency target of 59.55 Hz.

value is increased from 59.5 Hz to 59.55 Hz. For the system under study, this adjustment introduces an additional design margin that allows the proposed UFLS-RAS to maintain acceptable performance under positive droop-parameter increments of up to 9%. Increments beyond this range are considered significant and unlikely in a well-calibrated and properly parameterized model.

Figure 4.34 presents the performance of the proposed UFLS-RAS under this modified condition for a 9% positive droop-parameter increment. Within the digital twin stage, the *multi-run* approach implemented in *RTAC-B* estimates that a load-shedding action of 584.6 MW is sufficient to achieve the updated post-contingency frequency target of 59.55 Hz. This load-shedding action is then evaluated in the replica environment, where the dynamic frequency response exhibits satisfactory performance, successfully reaching and slightly exceeding the target value.

This type of analysis is not typically considered in conventional UFLS implementations, where parameters such as droop values are often assumed constant across different operating conditions. Such assumptions may not accurately reflect the variability observed in real power system operation. In contrast, the proposed UFLS-RAS provides a framework in which parameter sensitivities can be evaluated and incorporated into the design margins of the load-shedding strategy.

As a result, the proposed methodology demonstrates improved adaptability and robustness under parameter mismatch conditions. By combining a system-level digital twin, a UFLS-Replica, and a data-driven dynamic assessment stage, the proposed UFLS-RAS enables more informed decision-making than conventional UFLS schemes. Overall, the proposed approach overcomes several limitations of fixed-parameter UFLS schemes by maintaining the system closer to the desired post-contingency operating condition, providing enhanced dynamic awareness, and remaining compatible with existing RAS infrastructures.

Conclusions

Summary of Findings

The operational methodology proposed in this research satisfactorily addresses the objectives established at the outset of this work by overcoming several limitations of conventional remedial action schemes, which have historically relied on operational assumptions, offline studies, and fixed parameters. In contrast, the developed methodology enables the extraction of system information that is not directly observable from conventional measurements, supporting informed decision-making and the adaptive updating of RAS operating parameters. This is achieved through the integration of digital twins, replica-based schemes, and data-driven techniques, giving rise to a new generation of RAS with adaptive, dynamically aware, and mathematically grounded capabilities.

The proposed methodology is generalizable to different stability problems in power systems, because its architecture decouples three functions that are independent of the specific phenomenon being addressed: real-time estimation of a stability indicator through the digital twin, representation of controller-level constraints through the replica, and dynamic verification of the remedial action through data-driven analysis. This structural separation explains why the methodology, first developed for voltage stability, could be extended to frequency stability while preserving consistency in both structure and performance.

The methodological developments presented in this thesis rest on two formal constructs that are scientific contributions in their own right, independent of any specific hardware platform. First, the formulation of the voltage stability margin estimation embedded in the UVLS-RAS digital twin, which provides a real-time indicator that captures system proximity to voltage collapse and serves as a control variable for the adaptive load-shedding strategy. Second, the application of Dynamic Mode Decomposition as a diagnostic tool for assessing the dynamic impact of remedial actions on electromechanical oscillation modes, which constitutes a methodological bridge between data-driven analysis and the operation of remedial action schemes. These constructs retain their scientific value independently of the platform on which they are deployed; the hardware-in-the-loop validation reported in this thesis is the experimental confirmation that they remain valid under realistic implementation conditions, not their justification.

For the voltage stability problem, the real-time estimation of the voltage stability margin through the digital twin enables the RAS to adjust the amount of load shedding according to actual grid conditions. The two-stage strategy proved effective in addressing both steady-state and dynamic system responses. Compared against a conventional fixed-threshold UVLS scheme on the IEEE 39-bus test system, the proposed RAS dynamically adjusted the load shedding strategy according to the severity of each contingency evaluated in [Chapter 3](#). In highly stressed operating conditions, the scheme intentionally disconnected larger amounts of load when necessary to preserve system stability and maintain post-contingency voltage profiles within acceptable operating limits, whereas the conventional scheme exhibited insufficient corrective action under the same scenarios.

For the frequency stability problem, the UFLS-oriented RAS uses the power-flow-based digital twin with primary frequency regulation to estimate the post-contingency steady-state frequency, which allows the load-shedding action to be adjusted under varying operating conditions, including the online evaluation of $N - 1$ and $N - 2$ contingencies. The flexibility in selecting disconnection circuits further mitigates limitations in load availability. As a result, the proposed approach maintains the system frequency closer to the target steady-state value (59.5 Hz) across the contingencies evaluated, while also improving the frequency nadir with respect to the conventional multistage UFLS scheme implemented as a reference in this thesis. The incorporation of the UFLS-Replica also enables the explicit consideration of interactions with physical devices, providing a more realistic assessment of system behavior.

The integration of a dynamic assessment framework based on dynamic mode decomposition revealed that, although single-stage load-shedding strategies can be effective from a steady-state frequency standpoint, they may induce poorly damped electromechanical oscillations. In the cases evaluated, these oscillations remained stable; however, this behavior cannot be guaranteed under all operating conditions. This finding qualifies the single-stage strategy proposed in this thesis and justifies the inclusion of a dynamic assessment stage as an integral component of the RAS. Without this stage, a load-shedding action determined from steady-state criteria alone could compromise the dynamic response of the system under certain conditions. The ability of the proposed RAS to evaluate the dynamic impact of its remedial actions prior to their physical execution therefore constitutes a significant advantage over conventional schemes.

The parametric sensitivity analysis conducted on the governor droop gains shows that the proposed UFLS-RAS is affected by parameter mismatches between the physical system and the models embedded in the digital twin and the replica. Droop-gain deviations beyond 1% with respect to the nominal values produce noticeable departures from the target post-contingency steady-state frequency. The results also show that this sensitivity can be compensated by adjusting the post-contingency frequency target as a design margin, allowing the proposed scheme to maintain acceptable performance for positive deviations of up to 9%. This behavior should be interpreted as a sensitivity of the method that requires explicit management through the design margin, rather than as a property of the scheme that is intrinsically robust to parametric variations. Nevertheless, the proposed framework provides the means to identify and incorporate this margin systematically, which is not contemplated in conventional fixed-parameter UFLS implementations.

The methodological contributions described above are verified through hardware-in-the-loop testing, which serves as the empirical confirmation that the proposed formulations remain valid when subjected to the constraints of industrial implementation. The HIL platform is not the object of study of this thesis but the experimental setting through which the methodology is contrasted against realistic operating conditions. The use of SEL-3555 RTAC units together with the RTDS Novacor real-time simulator enables the evaluation of the proposed RAS under conditions that include processing delays, internal controller architecture, and standard communication protocols, which cannot be reproduced in pure offline simulation. This validation step closes the loop between methodological development and the operating constraints of real RAS deployments. In particular, the methodology is compatible with the existing protection and automation infrastructure of substations, since the proposed RAS is hosted on the same family of industrial controllers that is widely deployed for protection, automation, and special protection schemes in modern transmission systems. This compatibility reduces the implementation barrier for utilities and system operators interested in adopting next-generation adaptive RAS.

The body of results presented in this thesis supports the hypothesis formulated in the Introduction. Conventional static load-shedding schemes were shown to produce insufficient or exces-

sive remedial actions under the operating conditions evaluated, whereas the proposed adaptive model-based RAS, supported by digital twins, replicas, and data-driven dynamic assessment, addressed these limitations by adjusting load-shedding actions according to real-time operating conditions and by validating their dynamic impact prior to execution. The performance improvements were observed in terms of post-contingency steady-state values, frequency nadir, and load-shedding amount, in both voltage and frequency stability applications, while the methodology remained implementable on industrial-grade controllers as verified through hardware-in-the-loop testing.

Original Contributions

The original contribution of this thesis is the development of an integrated methodology for the design, operation, and hardware-in-the-loop validation of adaptive RAS for voltage and frequency stability applications. The methodology combines model-based digital twins, industrial-controller replicas, and data-driven dynamic assessment to determine, adjust, and evaluate load-shedding actions according to real-time operating conditions.

The originality of the proposed framework does not lie in the isolated use of digital twins, replicas, or dynamic mode decomposition, which have been previously reported in different contexts. Rather, the contribution lies in their operational integration within a unified RAS framework, where each element fulfills a specific function: the system-level digital twin estimates stability indicators in real time, the industrial-controller replica represents physical, computational, and communication constraints, and the DMD-based assessment evaluates the dynamic impact of remedial actions on electromechanical oscillatory behavior.

Within this central contribution, the specific contributions of the thesis can be classified into two groups: methodological and analytical contributions, which constitute the scientific core of the work, and experimental contributions, which provide empirical verification of the proposed methodology under industrial-grade implementation conditions.

Methodological and analytical contributions

1. An integrated operational framework for adaptive RAS, which combines three elements that, to the best of the author's knowledge, had not been jointly incorporated into a single RAS methodology: a system-level digital twin for real-time estimation of stability indicators, a replica of the industrial-grade controller for representing implementation constraints, and a data-driven dynamic assessment stage based on DMD.
2. The model-based UVLS-RAS, in which a system-level digital twin estimates the voltage stability margin in real time and uses it as an operational index to adjust the amount of load shedding. This formulation is complemented by a two-stage strategy that addresses both steady-state voltage stability and dynamic voltage recovery.
3. The model-based UFLS-RAS, in which a power-flow formulation augmented with primary frequency regulation estimates the post-contingency steady-state frequency and determines an adaptive single-stage load-shedding action according to the actual operating condition. The framework also enables the online evaluation of $N - 1$ and $N - 2$ contingencies.
4. The implementation of DMD as a real-time dynamic assessment stage within a frequency-stability-oriented RAS, enabling the identification of electromechanical oscillatory modes associated with UFLS actions. This contribution is not the DMD algorithm itself, but its integration into the proposed RAS framework and its deployment in an industrial-grade controller to assess whether single-stage load shedding may introduce poorly damped oscillatory behavior.

even when steady-state frequency criteria are satisfied.

Experimental contributions

5. The implementation and verification of the complete methodology on industrial-grade hardware, using SEL-3555 RTAC controllers interfaced with an RTDS Novacor real-time simulator. This validation demonstrates the feasibility of the proposed methodology under realistic processing delays, controller architecture, communication protocols, and implementation constraints, providing empirical evidence that the proposed formulations preserve their performance under conditions that cannot be fully reproduced through pure offline simulation.

Limitations

Several limitations of the present work should be acknowledged. First, the proposed methodology relies on dynamic and steady-state models embedded in the digital twin and the replica; significant model-system discrepancies beyond those compensable by the design margin may degrade its performance. Second, the load-shedding action is currently determined through iterative or empirical procedures within the digital twin rather than through a closed-form formulation, which leaves room for improvement in computational efficiency. Third, the dynamic assessment stage, although capable of identifying poorly damped oscillations, does not yet trigger automatic corrective adjustments to the load-shedding strategy; the proposed architecture is prepared to support this functionality, but it is not implemented in the results reported here. Fourth, the validation has been carried out on the IEEE 39-bus New England test system, and its extension to larger or operationally distinct systems remains subject to further verification.

Overall, this thesis develops a scientific framework for next-generation remedial action schemes, comprising mathematical formulations for the real-time estimation of stability indicators, a data-driven method for the dynamic assessment of remedial actions, and an operational integration of these elements within a unified architecture. The hardware-in-the-loop validation, although a substantial engineering effort, is the experimental verification of this scientific framework, not its substance. The integration of methodology and experimental verification opens a path toward intelligent, adaptive, and dynamically aware remedial action schemes that are mathematically grounded and operationally implementable on the industrial controllers currently deployed in modern transmission systems.

Future Work

The future work arising from this research includes:

- Reformulating the mathematical models underlying the digital twins for voltage-collapse and frequency-stability applications, with the aim of directly computing the required load-shedding actions and reducing the need for iterative or empirical procedures.
- Introducing optimization and artificial intelligence techniques as additional stages within the proposed RAS framework, with the objective of enhancing decision-making and improving the optimality of load-shedding actions.
- Extending the DMD-based data-driven assessment framework to estimate additional system parameters, such as system inertia, in order to provide the RAS with more informative indicators of power system dynamics.

- Implementing the automatic corrective logic that uses the output of the dynamic assessment stage to modify the load-shedding action (e.g., redistribution across stages or reduction of the total amount), enabling closed-loop interaction between the system-level digital twin, the UFLS-Replica, and the DMD-based assessment.
- Incorporating online identification of critical model parameters, particularly governor droop gains and equivalent system inertia, from post-disturbance PMU measurements, so that the digital twin can self-calibrate and reduce the dependence on fixed design margins to compensate for model-system mismatches.
- Investigating the coordinated operation of the proposed UVLS-RAS and UFLS-RAS when both schemes are triggered by the same contingency, in order to assess whether their actions reinforce each other, remain independent, or interact adversely, and to define coordination criteria within the digital twin and replica framework.
- Extending the validation of the proposed methodology to power systems with high penetration of inverter-based resources, including photovoltaic plants, wind generation, and grid-forming converters, in order to evaluate whether the digital twin based on power flow with primary frequency regulation remains representative under reduced-inertia conditions and non-synchronous frequency response.
- Evaluating the performance of the proposed RAS under degraded communication conditions, including variable latencies, packet loss, and partial unavailability of the communication channels between the system-level digital twin, the replica, and the industrial-grade controllers, taking advantage of the hardware-in-the-loop infrastructure developed in this thesis.
- Analyzing the computational scalability of the proposed methodology when applied to large-scale power systems, including the use of model-order reduction, coherency-based machine aggregation, or area-decomposition techniques, in order to preserve real-time operation on systems representative of national-scale grids.

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