



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

Análisis de la estabilidad dinámica en sistemas eléctricos de potencia con alta penetración de generación eólica

T E S I S

Que para obtener el grado de:

Doctor en Ingeniería Eléctrica
Con Opción en Control Automático

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Enero de 2019



20 de septiembre de 2018

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P R E S E N T E.**

En atención a su solicitud de Temario, presentada por los **Dres. Rafael Peña Gallardo y Juan Segundo Ramírez**, Asesor y Co-asesor de la Tesis que desarrollará Usted con el objeto de obtener el Grado de **Doctor en Ingeniería Eléctrica**, me es grato comunicarle que en la Sesión del H. Consejo Técnico Consultivo celebrada el día 20 de septiembre del presente año, fue aprobado el Temario propuesto:

TEMARIO:

“Análisis de la estabilidad dinámica en sistemas eléctricos de potencia con alta penetración de generación eólica”

Introducción.

1. Modelado de sistemas de generación hidráulicos y eólicos.
2. Equivalente del sistema eléctrico mexicano región sureste.
3. Representación gráfica de probabilidad para la evaluación de la penetración de generación eólica en sistemas eléctricos de potencia.
4. Mejoramiento de la estabilidad dinámica mediante la utilización de Sistemas Flexibles de Transmisión en Corriente Alterna.
5. Metodología para la estimación de la constante de inercia en parques eólicos.

Conclusiones.

Anexos.

Referencias.

“MODOS ET CUNCTARUM RERUM MENSURAS AUDEBO”

ATENTAMENTE

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UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

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Área de Investigación y Estudios de Posgrado

Aclaración

El presente trabajo que lleva por título:

“Análisis de la estabilidad dinámica en sistemas eléctricos de potencia con alta penetración de generación eólica”

se realizó en el periodo agosto de 2014 a noviembre de 2018 bajo la dirección del Dr. Rafael Peña Gallardo.

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UASLP
Universidad Autónoma de San Luis Potosí
Posgrado en Ingeniería Eléctrica

Analysis of dynamic stability in electric power system with high penetration of wind power plants

Thesis
by
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Presented for the Degree of Doctor in Sciences in
Electrical Engineering



Centro de Investigación y Estudios de Posgrado
Posgrado en Ingeniería Eléctrica
PhD Thesis
January 2019



UASLP
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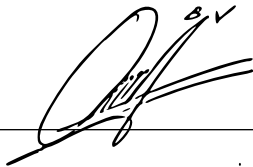
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Posgrado en Ingeniería Eléctrica
Doctorado en Ingeniería Eléctrica
Academic year: 2019

Declaration of authorship

I OMAR BELTRAN VALLE, declare that this thesis titled, 'Analysis of dynamic stability in electric power system with high penetration of wind power plants' and the work presented on it is my own. I confirm that this work submitted for assessment is my own and is expressed in my own words. Any uses made within it of the works of other authors in any form (e.g., ideas, equations, figures, text, tables, programs) are properly acknowledged at any point of their use. A list of the references employed is included. Signed:



Date: January 2019

Acknowledgments

I want to acknowledge the financial support received from Consejo Nacional de Ciencia Y Tecnología (CONACYT) through a scholarship to carry-out my PhD studies, without it, I would not have been able to finish this project in my life, thank you very much CONACYT.

I am grateful with the Universidad Autónoma de San Luis Potosí through the Facultad de Ingeniería in San Luis Potosí, México, the National Renewable Energy Laboratory in Golden and the University of Denver both of them in Colorado, United States for the facilities to carry-out my thesis. To my advisors in México Dr. Rafael Peña Gallardo, Dr. Juan Segundo Ramírez, thanks for your guidance, patience, and advice, with all of them I was able to finish this thesis. Also, to the professors, Dr. Eduard Muljadi and Dr. Wenzhong Gao for your friendly and grateful guidance in my visiting scholar in United States, it was a productive experience for me.

Special thanks to MsC. Jahel Ángeles Hernández, chief of Research Department of the National Center for Energy Control (CENACE, in Spanish) for the information provided, it was of great help to modeling and implementation of hydropower and their controllers and the power lines transmission parameters.

Dedictory

Nadie escoge la familia, ni el lugar, ni la posición donde nacer, pero si los amigos y hasta donde quieres llegar con tu vida...

No tengo palabras suficientes para expresar mi agradecimiento al creador por darme el mejor regalo de poner en mi camino a la personas correctas y por darme la oportunidad de forjar mi propio camino.

Gracias a mi padre Miguel Beltrán por poner tu esfuerzo en darme consejos desde mi infancia, y si he llegado hasta aquí ha sido por tus sabias palabras, gracias a mi madre María Teresa por acobijarme de tu ternura, paciencia y cálido amor, sin ellos hubiera sucumbido en los momentos de tristeza, soledad y necesidad; a ambos les debo mi vida y en el hombre que soy. Hoy les dedico esta alegría de culminar este proyecto de vida.

Tengo la dicha de contar con una maravillosa familia, hermanos, tíos, primos y abuelos, a ustedes, Jesús V., Hernán, Héctor, Néstor, Laura, Gabriela. A mis grandes amigos, protagonistas de este sueño, Edgar Hernández, Víctor Vega, Víctor Hugo por haberme apoyado cuando más lo he necesitado. Y a una larga lista con un gran etc. al final.

Este trabajo no es solo mío, se ha realizado con la ayuda de todos aquellos que me han apoyado directa o indirectamente en esta travesía, a todos ustedes les dedico esta obra.

Omar Beltrán Valle

Abstract

This thesis presents the analysis of dynamic stability of an equivalent power system with Wind Power Plants (WPPs). The equivalent power system includes the modeling of Renewable Energy Sources (RES) such as hydropower and wind generation units. This network is used for providing results about the impact of high penetration of WPPs and is carried out while steady and dynamic studies.

A new visual way to assess the impact of the WPPs in power system is presented, this methodology is called Graphical Probabilistic Representation. It has been developed to present in a clear, compact and visual way massive results of different scenarios in a single graphical representation. This representation can be used for short- and long-term planning tool, and it offers a better understanding of the impact of WPPs in power systems.

On the other hand, present problems in the area such as congestion management, stability improvement, and voltage support are represented in the equivalent model, with the aim to propose solutions through of Flexible Alternating Current Transmission System (FACTS) devices. To increase the power transfer in transmission lines, and offer voltage support the Thyristor-Controlled Series Compensator (TCSC), Static Synchronous Compensator (STATCOM), and a Unified Power Flow Controller (UPFC) have been implemented and connected in a critical point of the equivalent power system.

Finally, a methodology for inertia constant estimation is implemented in the equivalent power system under study. This methodology let to quantify the inertia in power systems where there is a high penetration of WPPs. The methodology is validated using DIgSILENT PowerFactory and experimental set-up in a RTDS. Also, it is applied to the inertia estimation of the hydropower and wind power plants of the southeast Mexican equivalent power system. The obtained results of the inertia estimation can be used to improve frequency stability problems.

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Abbreviations

AC	A lternating C urrent
AVR	A utomatic V oltage R egulator
BMA	B o M ban A
CENACE	C entro N acional de C ontrol de E nergía
CFE	C omisión F ederal de E lectricidad
DC	D irect C urrent
DFIG	D ouble F ed I nduction G enerator
DPF	D eterministic P ower F low
DPL	D Ig S ILENT P rogramming L anguage
EPS	E lectrical P ower S ystem
FACTS	F lexible A lternating C urrent T ransmission S ystems
FSIG	F ixed S peed I nduction G enerator
GWh	G iga W att per hour
GPR	G raphical P robabilistic R epresentation
IEEE	I nstitute of E lectrical and E lectronics E ngineers
IPO	I xtepec P Otencia
JUC	J UChitan
JUI	J UIle
kVA	kilo V olt A mpere
kW	kilo W att
MC	M onte C arlo
MPS	M al P aso
MMT	M anuel M a T amoros
MPI	M ultiobjective P erformace I ndices
MVA	M ega V olt A mpere

NREL	N ational R enewable E nergy L aboratory
PDF	P robabilistic D ensity F unctions
PEA	P Eñit A s
PFS	P ower F low S tudies
PLL	P hase- L ocked L ooop
PMU	P hasor M easurement U nits
OA	O il- A ir
PCC	P oint C ommon C oupling
PI	P roportional I ntegral
p.u.	p er u nit
POD	P ower O scillation D amper
RES	R enewable E nergy S ources
RMS	R oot M ean S quare
RTDS	R ea L T ime D igital S imulator
SEL	S chweitzer E ngineering L aboratory
SCH	S CHpoina
SLF	S tochastic L oad F low
SPD	S pecific P robability D istribution
STATCOM	S TATic C OMPensator
SVC	S tatic V oltage C ompensator
TCL	T eCa L li
TCSC	T hystor- C ontrolled S eries C ompensator
TAP	T APachula
TMD	T eMazcal D
TMZ	T ama Z ulapan
UPFC	U nified P ower F low C ontroller
WPP	W ind P ower P lant

Symbols

Symbol	Name	Unit
β	Blade pitch angle	degree
c	Turbine damping of wind power plant	N.m/rad
$C_p(\beta, \lambda)$	C_p -characteristic	
H	Inertia time constant	s.
i_d	Current in d -axis	p.u.
i_e	Current of excitation	i p.u.
i_r	Rotor current	i p.u.
i_s	Stator current	i p.u.
$i_{rd}^{ref}, i_{rq}^{ref}$	Referent current (d - and q -axis)	p.u.
H_{turb}	Inertia of turbine of wind power plant	kg/m^2
k	Shaft-stiffness	N.m/rad
λ	Tip speed ration	
n_{gear}	Turbine shaft	
p	Pole pairs	p.u.
Pm_d, Pm_q	Modulation index (d - and q - axis, referred to rotor angle)	p.u.
P	Active power	W (MW, p.u.)
P_{me}	Mechanical power extracted from turbine's shaft	
$P_{mec.gen}$	Mechanical power	W
P_{wind}	Wind power	W
ψ_d, ψ_q, ψ_0	Flux linkage (d -, q - and 0-axis)	p.u.
ψ_e	Excitation flux	p.u.
ψ_D	Flux in Damper Winding, d -axis	p.u.
ψ_R, ψ_S	Flux linkage (rotor and stator)	p.u.
Q	Reactive power	VAr (MVar, p.u.)

r_D, r_Q	Resistance of damper winding (d - and q -axis)	p.u.
r_e	Resistance of excitation winding	p.u.
r_r, r_s	Resistance (rotor and stator)	p.u.
r_x	Resistance of x -winding	p.u.
R	Rotor blade radius	m
ρ	Air density	kg/m^3
Rra	Rotor resistance (squirrel cage rotor)	p.u.
T_e	Electrical torque	p.u.
T'_d, T'_q	Transient time constant (short-circuit)	s.
T''_d, T''_q	Subtransient time constant (short-circuit)	s.
T_p	Pitch servo control system	
τ_{shaft}	Shaft turbine torque	N.m.
τ_{tur}	Turbine torque	N.m.
$\dot{\theta}_{tur}$	Angular speed of turbine	rad/s
$\dot{\theta}_k$	Angular difference between two flexible axis of the turbine	rad
v_d, v_q	Stator voltage (d - and q -axis)	p.u.
v_e	Excitation voltage	p.u.
v_r	Rotor voltage	p.u.
v_s	Stator voltage	p.u.
v_w	Wind speed	m/s
v_0	Stator voltage in 0-axis	p.u.
ω_{gen}	Wind generator angular speed	rad/s
ω_n	Angular speed of the network	rad/s
ω_r	Angular speed of the rotor	rad/s
ω_{ref}	Reference speed	rad/s
ω_{tur}	Turbine angular velocity	rad/s
X_r, X_s	Reactance (rotor and stator)	p.u.
X_m	Magnetization reactance	p.u.
X_d, X_q	Synchronous reactance (d - and q -axis)	p.u.
X'_d, X'_q	Transient reactance (d - and q -axis)	p.u.
X''_d, X''_q	Subtransient reactance (d - and q -axis)	p.u.
X_l	Stator leakage reactance	p.u.
X_{rl}	Rotor leakage reactance	p.u.

X_{md}, X_{mq}	Magnetizing reactance (d - and q -axis)	p.u.
X_{lD}, X_{lQ}	Leakage reactance of damper winding (d - and q -axis)	p.u.
X_{le}	Leakage reactance of excitation winding	p.u.
X_{lx}	Leakage reactance of x -winding	p.u.
X_{rA}	Rotor reactance (squirrel cage rotor)	p.u.

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Publications

Journal

1. O. Beltran, R. Peña, J. Segundo, A. Esparza, E. Muljadi, D. Wenzhong, “Inertia Estimation of Wind Power Plants Based on the Swing Equation and Phasor Measurement Units”, *Multidisciplinary Digital Publishing Institute, Applied Sciences*, vol. 8, 12, pp. 1-16
2. O. Beltran, R. Peña, J. Segundo, D. Wenzhong, E. Muljadi, “Power System Probabilistic Impact Assessment of Incorporating Wind Power Plants”, *Electrical Engineering (under review)*.

International conference

1. O. Beltran, R. Peña, J. Segundo, and E. Muljadi, “A comparative study of the application of facts devices in wind power plants of the southeast area of the mexican electric system,” in IEEE International Autumn Meeting on Power, Electronics and Computing, november, IEEE, 2016.

International poster

1. O. Beltran, “Wind power stability: Inertia estimation”, International Energy Africa Conference 2017 in Denver, Colorado, United States, november 2017.

Introduction

Renewable Energy Sources are constantly growing in power systems, in response to the reduction of CO_2 that is generated by other types of technologies and dependence on fossil fuels [1] - [8]. The amount of wind power generation has grown in recent years providing 3% of global power, for example, China is leading with 149 GW, United States with 8.2 GW, Germany with 5.3 GW, India with 3.6 GW, and Brazil with 2 GW [8].

In México, the Comisión Federal de Electricidad (CFE) is the utility that serves the electrical service in the country is in the process of increasing the current wind generation connected to the grid [9], specifically in the southeast area of México [9], where there is a wind resource that is considered the highest in the world (onshore) [10]. All of this, with the aim to encourage the use of RES to generate electric power [9].

Nowadays, in México, the hydropower and wind energy generation are the most kind of RES used to generate electricity. In case of hydropower, this provides a great flexibility based on the demand and storage of energy. While the initial cost is high, the simplicity of hydropower plants, their low maintenance cost, long life, and great reliability make them a great cost-benefit investment. Another important feature is the great stability they provide due to the robustness of the machines used, as well as also the rapid transfer of energy to the power system [11]. This kind of renewable source provides about 17% of the installed capacity in the entire Mexican power system (12,642 MW) [7]. Meanwhile, wind energy generation has re-emerged as one of the most important energy resources. The cost to produce energy with this kind of renewable source has fallen about one-sixth of the cost since the early 1980s. Being the wind energy boosted by new technologies to improve the cost of wind generation units, efficient and robustness [12]. Actually, the installed capacity of the WPPs is 4,199 MW, contributing 3% of the power generation of the entire power system [1]. Fig. 1 provides the location of hydropower and WPPs in México, while Table 3 shows the current-generation capacity of these types of renewable energies in the country [7].

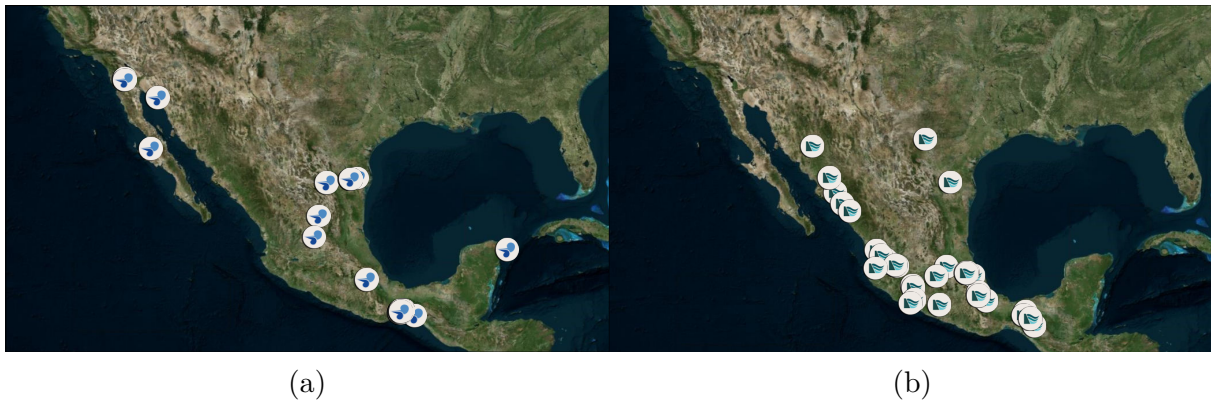


FIGURE 1: Renewable Energy Sources in México. (a) Wind power plants. (b) Hydropower plants (>30MW) [1].

TABLE 3: Renewable energy sources in México [7].

Power energy	Geothermal	Hydraulic >30 MW	Hydraulic ≤30 MW	Wind	Solar	Biomass
CFE	6,070	27,553	1,484	180	13	—
Private sector	95	257	635	8,966	107	1,481
Total	6,173	27,810	2,118	9,145	119	1,481

The most area of penetration of WPPs in México is the southeast area, specifically in the Istmo de Tehuantepec, Oaxaca [7] - [13] with 7,580.75 GWh/y that represents the 76.28% of the entire generation of this type of renewable source. Table 4 provides information about the installed capacity of WPPs.

TABLE 4: Wind power energy in México [7].

Place	Power (GWh/y)
Baja California	400.87
Chiapas	89.61
Jalisco	183.23
Nuevo Leon	726.35
Oaxaca	7,580.75
Puebla	252.58
Quintana Roo	2.32
San Luis Potosí	489.47
Sonora	4.14
Tamaulipas	168.83
Zacatecas	39.78

On the other hand, there are also a large number of on-going WPPs in México, Table 5 provides this information. Being the potential of this kind of generation of 87 600 GW/y [7].

TABLE 5: On-going wind power projects [7].

Place	Power (GWh/y)
Baja California	1,678
Chiapas	62
Chihuahua	93
Coahuila	4,291
Durango	387
Guanajuato	575
Hidalgo	168
Jalisco	1,830
Nuevo Leon	1,776
Oaxaca	1,356
Puebla	1,069
Queretaro	250
San Luis Potosí	2,415
Sonora	303
Tamaulipas	4,118
Veracruz	478
Yucatan	3,084

Motivation

Power system stability refers to the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium or move from one steady-state operating point to another steady-state operating point, after being subjected to a physical disturbance, without losing synchronism [14] - [15]. Inside the classification of power system stability, it is found the dynamic stability, which involves large-disturbances such as trip generation, line-switching operations, faults such as short-circuits, sudden load changes, among others [14]; disturbances that affects the dispatch of active and reactive power of generation units, the frequency stability and the voltage stability [16].

Maintaining power system stability depends mainly on factors such as the time of fault clearing, control systems, power electronic devices, and the inertia constant values of generation units [14], [17].

On the other hand, the increment of WPPs penetration in electrical networks brings new opportunities and also challenges in the electric power system [18]. The safety, stability and the operation of the power system could be affected when there is a high amount of penetration of WPPs [19] - [20], e.g., problems like dispatch of active and reactive power, congestion and frequency problems, voltage stability, subsynchronous resonance, power quality, among others can be produced due to the nature of this type of energy generation [18], [21]. One example of these problems is at Penghu Island in Taiwan, with abundant wind resources and high penetration of wind power that has reached 34%, although it has an impact on the Penghu network. Problems like voltage and frequency variations at the point of common coupling and angle-rotor variations of the machines are produced due to the high penetration of WPPs [22].

In order to attend the present problems and guarantee the dynamic stability where there is a high penetration of WPPs, such as in México, specifically in the southeast area, it is necessary to develop methodologies and studies that allow quantifying their impact to the power systems. The obtained results will be used as support for the operation, planning, and prevention of future problems. In this way, in this thesis, due to the importance of the study of stability problems related to high penetration of WPPs, has been addressed the following questions:

1. Is there an equivalent model of the Mexican southeast region for academic-research purposes?
2. How can we improve the dynamic stability Mexican southeast region?
3. How many ways there are to improve the dynamic stability Mexican southeast region?
4. What are the options in accordance with the problems to improve?
5. Is there a methodology that lets to evaluate the impact of WPPs in power systems?
6. Which methodologies let to improve frequency stability issues in power systems where there is a high penetration of WPPs?

In this thesis, it is addressed all the mentioned questions to the aim to improve the dynamic stability. To determinate the stability of the southeast region in México, it is important to have an equivalent model to represent the present problems. After, implement mathematical models to reproduce the dynamic behavior of the elements of the network. Later on, propose solutions through of technologies that let to improve actual problems about dynamic stability. Then, with the increase of penetration of WPPs, research and development methodologies to evaluate the impact of WPPs in power systems.

Thesis objectives

The purpose of the thesis is to evaluate the dynamic stability of power systems with a high concentration of hydropower generation and WPPs, and propose methodologies to assess their impact.

Specifics goals

This work considers the following specific goals:

1. Develop an equivalent network of the southeast of the Mexican electric system where there are large blocks of hydropower generation and high penetration of WPPs.
2. Evaluate the *bottleneck* of the equivalent network with steady and dynamic studies, where there is a high concentration of hydropower and WPPs.
3. Check the hypothesis about the installed power capacity can be increased from the “*critical point*” incorporating power electronic devices through of steady-state and dynamic studies.
4. Provide a methodology that let quantifying the impact of wind generation penetration in power systems.
5. Implement a methodology that let to quantify the inertia at the Point of Common Coupling (PCC) with WPPs, due a high penetration of this type of generation could produce frequency stability issues in the system.

Thesis outline

This Section provides information about structure of the thesis:

- **Chapter 1:** Presents the mathematic models of generation units used in this thesis. In the case of the hydropower plants is used the synchronous machine model, for the WPPs is used the doubly-fed induction generator, also, their control systems are presented in this Chapter.
- **Chapter 2:** Provides an equivalent model of the network of the southeast region of the Mexican power system. The primary objective is to represent the present problems in the system and propose solutions, some of the common problems are congestion management, stability improvement, and voltage support. This equivalent incorporates the dynamic models of the generation units, their controllers and the main elements of the network.
- **Chapter 3:** A novel graphical probability representation is proposed. This representation includes the probability that an operating condition occurs in the different scenarios under study, for instance, with changes in the network configuration, load and generation variations, among other, all of this in a clear, compact and visual way.
- **Chapter 4:** Presents an analysis and improvement of the dynamic stability of the network under study through FACTS devices. They are implemented in the equivalent model of the network to increase the available power transfer/capacity of transmission lines and voltage support.
- **Chapter 5:** Provides a methodology for the inertia estimation of WPPs. It takes advantage of using Phasor Measurement Units technology and provides great accuracy in the values of the inertia estimation. The obtained results are useful to estimate the inertia of generation units of the equivalent model.
- **Chapter 6:** Draws conclusions from the presented results and future work.

Chapter 1

Modeling of hydraulic and wind generation systems

1.1 Introduction

Most of the entire power generation in the world is generated by synchronous machines driven by hydropower generators, steam turbines or by the fossil fuels [8]. In the case of hydropower generation, salient-pole synchronous machines are used to generate electric power, while for WPPs, DFIG technology¹ is the most widely adopted [23]. Currently, in the south-east México region, hydropower in combination with high penetration of WPPs are the most generation units to provide electric power to the Mexican power system, being the salient-pole synchronous machines and DFIG technology used by these generation units [10], [13].

In this Chapter, mathematical models of hydropower and WPPs are presented. They are represented by the dynamic equations that define the electrical and mechanical behavior of these generation units. In addition, control system models of the generation units are included.

1.2 Hydropower plant model

Hydropower plants belong to RES, they work using a natural resource such water to generate electricity, this kind of generation produce zero CO_2 emission during its operation. In a simple way, hydropower plants generate electric power by water flow from store supply, which runs down in large pipes known as penstocks. The water moves turbines, that drive generator units supplying electric power to power system [24]. Next Subsections present the models of elements of hydropower plants used in this thesis. These elements are salient-pole synchronous machine, turbine, governor and control systems such as Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS). Fig. 1.1 shows the main elements of hydropower plants.

¹Especially for wind parks above 2 MW [8]

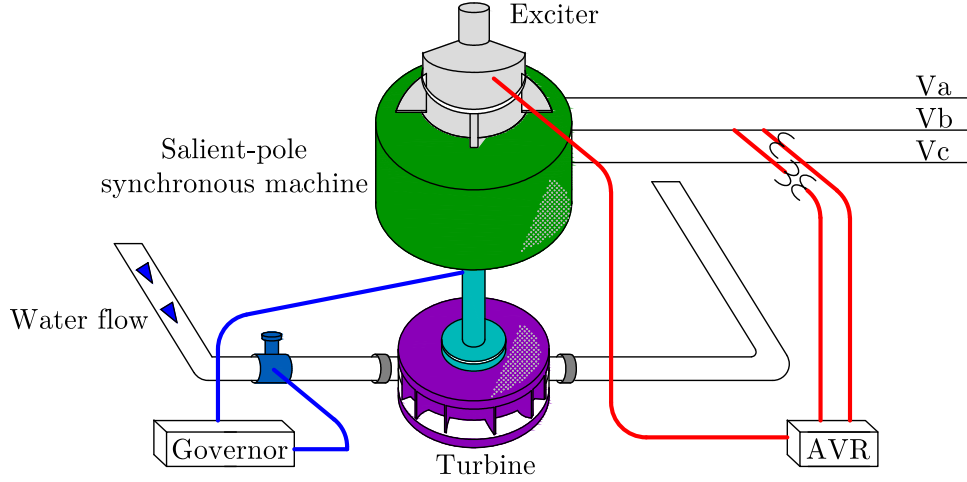
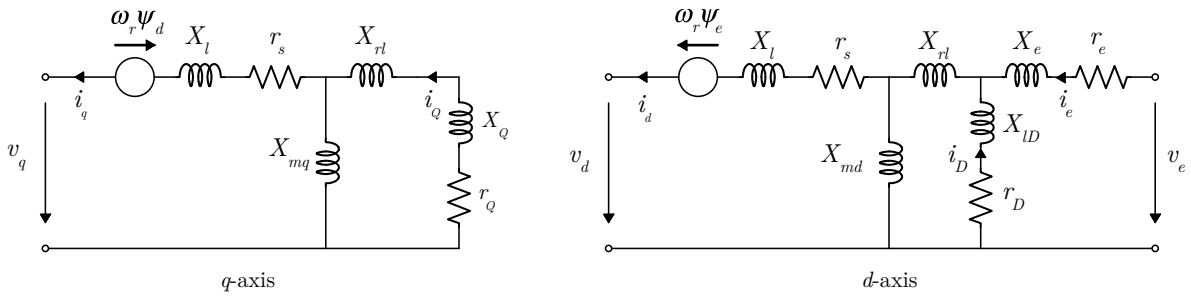


FIGURE 1.1: Main elements of hydropower plant.

1.2.1 Salient-pole synchronous machine

The main element of hydropower plants is the electric generator. This Subsection presents the model of this element. Fig. 1.2 shows the equivalent circuit of a salient-pole synchronous machine [2].

FIGURE 1.2: dq -axis equivalent circuit for a salient-pole synchronous machine.

From the equivalent circuit, the stator voltage equations can be described as follows:

$$v_d = r_s i_d + \frac{1}{\omega_n} \frac{d\psi_d}{dt} - \omega_r \psi_q \quad (1.1)$$

$$v_q = r_s i_q + \frac{1}{\omega_n} \frac{d\psi_q}{dt} - \omega_r \psi_d \quad (1.2)$$

$$v_0 = r_s i_0 + \frac{1}{\omega_n} \frac{d\psi_0}{dt} \quad (1.3)$$

where v_d , v_q and v_0 are the stator voltages in d , q , 0-axis, respectively, r_s is the resistance of the stator, ω_n is the angular speed of the grid, ψ_d , ψ_q , and ψ_0 are the flux linkages in d , q , 0-axis, respectively, ω_r is the angular speed of the rotor, i_d , i_q , and i_0 are the currents in the d , q , 0-axis, respectively.

The rotor voltage equations in the d -axis, are expressed as follow:

$$v_e = r_e i_e + \frac{d\psi_e}{\omega_n dt} \quad (1.4)$$

$$v_0 = r_D i_D + \frac{d\psi_d}{\omega_n dt} \quad (1.5)$$

where v_e is the excitation voltage, r_e , i_e , and ψ_e are the resistance, current and flux linkage of the excitation winding, respectively, in the case of r_D , i_D , and ψ_d are the resistance, current and flux linkage of damper winding in the d -axis, respectively.

While, rotor equation in the q -axis is represented by:

$$v_0 = r_Q i_Q + \frac{d\psi_Q}{\omega_n dt} \quad (1.6)$$

where r_Q , i_Q , and ψ_Q are the resistance, current and flux linkage of the damper winding in the d -axis, respectively.

Flux linkage rotor equations in the d -axis are expressed by:

$$\psi_d = (X_l + X_{md}) i_d + X_{md} i_e + X_{md} i_D \quad (1.7)$$

$$\psi_e = X_{md} i_d + (X_{md} + X_{rl} + X_{le}) i_e + (X_{md} + X_{rl}) i_D \quad (1.8)$$

$$\psi_D = X_{md} i_d + (X_{md} + X_{rl}) i_e + (X_{md} + X_{rl} + X_{lD}) i_D \quad (1.9)$$

where X_l is the stator leakage reactance, X_{md} is the magnetizing reactance in the d -axis, X_{rl} is the rotor leakage reactance, X_{le} is the leakage reactance of excitation winding, and X_{lD} is the leakage reactance of damper winding in d -axis.

Flux linkage rotor equations in the q -axis are represented by:

$$\psi_q = (X_l + X_{mq}) i_q + X_{mq} i_Q \quad (1.10)$$

$$\psi_Q = X_{mq} i_q + (X_{mq} + X_{rl} + X_{lQ}) i_Q \quad (1.11)$$

where X_{mq} is the magnetizing reactance in the q -axis, X_{lQ} is the leakage reactance of damper winding in the q -axis.

The electromagnetic torque T_e is expressed as:

$$T_e = \psi_d i_q - i_d \psi_q \quad (1.12)$$

Finally, the motion-equation generator can be expressed as:

$$J \frac{\omega_n}{dt} = T_e + T_m \quad (1.13)$$

where J is the inertia of the machine and T_m are the electromagnetic and mechanical torque, respectively.

1.2.2 Hydropower control systems

1.2.2.1 Synchronous generator excitation system

An important element in the generation units is the AVR. It is a device for continually adjust the voltage at terminals of the generator to a preset value, despite of the varying electrical load in the power system. It controls the output by sensing the voltage output and comparing to

a reference value. The difference between the voltage-output signal and the reference value is used to adjust an average value of the field current of the generator [25] - [26]. For the case of the excitation system, the IEEE1 model is used [27]. This is shown in Fig. 1.3, whereas its value parameters can be consulted in Table A.2 of the Appendix A.

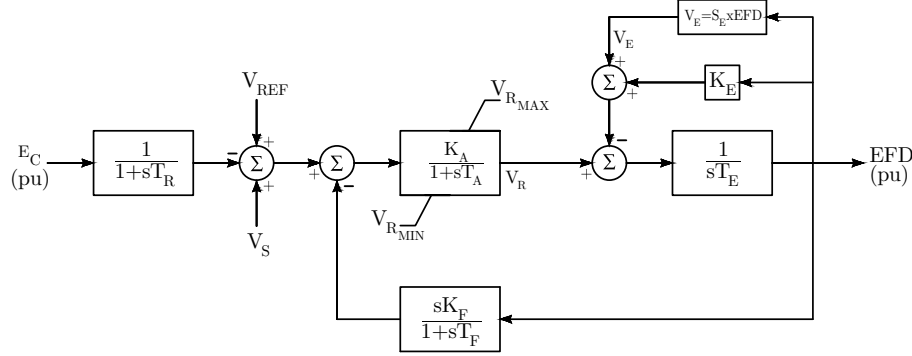


FIGURE 1.3: AVR model used in the hydropower plants, AVR IEEE1 type.

1.2.2.2 Power system stabilizer

The Power System Stabilizer is a device that improves the electromechanical oscillations present in generator units. It was developed to aid the damping of power oscillations by modulating the excitation supplied to the synchronous machine [15]. The PSS2A model is used in this thesis [2], [28]. This is shown in Fig. 1.4 and its value parameters are shown in Table A.3 of the Appendix A [28].

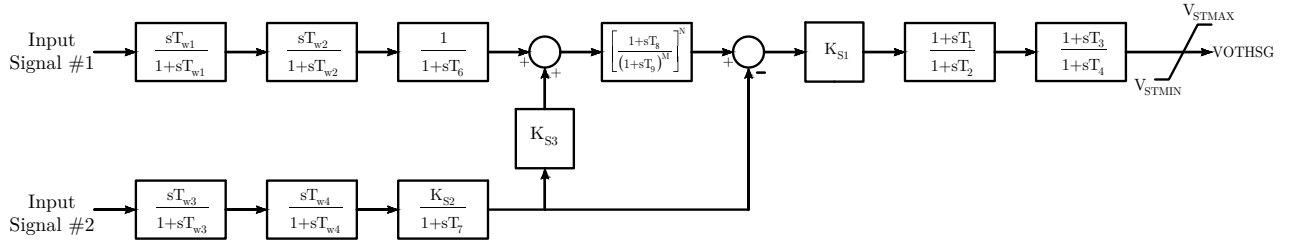


FIGURE 1.4: PSS model used in the hydropower plants, PSS2A type.

1.2.2.3 Turbine-governor model

Turbine governor is the main controller of a hydropower plant. This element varies the water flow through the turbine and controls the input of the mechanical power of the synchronous machine, controlling the output of electrical power into the network. Fig. 1.5 shows the turbine-governor model used in this thesis, while its value parameters are shown in Table A.1 of the Appendix A.

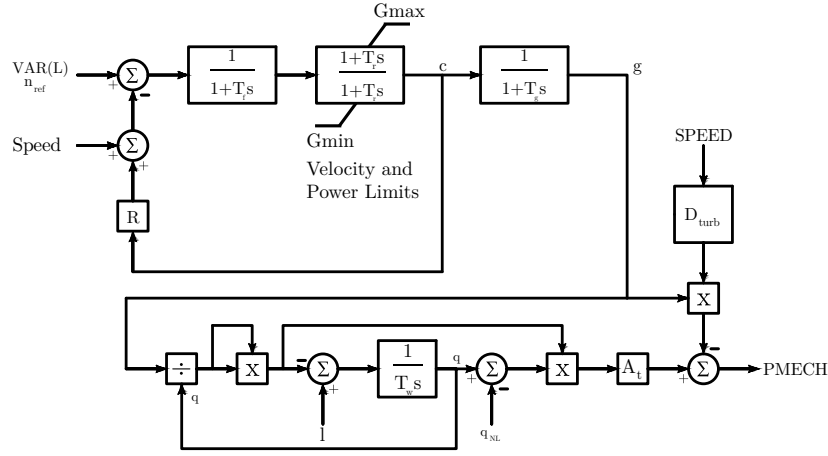


FIGURE 1.5: Water turbine model [2].

1.3 Wind power plant model

Wind Power Plants or Wind Energy Conversion Systems (WECS) transform wind energy into mechanical energy by using rotor blades [12]. This energy is used by generator units to provide electrical power into the power system. These plants include several components for their operation and reliability [29]. Fig. 1.6 presents the concept of a WPP and its main elements implemented in this thesis, the Type C model is used in this thesis [12].

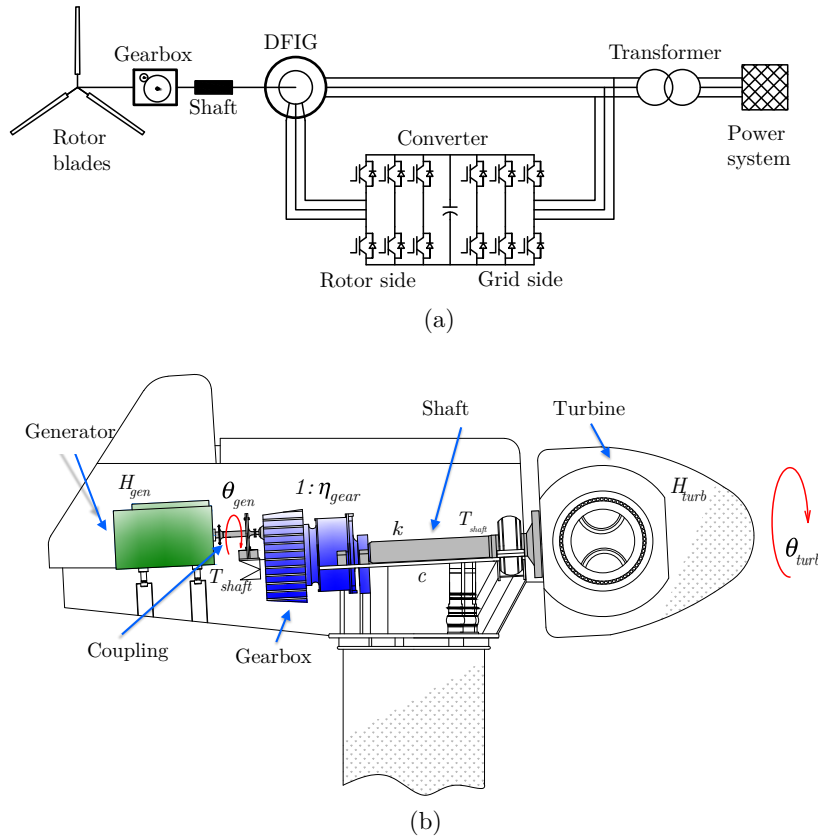


FIGURE 1.6: Wind power plants or WECS. (a) Type C wind turbine configuration. (b) Main elements.

1.3.1 Doubly-fed induction generator

The main characteristic of the DFIG is the control of their speed. This, due to the rotor winding is connected to the main grid by self-commutated AC/DC converters, being controlled the magnitude and phase angle [23]. Therefore, with the wind turbine at the aerodynamically optimal point (in certain wind speed range), it is possible to adjust the mechanical speed.

1.3.1.1 $dq0$ -reference frame

In order to derivate a simple model of the DFIG, it is convenient to work with a more suitable reference frame. One of them is known as $dq0$ reference frame. It converts from rotating reference frame abc to constant values in stationary reference frame $dq0$. This frame uses as the reference the voltage of the grid-side that is collinear with d -axis. This is measured through a Phase-Locked Loop (PLL) [30], its function is to synchronize the AC voltage of the inverter with the grid. The matrix transformation of reference frame from abc to $dq0$, is [31] - [32]:

$$[i_{dq0}] = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1.14)$$

1.3.1.2 Electrical equations

Figure 1.7 shows the equivalent-circuit diagram of the DFIG, its model can be derived from the single-fed induction machine by modifying the rotor voltage equations.

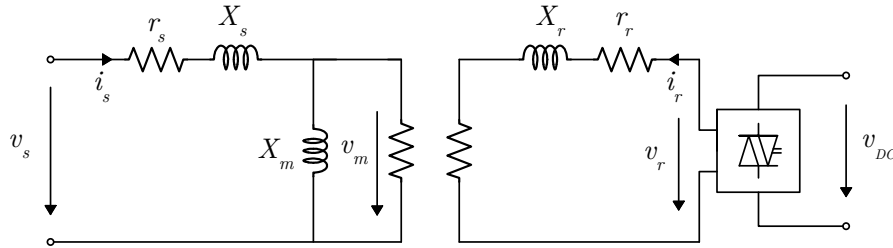


FIGURE 1.7: Equivalent circuit of the doubly-fed induction generator.

In this way, the rotor voltage equations are:

$$v_s = r_s i_s + \frac{d\psi_s}{\omega_n dt} + j \frac{\omega_{ref}}{\omega_n} \psi_s \quad (1.15)$$

$$v_r = r_r i_r + \frac{d\psi_r}{\omega_n dt} + j \frac{\omega_{ref} - \omega_r}{\omega_n} \psi_r \quad (1.16)$$

where v_s , r_s , i_s , and ψ_s are the voltage, resistance, current, and the flux linkage in the stator, respectively, in the case of v_r , r_r , i_r , and ψ_r are the voltage, resistance, current, and flux linkage in the rotor, respectively, and ω_{ref} is the reference speed.

The flux linkage can be expressed by the following equations:

$$\begin{aligned}\psi_s &= X_s i_s + X_m i_r \\ \psi_r &= X_m i_s + X_r i_r\end{aligned}\tag{1.17}$$

where X_s is the reactance in the stator, X_r is the rotor reactance and X_m is the magnetizing reactance.

The electromagnetic torque is calculated from the imaginary part (Im) stator current and the stator flux:

$$T_e = Im(\psi_s i_s)\tag{1.18}$$

The dynamic behavior of the generator shaft relates the rotor speed and the electromagnetic torque:

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_m)\tag{1.19}$$

where J is the inertia of the machine, T_m is the mechanical torque and T_e is the electromagnetic torque. T_m is related to the mechanical power P_{me} extracted from the wind available of the turbine's shaft [33]:

$$T_m = \frac{P_{me}}{\omega_n} = \frac{p}{\omega_r} P_{me}\tag{1.20}$$

where ω_r is the rotor electrical speed and p is the number of pole pairs.

1.3.2 Rotor and grid-side converters

The Pulse-Width Modulation (PWM) converter used by DFIG, usually is composed by six-pulse bridges, and they are commutated converters. It is connected to the slip-rings and it controls the magnitude and phase-angle rotor voltage. Fig. 1.8 shows the rotor-side converter:

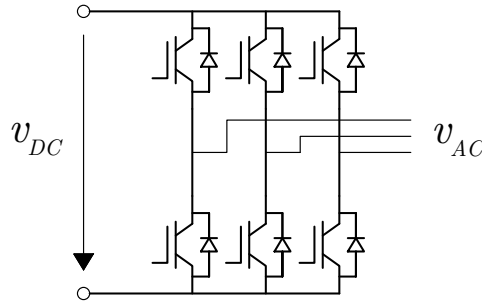


FIGURE 1.8: Rotor-side PWM converter.

The converter is modeled by fundamental frequency. The modulation index P_m relates the AC from the grid and DC voltages of the converter. These voltages are defined by magnitude and phase angle in real and imaginary parts as follows [34]:

$$v_{ACr} = \frac{\sqrt{3}}{2\sqrt{2}} P_{m_r} v_{DC}\tag{1.21}$$

$$v_{ACi} = \frac{\sqrt{3}}{2\sqrt{2}} P_{m_i} v_{DC}\tag{1.22}$$

where v_{ACr} and v_{ACi} are the voltages in alternating current in the real and imaginary part, respectively, v_{DC} is the voltage in direct current, Pm_r and Pm_i are the modulation index in real and imaginary part, respectively.

Equations (1.21) - (1.22) are valid for $0 \leq Pm < 1$. For values larger than 1, the level of order harmonics and saturation will increase. On the other hand, the grid-side converter does not generate or consume reactive power from the grid, it is because this converter keeps the voltage of DC link at desired value by using the Pm_r and Pm_i control signals, controlling the power factor to 1 in p.u., independent of the magnitude and power flow of the rotor.

In summary, transmission of reactive power from the WPPs with DFIG technology is through the stator, while the active power exchange with the grid is by the grid converter [2], [23].

1.3.3 Wind turbine model

The wind-turbine model used in this thesis is the two-masses with variable speed. This model considers electromechanical interaction [12], [23], generating speed, voltage and current fluctuations in the machine. Furthermore, it includes low and high inertia of the wind turbine. The equations of two-masses model are [30], [35] :

$$\dot{\theta}_{tur} = \omega_{tur} \quad (1.23)$$

$$\dot{\theta}_k = \omega_{tur} - \frac{\omega_{gen}}{n_{gear}} \quad (1.24)$$

$$\dot{\omega}_{tur} = \frac{\tau_{tur} - \tau_{shaft}}{H_{tur}} \quad (1.25)$$

$$\tau_{shaft} = c\dot{\theta}_k + k\theta_k \quad (1.26)$$

$$P_{mec-gen} = \frac{\omega_{gen}\tau_{shaft}}{n_{gear}} \quad (1.27)$$

$$\tau_{tur} = \frac{P_{wind}}{\omega_{tur}} \quad (1.28)$$

where $\dot{\theta}_{tur}$ is the angular speed of the wind turbine, ω_{tur} is the turbine angular speed, $\dot{\theta}_k$ is the angular difference between two flexible axis of the wind turbine, ω_{gen} is the wind generator angular speed, n_{gear} is the turbine shaft, $\dot{\omega}_{tur}$ is the turbine angular speed, τ_{tur} is the turbine torque, τ_{shaft} is the shaft turbine torque, H_{tur} is the inertia constant of the turbine, c is the wind turbine damping constant, k is the shaft-stiffness, $P_{mec-gen}$ is the mechanical-power generator, and P_{wind} is power extracted from wind.

Equations (1.23) - (1.28) are implemented in DigSILENT PowerFactory by *shaft block* of Fig. A.1, this block and its values are presented in the Appendix A [36].

1.3.4 Aerodynamic control

Equation (1.29) shows the aerodynamic behavior of a wind turbine that relates mechanical power extracted p_w from the wind and the mechanical speed of the turbine.

$$p_w = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) V_w^3 \quad (1.29)$$

where, ρ is the air density, R is the rotor radius, C_p is the power coefficient, λ is the tip-speed ratio, β is the blade-pitch angle, and V_w is the wind speed.

The tip-speed ratio λ is defined as follows:

$$\lambda = \frac{\omega_{tur} R}{v_w} \quad (1.30)$$

On the other hand, only a fraction of the total kinetic power of the wind can be extracted and converted in mechanical power by the wind turbine. It depends of the blade-pitch angle, rotor speed (ω_{tur}) and wind speed (v_w). This fraction usually is denominated power coefficient. It can be calculated from next expression [12], [29]:

$$C_p = 0.5(\lambda - 0.022\beta^2 - 5.6) \exp^{-0.17\lambda} \quad (1.31)$$

The active power transmitted by WPPs to the grid is according to the Maximum Power Tracking (MPT) characteristic. It depends of the power reference and the shaft speed. When the maximum-shaft speed is reached, the set-point control (active power) is kept in a constant value and the pitch-angle control (see Fig. 1.9, parameters of the pitch control can be consulted in Table A.8 of the Appendix A) drives the shaft speed into permitted values.

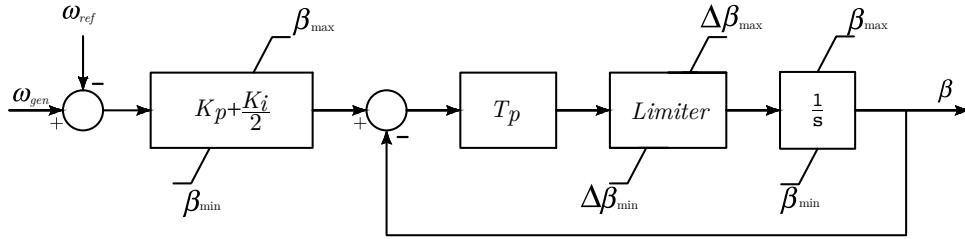


FIGURE 1.9: Model of the pitch-control system.

1.4 Conclusions

This Chapter presents the equations that represent the dynamic behavior of the hydropower and WPPs. The salient-poles synchronous machine model is used for the hydropower plants, while the DFIG model is implemented for WPPs. Furthermore, turbine-governor model and control systems such as AVR and PSS are included for the hydropower generation units, while, wind turbine, converters, and aerodynamic control are used for the WPPs.

Chapter 2

Equivalent model of the Mexican electric power system southeast region

2.1 Introduction

In recent years, wind generation in México has increased, mainly in the Istmo of Tehuantepec, Oaxaca, where the wind resource is considered the highest in the world (onshore), with an annual average of the wind speed reaching up to 10 m/s [10].

With the increase of this type of generation is necessary to know the steady-state, as well as, dynamic behavior of power systems with renewable energies, in order to identify requirements and expectations in the future. To realize these purposes is important to have an equivalent model of the Mexican power system of the southeast region, that incorporates the models of mains components and their controllers. The primary objective of this equivalent model is to represent problems present in this region and carry-out steady-state and dynamic simulations.

2.2 Particular problems in the electric power system southeast region

Actually, in the Istmo of Tehuantepec there is a high penetration of WPPs. It is installed a wind power generation capacity of 4,199 MW, that represents 3% of the entire power system [1], and it expected to install more WPPs in this region [7].

Some problems present in the interconnection of wind power parks located in the mentioned region are: congestion of power flow caused by a large amount of WPPs in combination with the associated network topology, frequency regulation produced by low demand on electrical loads, or disturbances present in the network, and voltage support and injection of electric power to the system, due the intermittence and fluctuation of wind speed during the year [13].

2.3 The Mexican grid code for integration of wind power plants

This Subsection provides the technical requirements for interconnection of renewable sources, such as WPPs, in high voltage (from 69 kV to 400 kV) according to [3] of the Mexican power system.

According to the voltage and frequency range, WPPs in steady-state must operate at $\pm 5\%$ of the nominal voltage at the PCC with the power system, and $\pm 10\%$ in emergency conditions. According to the frequency range, WPPs must be able to work in response to frequency change in the network from 57.5 Hz to 62 Hz in steady-state, while above of 62 Hz and under 57.5 Hz, WPPs must be disconnected.

In reference to unbalance and transient events related to voltage, WPPs must stay connected to the network without losing stability after being subjected to transient faults during the maximum clearing time; in this period, they must provide reactive power to the system. After a transient failure, WPPs must provide active and reactive power previous to the fault. Table 2.1 and Fig. 2.1 show types and times of clearing time at the PCC for WPPs, when there is a disturbance in the network.

TABLE 2.1: Types and clearing times of faults at PCC [3].

Transient failure	Clearing time (ms)		
	Voltage		
	69-161 kV	230 kV	400 kV
Three-phase	150	100	80
Bi-phase	150	100	80
Single-phase	150	100	80

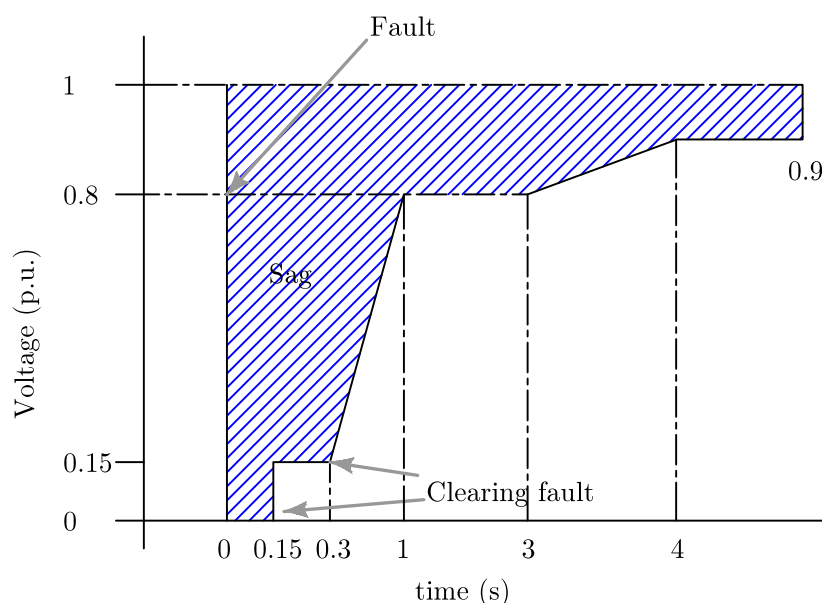


FIGURE 2.1: Clearing time during a short duration reduction in RMS voltage (SAG) for wind power plants [3].

Regarding to reactive power, WPPs have to provide and consume this power as a requirement of the power system. Finally, they must be able to control the power factor in 0.95 in lagging and leading, and they have to take part of the voltage support.

2.4 One-line simplified diagram of southeast region of México

The hydropower generation in the southeast of México is composed of the following plants: Angostura (5 units, 900 MW), Chicoasen (8 units, 2,400 MW), Malpaso (6 units, 1,080 MW), Peñitas (4 units, 420 MW), Temascal II (6 units, 354 MW), Bombana (4 units, 5.24 MW), Tapachula (3 units, 21 MW), and Schpoina (3 units, 2.24 MW), this generation represents the 41.6% of the total hydropower capacity in operation in México [9]. Currently in the Istmo of Tehuantepec, Oaxaca, are installed 24 wind farms and they are distributed in Ixtepec (14 units, 1,438 MW), and Juchitan (10 units, 782.75 MW), with a total installed capacity of 2,220.75 MW, representing nearly the 4% of the entire generation of the Mexican Interconnected System [13]. In case of transmission lines, reference [28] provides the information about power transfer and operative voltages of these elements. Meanwhile, the active power to peninsular, center of México, Tecalli and Matias Romero region is modeled like an equivalent-constant load.

In the case of wind power generation, reference [10] provides information about the technology of one of the WPPs installed in the Istmo of Tehuantepec, it is called is Bii Nee Stipa II, and it uses the DFIG technology that is used in the most parks in this area. This park was built by the Spanish wind company Gamesa, the wind turbine used is the G52-800, which is a horizontal axis turbine with a rotor of 3 blades (propellers), upwind, active-gondola orientation, with variable pitch blade and variable speed of rotor rotation. For the control of the power generated, the park has a substation with a capacity of 20/22 MVA and a voltage transformation ratio of 34.5 to 115 kV. The substation is connected to the CFE grid of 115 kV through the transmission line No. 73,570, between the Juchitan II substation and Matias Romero in the distribution area in the Southeast [10]. The distance between the WPPs and substations was estimated according to their physical location. Another consideration about the area of the Istmo of Tehuantepec, is that, there are two-main wind parks, Juchitan II (782.75 MW) and Ixtepec Potencia (1,438 MW). All this information in addition to the WPPs control systems was implemented in the professional software DIgSILENT PowerFactory.

Tables B.1 - B.3 of the Appendix B provide the information of the synchronous machines used for the hydropower generation (salient-poles rotor), while in the Tables B.4 and B.5 are shown the parameters of the WPPs (DFIG technology). For the transmission lines, the parameters can be consulted in the Table B.6 of the Appendix B. The parameters were provided by the CENACE.

Figure 2.2 shows the equivalent diagram of the network developed for all the case studies presented in this thesis. This information is referenced to [5], [7] - [13], [37].

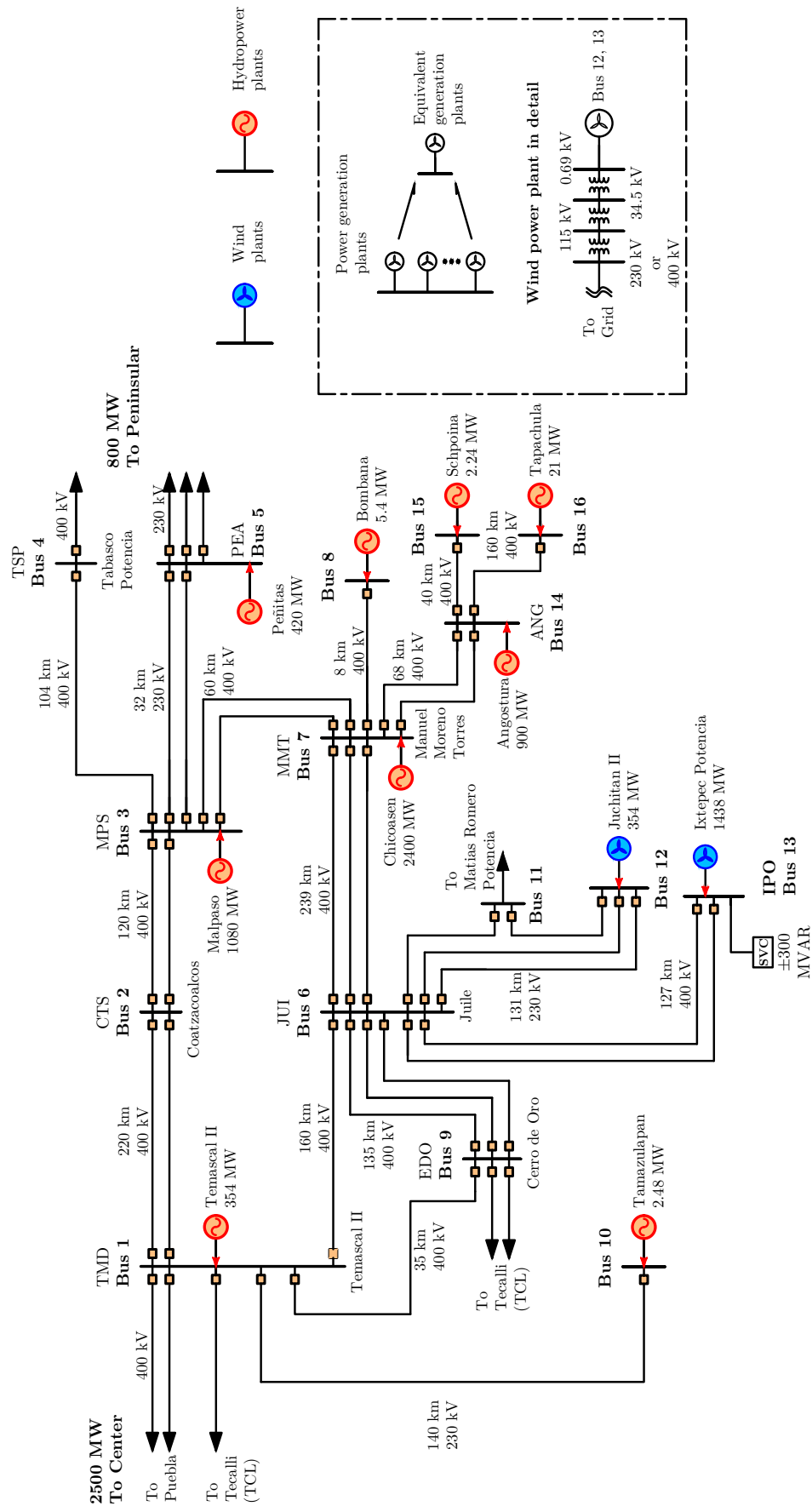


FIGURE 2.2: One-line simplified diagram of southeast region of México.

2.4.1 Steady-state studies

Power Flow Studies (PFS) provide information about the analysis, planning, and steady-state operation of power systems [26]. It is a very important tool for power systems, its purpose is to compute the angles and magnitude of the voltages in all buses in the network, real and reactive power flows into every transmission line and transformer, under the assumption of known generation and load parameters [38] - [39]. This Subsection provides results about PFS of the equivalent network under study. The PFS results were obtained for the entire equivalent power system, however, the purpose of the studies is to focus only in the area of the Istmo of Tehuantepec, because the high penetration of wind farms. For this reason, in the next studies it is only presented the results obtained in this area. Finally, the main objective is to reproduce real situations in the southeast area of the Mexican electric system [13] such as congestion in transmission lines and voltage support.

2.4.1.1 Congestion in transmission lines

This Subsection presents the problems of congestion in transmission lines implemented in DIgSILENT PowerFactory. Fig. 2.3 shows that the transmission lines are transmitting 1,438 MW from the WPPs of Ixtepec Potencia, each one of the transmission lines can transmit 1,200 MW [13] to the power system, the PFS results show that each transmission line is transmitting 719 MW and 64.5 MVar, that is, 59.2% of their capacity. On the other hand, when a fault occurs that requires disconnecting one transmission line of the IPO-JUI bus, then all power is flowing through a single line and causes that this transmission line is overloaded to 120.4% of its capacity, this is shown in Fig. 2.4. A possible solution to protect the transmission lines, it would be to limit the power transfer [13], otherwise the transmission lines could be disconnected by overload.

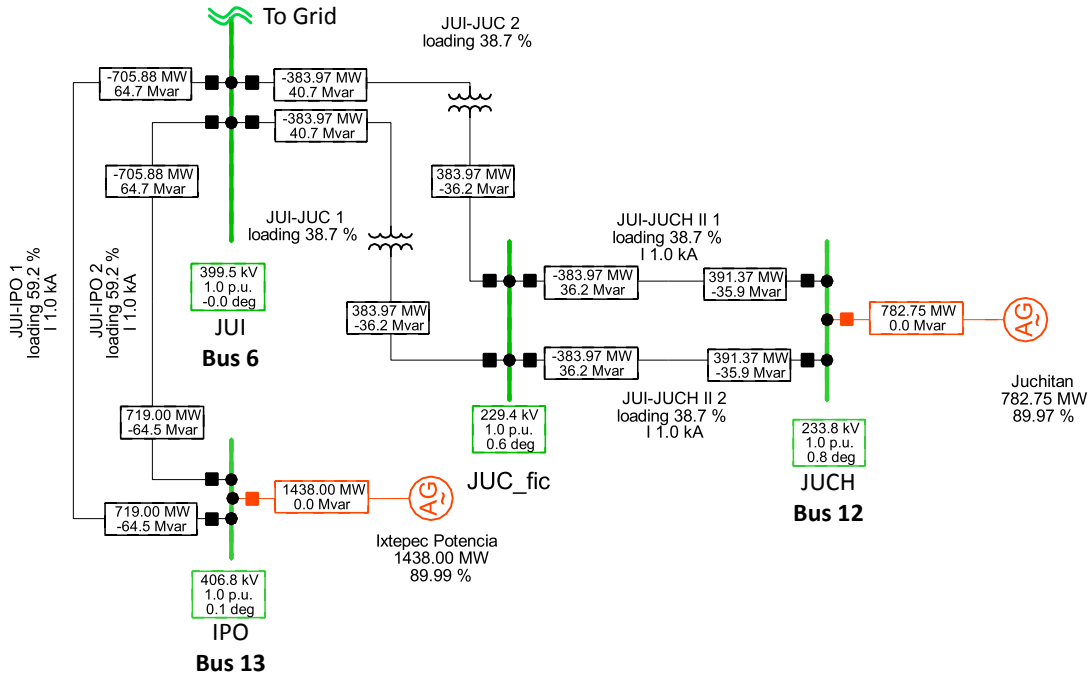


FIGURE 2.3: Results of power flow in the Istmo of Tehuantepec in DIgSILENT PowerFactory.

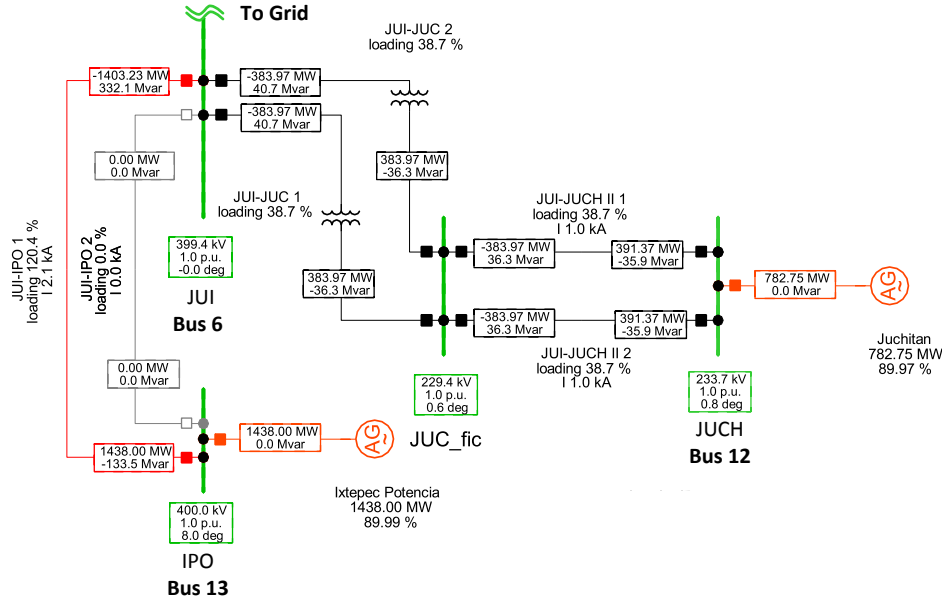


FIGURE 2.4: Results of congestion in the lines transmission in the Istmo of Tehuantepec in DIgSILENT PowerFactory.

2.4.1.2 Reactive power compensation: SVC

A case study of the Static Var Compensator (SVC)¹ performance installed at the bus 13 is presented. This device has the function of reactive power compensation in the bus which is connected, its aim is the voltage support in this area [13]. In this case study one of the two transmission lines is not in operation in JUI-IPO, the WPPs of IPO is limited to 1,000 MW, and an inductive load of 2,695 MVar is connected at bus 6 to increase the demand of reactive power, decrease the voltage in the buses. Fig. 2.5 presents the case without SVC, it can be seen that the transmission line is close to its limits of power transfer, and in the buses 6 and 13 the voltages are decremented to 0.93 p.u. and 0.94 p.u., respectively.

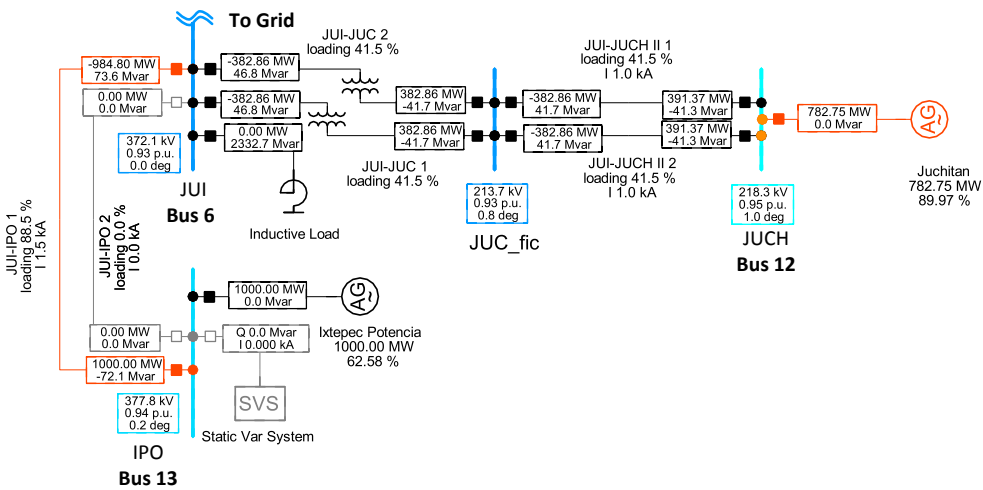


FIGURE 2.5: Results of power flows without SVC in IPO bus in DIgSILENT PowerFactory.

¹ ± 300 MVar, according to [13]

Figure 2.6 shows the connection of the SVC at the bus 13. It is observed that the SVC provides reactive power, reducing the loading of the transmission line and increasing the voltages in buses 6 and 13 at the values of 0.99 p.u. and 1 p.u., respectively.

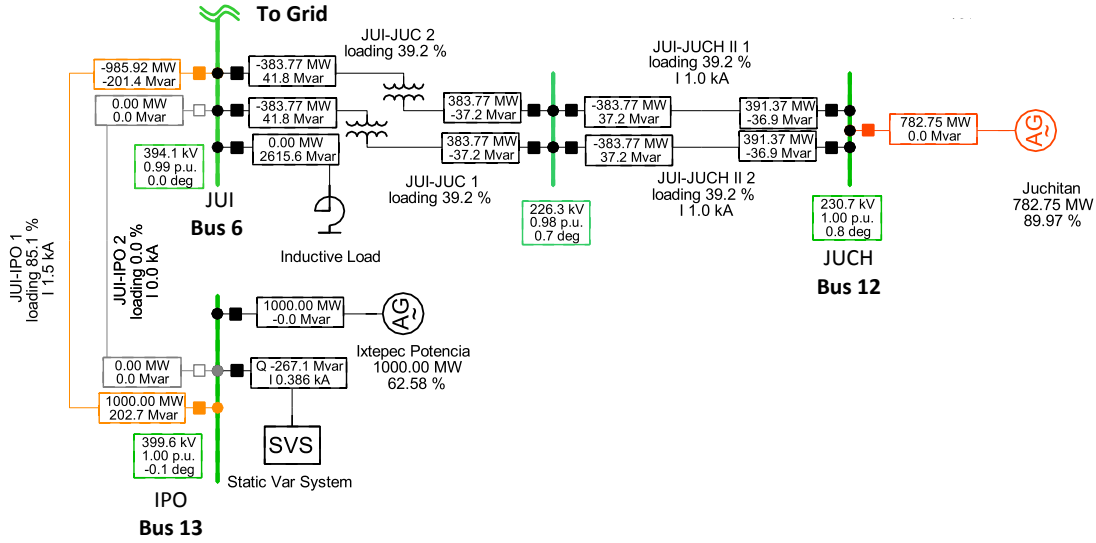


FIGURE 2.6: Results of power flows with SVC in IPO bus in Digsilent PowerFactory.

2.4.2 Transient stability study

Transient stability studies reflect the dynamic behavior of the elements connected to the networks, such as generation units and their controllers, transformers, transmission lines, etc., and they are used for planning, design, and operation of modern power systems and solution of dynamic stability problems. This kind of simulation lets to know if the power system regains the state of operating equilibrium when is subjected to severe disturbances such as faults, load changes, loss generation and switching operations without losing synchronism. Besides, it lets to determinate if the magnitude of oscillations due to the disturbance can produce an instability scenario or if they are in the range of the grid code [16] - [17], [25].

This Subsection provides results about the dynamic behavior of the elements of power system for a transient stability study. Results like active and reactive power, frequency, turbine power of WPPs, and speed of the hydropower plants are presented.

2.4.2.1 Solid three-phase fault

A solid three-phase fault was applied at bus 6 in $t = 0.5$ s, then at $t = 0.6$ s is cleared (see Fig. 2.2). The wind speed is 10 m/s. In this simulation, the SVC is not connected. Fig. 2.7 shows the frequency in the buses 6 (JUI) and 13 (IPO). It can be noticed that there are some oscillations in the frequency due to the solid three-phase fault. In the case of IPO, peak values in the first oscillations are 56.26 Hz and 63.45 Hz. These values are higher than JUI (frequency power system), because the inertia of the WPPs is lower in comparison with hydropower plants. Nevertheless, these values not exceed the time of 80 ms presented in Table 2.1, therefore WPPs must remain connected to the power system. After some oscillations, the frequency signal reaches steady-state in $t = 0.66$ s.

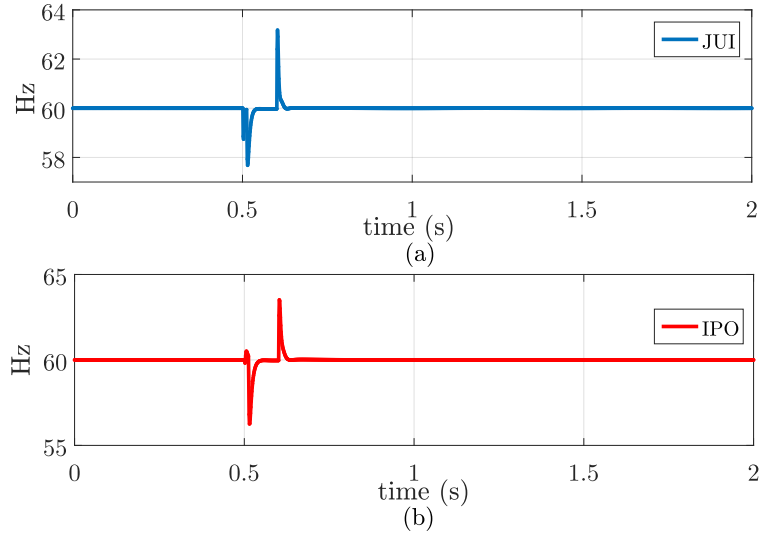


FIGURE 2.7: Comparative frequency. (a) JUI (power system). (b) IPO (WPPs).

Figure 2.8 shows active and reactive power of WPPs, in IPO (bus 13); its nominal power is 1,438 MW and decreases to 663.8 MW. Meanwhile, in the case of JUCH (bus 12), its nominal power is 782.85 MW and decreases to 305.5 MW. When there is a fault in the power system, WPPs with DFIG technology must remain connected to the system at PCC, and inject reactive power to mitigate the possible negative impacts of the fault [40] - [41]. Fig. 2.8 shows that IPO and JUCH are injecting 481.4 MVar and 288.9 MVar, respectively. The active and reactive power reach the steady-state in $t = 0.78$ s and $t = 1.02$ s, respectively.

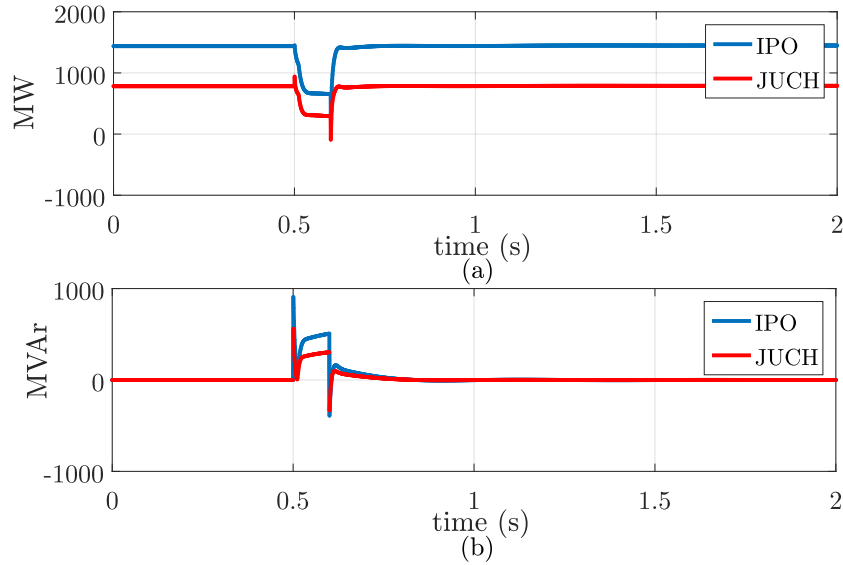


FIGURE 2.8: Active and reactive power in WPPs. (a) Active power in MW. (b) Reactive power in MVar.

Figure 2.9 shows the turbine powers of the WPPs, these values are 0.38 p.u. and 0.45 p.u. in buses 12 and 13, respectively, in the first oscillations. These signals reach the steady-state in $t = 1.2$ s. In this case, it can be seen that turbine power and electrical power are affected by the fault. This is because, during short circuits in the system, they are related by the wind turbine model of two-mass, that represent the coupling of the wind turbine and generator inertia [36].

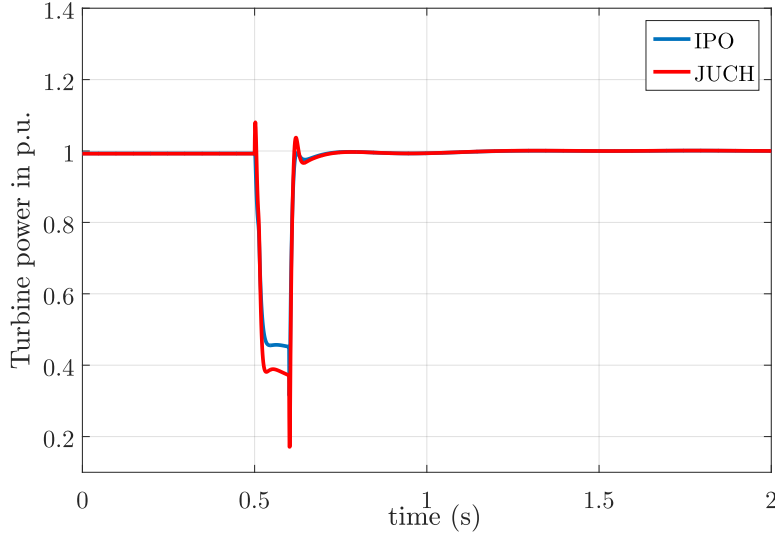


FIGURE 2.9: Turbine power in the wind power plants.

Finally, Fig. 2.10 presents the results of the speeds in the hydropower plants, it can be seen that there are oscillations by the presence of the fault in the network, these oscillations tend to decrease until they reach their previous steady-state in $t = 10$ s, this behavior is due the high-inertia value in comparison with the WPPs.

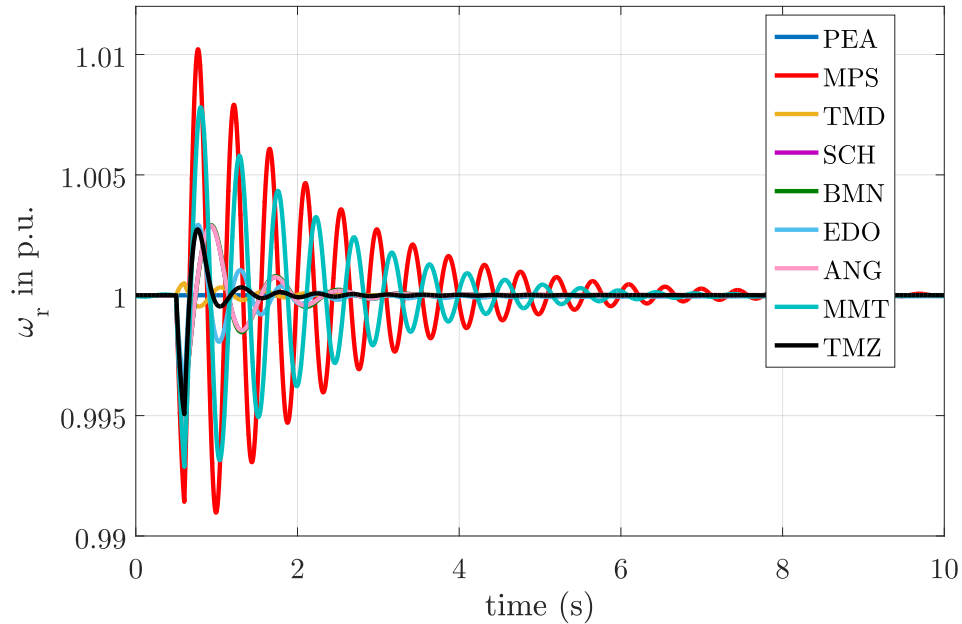


FIGURE 2.10: Speeds in the hydropower plants.

2.5 Conclusions

An equivalent model of the Mexican electric power system southeast region was presented in this Chapter. The equivalent model includes the dynamic models of hydropower and WPPs with their controllers (turbine-governor, AVR, PSS, wind turbine model, gearbox, aerodynamic controls, etc.), transformers, transmission lines, and electrical loads. In the first case study, power flow limitation in the transmission lines was presented in steady-state simulation, in addition, a case with SVC was implemented, the results demonstrate that these devices provide reactive power for voltage support in the power system. On the other hand, in RMS-type simulation, dynamic models of hydropower and WPPs and their controllers were analyzed and discussed. Besides, it presents information about the mechanical-electrical behavior of the elements of the power system along throughout the simulation time. These results can be used in the planning and control strategies to keep the power system stability or determinate if the results are around the limits of the grid code.

Finally, it is important to mention that this equivalent model plays a key role in the development of solutions about the common problems in the southeast region, it is used in every case study implemented in this thesis. In addition, the model developed is not reported by any other researcher, and it is presented for the first time, this represents a high effort, due to the detail of the information about the network topology, their elements, and grid code.

Chapter 3

Graphical Probabilistic Representation for the assessment of the penetration of wind power generation in electric power systems

3.1 Introduction

Power flow studies (PFS) have been used for planning, analysis, and assessment of the steady-state operation of typical power systems [26]. However, these studies use specific values for generation, loads, and configuration of the network [26]. Therefore, the PFS are ineffective to face the challenges of modern power systems with uncertainties, like variations of the electrical load, changes on the configuration of the network, and power fluctuations produced by the penetration of RES units. This behavior is known as stochastic behavior [42], i.e., PFS do not include the stochastic nature of RES, therefore it is necessary to develop methodologies that include this behavior.

In this Chapter, a new visual way to assess the impact of RES in power systems is proposed. The Graphical Probabilistic Representation (GPR) is a methodology developed in combination with Multiobjective Performance Index (MPI) to present in a clear, compact and visual way, complex results of different scenarios in a single graphical representation.

3.2 Literature review

The increment of the penetration of WPPs and their location has impact on the operation of power systems [43]. WPPs can produce voltage oscillations, diminish or increase power losses, frequency stability problems, fault currents, inertia reduction, etc. [44].

To address these challenges, it is necessary to develop methodologies that let analyze the stochastic nature of RES, with the objective to make the best decision about the planning, operation and control strategies for the power systems [17] - [29]. In [45] are presented different Probabilistic Load Flow (PLF) techniques. The PLF is applied to analyze the impact of the large integration of WPPs. PLF is used like a short and long term planning tool [46] - [47],

and it can be solved numerically using the Monte Carlo (MC) method, or analytically using convolution techniques or a combinations of them [48] - [49].

In [50] is adopted an analytical method, and it is used for reliability of a power system with high penetration of wind and photovoltaic power plants. Reference [51] presents a method to determine the optimal capacity of WPPs in a power system. It uses a genetic algorithm in conjunction with the discrete-convolution-based method, and it uses the system reliability improvement as a criterion to estimate the size of wind power penetration level. In [52] is proposed a method to determine the place and ideal size of the grid-connected WPPs. The optimal place is obtained by modal analysis, while the penetration is determined through a wind energy intermittence assessment subject to stability-voltage constraints. The variability of power flows on the Paraguaná transmission system due to integration of WPPs is evaluated in [53]. Power flows were obtained by using a Stochastic Power Flow (SPF) analysis; it uses the MC method to solve the SPF problem. In [54] is reported the influence of WPPs in the operation of transmission networks using the MPI. These indices try to quantify the impact of the penetration of WPPs, by evaluating the active and reactive losses, voltage deviation, system line capacity, among other parameters of the system.

The results obtained from the mentioned methodologies were carry-out from only one operating condition in one scenario under study; while the GPR proposed in this contribution combines the use of Stochastic Load Flow (SLF), MC and MPI to develop a new visual analysis, and let to present multiple and complex results about the impact of WPPs in power systems in a single graphical representation. In addition, GPR provides the percent of the probability of occurrence of uncertainties, and their impact in the power system.

3.3 Stochastic load flow

In order to compute the MPI, it is necessary to carry-out load flow studies. One of the best-known methods for computing load flows uses fixed values for the network elements. This method is known as Deterministic Power Flow (DPF) [45]. However, uncertainties, variations in the load or generation, and changes in the network are not considered in DPF studies. Consequently, the DPF is incapable of taking into account the stochastic behavior of WPPs [53].

Thus, the challenge is to properly represent the behavior of wind power generation. A useful method for doing this is the Stochastic Load Flow (SLF) [46]. With the application of this method is possible to deal with discrete-random variables, which are appropriate for representing uncertainties of the WPPs. The SLF considers the wind power generation as a discrete-random variable, while the load demand is considered as a continuous random variable [55] - [56]. This method is subdivided into two categories: numerical and analytical approach [4], [53]. A brief summary of the subdivisions of the SLF is presented below.

3.3.1 Analytical approach

This method computes the system states and power flows by using convolution techniques with DPF and includes mathematical expressions to facilitate the calculation of the stochastic variables [53]. As a result, the uncertainties are incorporated in the analysis [45]. However, there are some difficulties to resolve SLF equations by DPF convolution in power systems that include stochastic behavior [45], [55] :

1. The equations of the power flow study are non-linear [45].
2. The input variables of the system are not linearly-correlated or not totally independent.

Therefore, some assumptions are usually made in order to perform the SLF by applying the analytical approach, as follows [45]:

1. Power flow equations are linearized in each iteration.
2. It is considered that input variables of the power system are linearly-correlated and completely independent.
3. The distributions of the load and generation are considered normal and discrete, respectively.
4. Some specific parameters of the network are constant.

A well-known method to obtain the linearized equations around the estimated values of the system states $\hat{X}$ is the first-order Taylor expansion [45], [57].

3.3.2 Numerical approach

The MC method is a numerical approach for iterative evaluation of SLF problems and provides significantly accurate results [48]. On the downside, its computational time is too high for large systems [48], [53].

The MC method examines virtually all possible combinations of load and wind generation levels and helps to solve SLF problems that include WPPs by repeated simulations [53]. The equations used to represent SLF problems by this numerical approach are based on DPF, with different combinations of inputs, i.e., the nodal power values, that is, the non-linear form of the load flow equations are used in SLF [45]. In this thesis, the MC method is used because it can be combined with pre-existent DPF programs and the SLF is easy and fast to implement [53].

3.4 Multiobjective performance indices

One way to quantify the wind power penetration in power systems is through MPI [44] - [54]. In this thesis are used three MPI: active (*ILP*) and reactive power losses (*ILQ*) and line loading (*ILL*). These indices compare the initial state of the network to each potential future configuration and they can be used like a long-term analysis tool. In this thesis is used the script and the methodologies presented in [4] and [44], respectively, to create the GPR. Next subsections present a brief information about the MPI and the script implemented in the professional software DIgSILENT PowerFactory using the DIgSILENT's Programming Language (DPL) [4].

3.4.1 Real and reactive power losses indices

Power losses are present in a power system in the generation, transmission, distribution and even consumption systems [58]. From a technical point of view, power losses are a way to quantify the efficiency of the power systems [4].

Their mathematical formulation is [4], [44]:

$$ILP = 1 - \frac{Re\{Losses\}}{Re\{Losses^0\}} \quad (3.1)$$

$$ILQ = 1 - \frac{Im\{Losses\}}{Im\{Losses^0\}} \quad (3.2)$$

where $Losses$ represents the total power losses of the RES scenario under study, and $Losses^0$ represents the total power losses in the base scenario (without RES generation) [4].

3.4.2 Line loading index

Transmission lines are a key element in power systems, because they transport the electric power to the whole system. A proper planning about their power flow capacity allows a good tolerance of growth for the networks. A high level of loading in the transmission lines indicates congestion in the power flows and can compromise the system stability in the area where they are installed [44].

$$ILL = \max \left(\frac{SL_m^0}{SR_m} \right)_{m=1}^{NL} - \max \left(\frac{SL_m}{SR_m} \right)_{m=1}^{NL} \quad (3.3)$$

where SL_m^0 and SL_m are the loading of the line m for the base and the RES scenario, respectively; SR_m is the rated ampacity of the line m ; and NL refers to the number of transmission lines in the power system under study [4].

3.4.3 Script to evaluate RES penetration

A script to evaluate the impact of the WPPs penetration in power systems was implemented in the software DIGSILENT PowerFactory in [4]. The script is based on the MC method and the SLF. The MC method takes several combinations of input values of elements of the network, these combinations are called scenarios; then, the SLF is applied to the scenario under study in order to obtain the current operating condition of the power system. This process is repeated several times (simulated scenarios), being the number of simulated scenarios (SSCs) defined by the user. In the case of loads and WPPs, at each SSC, the MC assigns random values to them based on a Specific Probabilistic Distribution (SPD)[4].

Figure 3.1 shows the flow chart of the script implemented in the DPL [4], where N is the number of SSCs. The script starts in the MAIN routine, where all the subroutines are called, and indices values are stored at each simulated scenario. The Load Scaling routine assigns random values based on SPD to all loads. The Base Scenario excludes all WPPs and execute the SLF study; within this routine are also included the Power Losses (PLs) and Line Loading (LLs) routines [4]. The Wind Scaling routine assigns random values based on SPD to all wind generators, taking into account their Weibull distribution. The RES Scenario routine includes all WPPs and executes the SLF study and saves the obtained results; within this routine are

also called the PLs and LLs routines. Towards the end, the results of the Base and the RES scenario are compared; finally, this process is repeated until the maximum number of SSCs is reached.

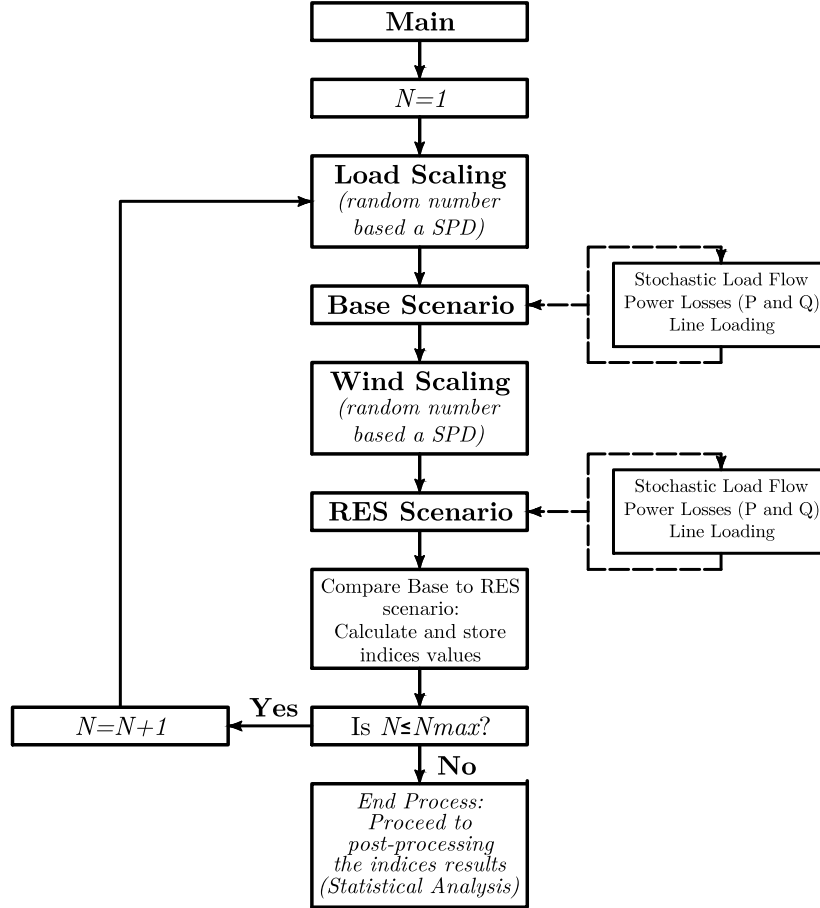


FIGURE 3.1: Flow chart of the script implemented in the DPL [4].

3.5 Graphical Probabilistic Representation

The MPI obtained from the different scenarios can be plotted in a curve that shows their behavior under changing conditions of the power system. However, it is necessary one curve for each MPI but the probability that an operating condition occurs in the system is not considered. This leads to complex analysis with different MPI curves, mainly because the considerable amount of information contained on each curve. To solve this problem, in this thesis is proposed the GPR. This representation arises from the need of presenting different MPI in a clear, compact and visual way, including the probability that an operating condition occurs in the different scenarios under study, for instance, with changes in the network configuration, load and generation variations, among others.

The potential applications of the GPR are the quantification of the probability that a given operating condition occurs in the power system, identification of the most and least probably operating regions, the magnitude of the MPI that show the loading in transmission lines and

transfer capability, etc. Besides, this representation can be used as an analysis tool in planning studies. The key feature of the proposed graphical representation is the possibility of performing several analyses in one single graphic such as different values of wind speeds or capacities of a compensation device.

To assign the probability to wind speed values, the GPR uses the Weibull distribution, this implies that each MPI curve has a percentage in accordance with the wind speed used to generate it [59]. The Weibull and Rayleigh distributions are commonly used to describe the wind-speed-probabilistic distribution, because they give a very good approximation of the real behavior [59]. The Weibull distribution can be represented as:

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (3.4)$$

where f is the percentage of probability in per unit (p.u.), v is the wind speed in m/s, c and k are the scale and shape parameters of the Weibull distribution, respectively. In other elements of the power system, such as compensation devices, the percentages can be assigned based on their compensation capacity.

In order to obtain the GPR, the information contained in the MPI curves is stored in a proposed matrix, called GP matrix. Therefore, this matrix contains the probability percentages of occurrence of each MPI at each operating scenario. The GP matrix is expressed as follows:

$$[\mathbf{GP}] = \begin{matrix} & \mathbf{WL}_1 & \cdots & \mathbf{WL}_m \\ & \downarrow & & \downarrow \\ \begin{bmatrix} \Delta iLP_{\langle 1,1 \rangle} & \cdots & \Delta iLP_{\langle 1,m \rangle} \\ \vdots & \ddots & \vdots \\ \Delta iLP_{\langle n,1 \rangle} & \cdots & \Delta iLP_{\langle n,m \rangle} \end{bmatrix} & \leftarrow & \begin{matrix} \mathbf{rMPI}_1 \\ \vdots \\ \mathbf{rMPI}_n \end{matrix} \end{matrix} \quad (3.5)$$

where $\mathbf{WL}_{mi}$ (Wind-Load increment index) is the i -th column vector that contains the results of the simulated scenarios, varying from 1 to m ; $\mathbf{rMPI}_{ni}$ (round Multi-objective Performance Index) is the i -th row vector and contains the probability-percentage values, with values from 1 to n ; where m is the number of SSCs, n is the number of points that divide the $\mathbf{WL}_{mi}$ vector, and $\Delta iLP_{\langle n,m \rangle}$ (rounded iLP index) represents the value of the $\mathbf{rMPI}_n$ vector, which is obtained as:

$$\Delta iLP = \mathbf{rMPI}_{\langle 1,1 \rangle} - \mathbf{rMPI}_{\langle 2,1 \rangle} \quad (3.6)$$

At this point, the values of the MPI are rounded off two decimal places and stored as GP matrix elements. This process is shown in Fig. 3.2.

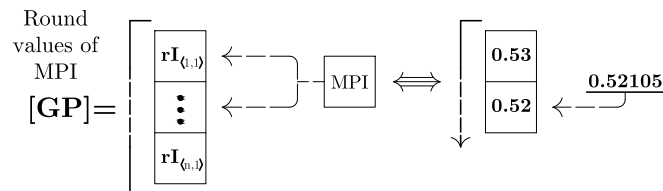


FIGURE 3.2: MPI Storage process.

Finally, each element of the GP matrix represents a percentage value. To represent the GPR concept described previously, Fig. 3.3 illustrates the *ILP* index at different wind speeds. This Fig. has probability regions and different colors are used to denote the percentage values. Also, each MPI curve has a percentage assigned according to the probability that a wind speed value occurs, i.e., the percentage is relative to the nominal speed with the highest probability, in this case is 10 m/s in agreement with [10].

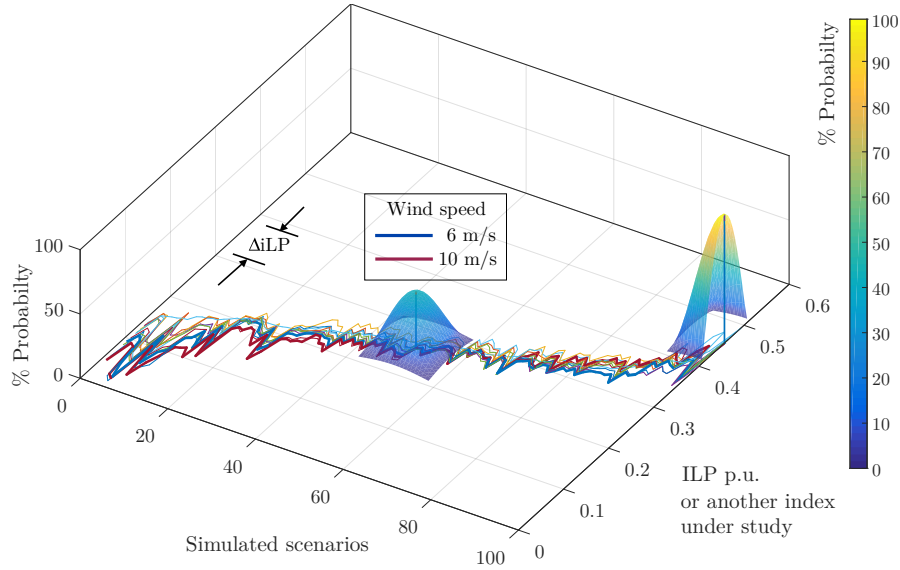


FIGURE 3.3: Concept of the Graphical Probabilistic Representation (GPR).

3.6 Test network and results

3.6.1 Test network

The equivalent power system model of the area of the Istmo of Tehuantepec, Oaxaca, México will be used as a test system to show the application of the GPR. The single-line simplified diagram of this power system is shown in the Fig. 3.4. It is composed of hydropower generation and 24 WPPs with the DFIG technology; WPPs are distributed in the locations of Itepec (14 wind parks, 1,438 MW) and Juchitán (10 wind parks, 782.75 MW), with a total installed capacity of 2,220.75 MW [13]. For this Chapter, a compensation device (SVC) is connected in parallel at bus 4.

To consider the stochastic behavior of the wind and an increase in the size of the loads, the load installed at the bus 2 is represented by a normal distribution $X \sim N(\mu, \sigma^2)$, with $\mu = 1$, and $\sigma = 0.07$ on a per unit scale, and the wind generation follows a Weibull distribution with a shape parameter $k = 0.3$ and a scale parameter $c = 2$. Also, the SVC device was modeled as a controlled current source [60].

3.6.2 Case studies

The obtained results are divided into two parts. The first one presents a brief summary of the results and analysis of the MPI indices and their comparison with the GPR, for this purpose,

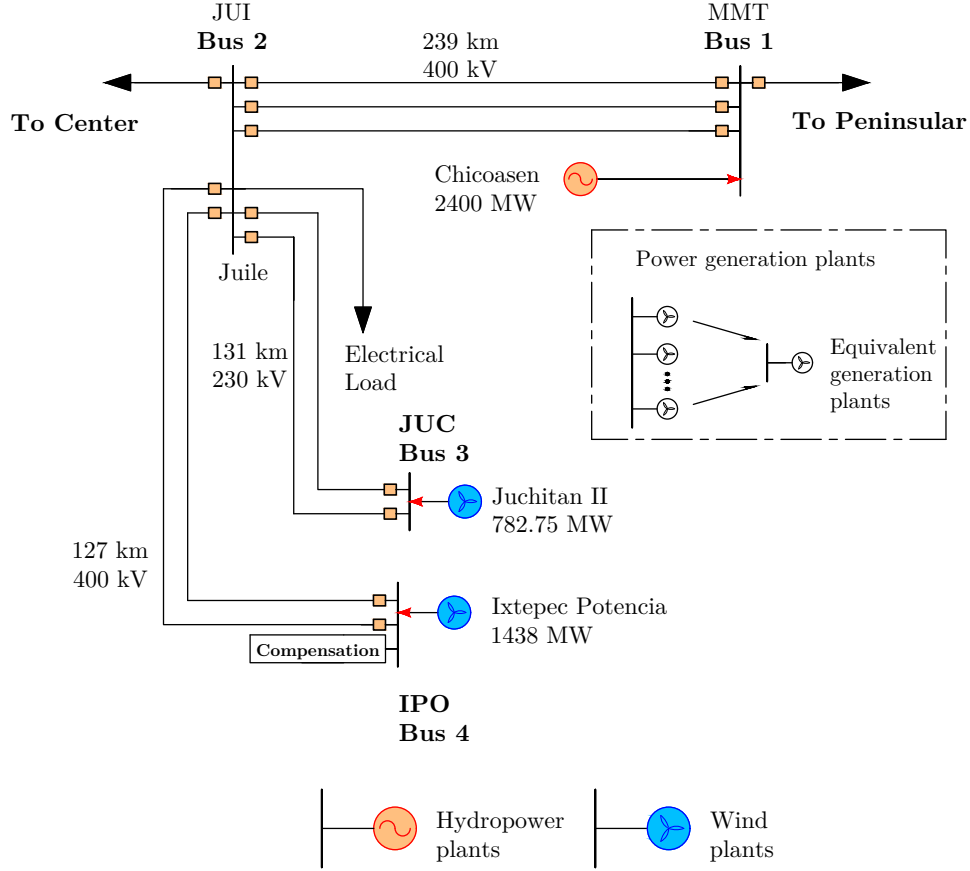


FIGURE 3.4: Single-line simplified diagram of southeast region of México [5] - [6].

only the ILP index is reported. The second part presents in detail the comparison between the results of the GPR with and without SVC connected at the bus 4.

The reader should be aware of the following considerations regarding the presentation of the indices results: the number of simulated scenarios is in proportion to the value of the loads and the RES penetration, several simulations using the SLF have been carried-out to obtain these results, and are reported in descending order with aim to create an empirical cumulative distribution function [4]. After a some SSCs (100), the slight accuracy improvements of the results does not justify the computation effort. Furthermore, MPI and GPR values near to the unity (1 p.u.) mean a positive effect, e.g., ILP and ILQ values represent less power losses present, while in case of ILL , represents less loading in the transmission lines; by contrast, negative values of ILP , ILQ and ILL , represent an increase of power losses and the loading level in transmission lines.

3.6.2.1 Multi-objective indices and GPR performance

Figure 3.5 (a) shows the results of the ILP index when the wind speed varies from 6 m/s to 16 m/s, with an increment of 1 m/s between them, i.e., 11 case studies were carried-out, but even with this small number of case studies is complex to identify a pattern behavior. In this way, including a large number of results of MPI indices in the same figure could be impractical, even misunderstand the results. In this sense, Fig. 3.5 (b) illustrates the same results of ILP

index, but they are represented using the GPR. In this representation, the MPI indices are represented as regions with a value of magnitude and probability percent.

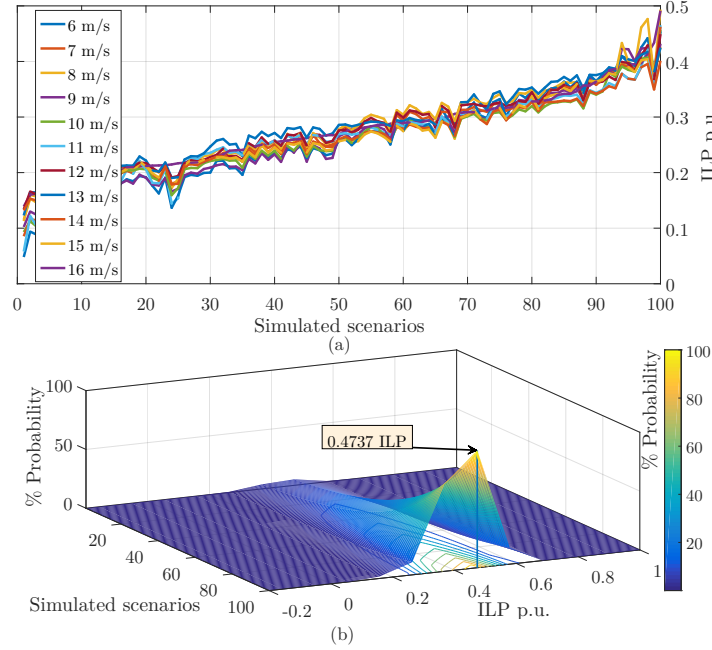


FIGURE 3.5: Results of the *ILP* index when there are variations in the wind speed. (a) MPI indices. (b) GPR.

For example, in the SSC no. 50, for 10 m/s, the magnitude of *ILP* is 0.2584 p.u., and represents 22% of probability to be present in the power system. Meanwhile in the SSC no. 100, *ILP* is 0.4737 p.u., and represents the 99% of probability. These results imply the knowledge about the actual condition of the power system, e.g., there is active power losses. Then, the next step is providing solutions to decrease these losses. In addition, GPR lets to determine regions with different percent of probability according to the Weibull distribution, i.e., a curve obtained with a wind speed of 7 m/s corresponds to a percent of probability of 62%, while with a wind speed of 10 m/s its probability percent is 100%, for this case of study.

On the other hand, Fig. 3.6 illustrates the results of the *ILP* using the MPI indices and the GPR when the SVC device is connected at the bus 4. Several simulations were conducted varying the capacity of this device from 240 MVar to 490 MVar, and considering a constant wind speed, with a value of 10 m/s.

Results of the *ILP* index indicate the impact of the SVC device in the power system. From Fig. 3.6, with 240 MVar of SVC, *ILP* is 0.6798 p.u., while for 490 MVar *ILP* is 0.8077 p.u., these values demonstrate the appreciably improvement of active power losses in the system, even in the lowest capacity of SVC in comparison without SVC. As it can be seen, the reduction is in proportion to the capacity of the SVC device. Besides that, based on the results about the probability region, the SVC has a high probability to work between 310 MVar and 420 MVar with *ILP*=0.75 p.u. and 99% of probability. This study can be used as a planning tool to select the capacity of the SVC device according to the operating condition and configuration of the power system.

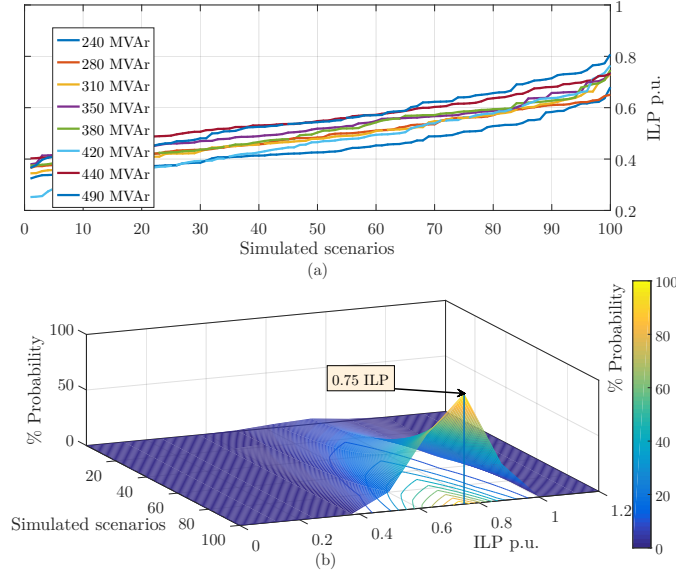


FIGURE 3.6: Results of the *ILP* index with different capacities of the SVC device. (a) MPI indices. (b) GPR.

3.6.2.2 Graphical Probabilistic Representation: comparison with and without SVC

This Subsection presents the comparison results of the computed GPR with and without SVC. The GPR includes all cases studies considering all the variations of wind speed and capacities of SVC in only one representation.

Figure 3.7 represents the results of the magnitude and probability of the *ILQ* index. The values with high probability (99%) to be present in the system are 0.4161 p.u. and 0.625 p.u. without and with the SVC connected to the test system, respectively. They indicate that the reactive power losses in the power system are reduced when SVC is connected, also, imply a reduction in transmission lines currents and an increment in the voltages of the buses near bus 4. For this case study the capacity of SVC is 380 MVar with 99% of probability.

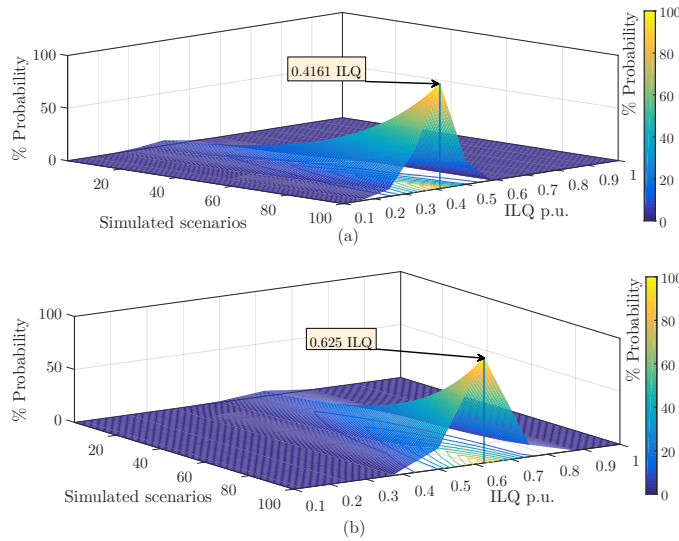


FIGURE 3.7: *ILQ* index. (a) With and (b) Without SVC device.

Figure 3.8 reports the results of the *ILL* index with and without the SVC. The values of *ILL* index are 0.2632 p.u. and 0.3305 p.u. without and with SVC, respectively. These values represent the 99% of probability to be present in the system. In addition the capacity of SVC is 350 MVar with the same probability value. Nevertheless, these values are small and suggest problems in transmission lines. That is, the SVC reduces active and reactive losses in the power system, increasing the transfer capacity in transmission lines, but there are still congestion problems in transmission lines due to the network topology. This is because only two transmission lines deliver the power of the WPPs to the system.

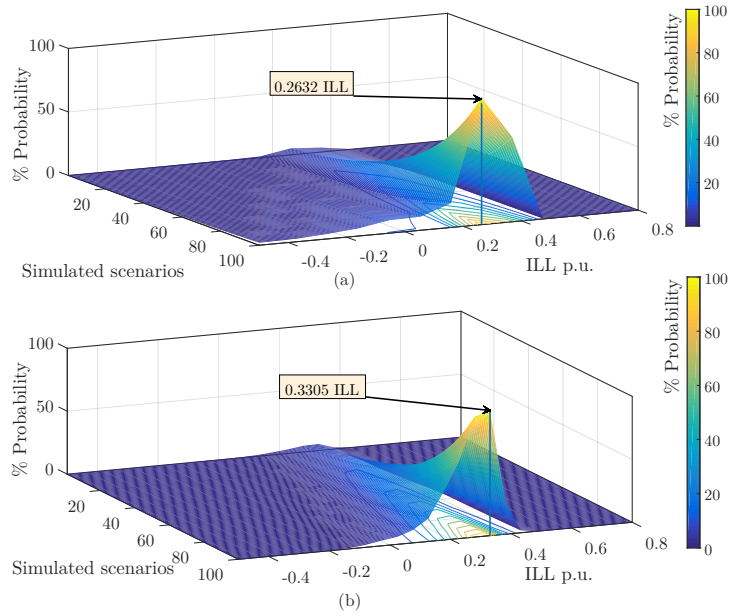


FIGURE 3.8: *ILL* index. (a) With and (b) Without SVC device.

3.7 Conclusions

In this Chapter, a new graphical probabilistic representation has been proposed and used to evaluate the impact of WPPs penetration in the equivalent of the Mexican power system; also, it was considered the connection of the SVC device to help with the compensation of reactive power.

This representation is a novel expansion of the application of the MPI to evaluate the impact of the WPPs in the system, by a probabilistic impact assessment. It provides the region with highest and lowest probability of operating conditions, such as the stochastic behavior of electrical loads and WPPs, provides the probability of these conditions to be present in the power system, and lets to carry-out several analyses in one single graphic.

From the obtained results without SVC, the *ILQ* index shows the influence of the WPPs on reactive power losses. Because in the test network there is only one hydropower generator (Chicoasen) which can provide reactive power support to the grid, this influence, in addition with the length of the transmission from Chicoasen to the WPPs produces voltage problems.

In the case of the *ILL* index results, confirms that there are congestion problems due the wind power penetration and the topology of the network. On the other hand, when the SVC

device is connected, the active and reactive power losses in the power system are reduced, and congestion in transmission lines as well. Although there is a reduction about the congestion problem in transmission lines, it is not enough, and it is reflected in the results.

The GPR offers a better understanding of the impact of WPPs in power systems, and provides support for further studies, such as optimal location, selection of capacity of FACTS devices, quantification of the probability given an operating condition, among others. Finally, GPR can be used to evaluate and compare the results of alternatives, such as SVC or FACT devices to improve the losses where there is a high WPP penetration in the power systems.

The computational effort of the GPR is according to the topology network and the number of simulations carried-out. In the case of the topology network used as test case, a high number of elements like loads and wind generation produces a high computation effort, because on each simulated scenario a specific probabilistic-distribution value is assigned according to the type of element.

On the other hand, the GPR proposed in this work is used for a particular case with three MPI, i.e., it can be applied for different values of wind speed or for reactive compensation. But, as future work, the GPR can be extended to any kind of RES or to analyzed different changing values of parameters at the same time.

Chapter 4

Improvement of the dynamic stability using Flexible Alternating Current Transmission Systems

4.1 Introduction

Some works, such as [61] – [62], show the effectiveness of FACTS devices for solving problems related to WPPs. In the most general expression, the FACTS concept is based on the substantial incorporation of power electronic devices and methods on the high-voltage side of the network to make it electronically controllable [63]. FACTS technology comprises a set of controllers that offer the possibility of controlling one or more parameters that modify the operation of the transmission system [39] and controlling transmission capability enhancement, voltage stability improvement, power conditioning, and power quality improvement, among others [21]. In fact, the main purposes of connecting FACTS devices in a power system, that includes WPPs, is to have a controlling dynamic power flow in transmission lines and to damp power oscillations [64].

In this thesis, FACTS devices are proposed to increase the available power transfer/capacity of transmission lines [65] – [66] and offer voltage support [67] – [68] in the area of Istmo of Tehuantepec. The TCSC, STATCOM, and a Unified Power Flow UPFC have been implemented and studied. These dynamic models were done in the DIgSILENT Simulation Language (DSL) in DIgSILENT PowerFactory. This programming language let to implement every linear or nonlinear system of differential equations, arithmetic or logic expression, program code or graphical macros or a combination of both approaches provided by the user to implement any kind of controller, in this case FACTS devices.

4.2 Impact of high penetration wind power plants in power systems

Wind power generation is the most economically attractive renewable power source for power systems. For example, the European power system has reported more than 44% of wind generation penetration [69].

Although there are all kinds of RES like WPPs, which are considered as alternatives to fossil fuels in the future, they can produce unforeseen problems as they are connected to the main electric grid [18].

The authors of [70] studied the impact on transient and frequency stability for a power system with high wind penetration; analysis in this work showed that the performance in the transient stability is adversely affected when faults are initiated close to areas with high wind penetration, due to the significant reduction in active power generation and high reactive power absorption during crowbar operation at wind generators. Frequency stability analysis has shown that synchronous areas with less inertia (due to wind integration) can be noticeably affected by generator outage events in other synchronous areas due to strong tie-line interconnection. System damping capability has been significantly reduced at high penetrations, with rotor angle oscillations exacerbated when faults occur closer to WPPs.

In addition to previous examples, the authors of [71] – [72] reported how the high penetration of wind energy impacts the power system and showed that the main factors that modify the performance of the system are wind turbine generator technology, WPP location, level of penetration, voltage level of the connection point, parameters of the controllers, and stress level of the system.

4.3 Flexible AC transmission system devices to improve the dynamic stability

This Section describes the model of TCSC, STATCOM, and UPFC. These controllers are represented by simplified models that capture the corresponding controller response to the fundamental frequency. These devices were implemented in the professional software DigSILENT PowerFactory. The authors of [4] and [60] described in detail the control techniques used in these devices.

4.3.1 Thyristor-Controlled Series Capacitor

One of controllers in the FACTS family is the TCSC, which allows the rapid and continuous adjustment of the transmission line impedance. As a result of this control, the active power flowing along the compensated transmission line can be maintained at a specified value under a range of operating conditions [21]. Fig. 4.1 shows a general configuration of a TCSC [21], which consists of a series capacitor bank in parallel with a thyristor-controlled reactor. The purpose of the TCSC control is to modify the reactance on the transmission line to maintain a constant power flow [60].

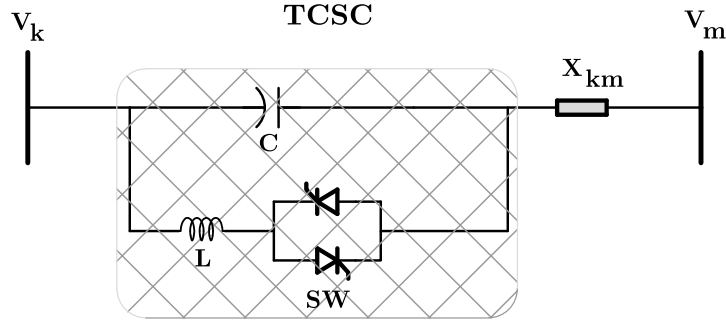


FIGURE 4.1: TCSC scheme.

On the other hand, the output signal of the block diagram of the TCSC is its variable susceptance (b_{TCSC}), whose expression is:

$$b_{TCSC}(X_C) = -\frac{X_C/X_{km}}{X_{km}(1 - X_C/X_{km})} \quad (4.1)$$

where X_C is the control signal, and X_{km} is the line reactance between the node k and m . The control system of the TCSC measures the power flow in the line P_{km} and it compares with the power reference P_{ref} . As result of this action, if P_{km} is higher than P_{ref} , X_C signal is negative, which means b_{TCSC} is positive and it implies that the reactance of the transmission line increases (simulating an increasing in the line length), decreasing the active power flow. By contrast, if P_{km} is lower than P_{ref} , X_C signal is positive, which means b_{TCSC} is negative and it implies that the reactance of the transmission line decreases (simulating a short transmission line in its length), increasing the active power flow [4].

In addition, the control system of the TCSC includes a linear controller that responses to steady-state variations produced by the input signal, this controller is the Power Oscillation Damper (POD). The POD is a dynamic compensator that increases the synchronizing damping torques and only acts when there are transient perturbations. This controller is explained in detail in [4].

In reference with Fig. 4.1, the total reactance X_T in the branch is expressed as:

$$X_T = X_{km} + X_{TCSC} \quad (4.2)$$

Besides, the X_{TCSC} reactance is result of the parallel equivalent of the inductor and the capacitor, and its expression is:

$$jX_{TCSC} = -\frac{j}{b_{TCSC}} = \frac{(-jX_{cap})(jX_{ind})}{jX_{ind} - jX_{cap}} = \frac{X_{cap}X_{ind}}{j(X_{ind} - X_{cap})} = -j\frac{X_{cap}X_{ind}}{(X_{ind} - X_{cap})} \quad (4.3)$$

where X_{cap} is the reactance of the fixed capacitor, X_{ind} is the controlled reactance of the variable inductance and b_{TCSC} is the total susceptance of the TCSC.

For the control system, the control signal X_C of the TCSC is the controlled inductive reactance X_{ind} , i.e., $X_C = X_{ind}$. Then, is necessary to establish the relationship between X_C and X_{ind} . For this purpose, it is known that $X_{TCSC} = 1/b_{TCSC}$, hence, it can be rewritten as:

$$b_{TCSC} = \frac{1}{X_{TCSC}} \quad (4.4)$$

Equation (4.3) can be expressed as:

$$b_{TCSC} = \frac{X_{ind} - X_{cap}}{X_{cap}X_{ind}} \quad (4.5)$$

Establishing the relation from the Eqs. (4.1) and (4.5), and after several simplifications, the expression for the control system X_{ind} is given by the next equation:

$$X_{ind} = \frac{X_{cap}X_{km} - X_{cap}X_C}{\frac{X_{cap}X_C}{X_{km}} + X_{km} - X_C} \quad (4.6)$$

The rest of the control system blocks of the TCSC are presented in the Appendix D, and the development of the equations is presented in detail in [4] and [60].

4.3.2 Static Synchronous Compensator

The main feature of the STATCOM is to provide voltage support without using large banks of capacitors and reactors to supply or absorb reactive power [21]. The STATCOM generates a balanced set of sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle to compensate the active and reactive power needed by the system. This can be obtained by the STATCOM controller, that check a reference voltage v_{ref} with the controlled voltage $v \Rightarrow V_k$, with the purpose of maintaining the desired voltage.

Figure 4.2 shows the scheme of the STATCOM, while the control block system is shown in Fig. D.4 of the Appendix D. The model in detail can be found in [4] and [60].

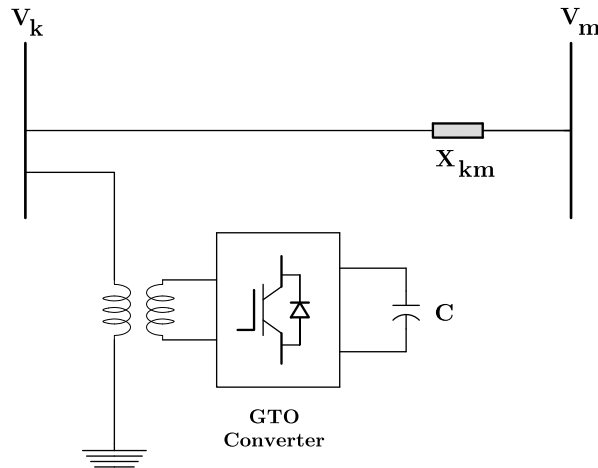


FIGURE 4.2: STATCOM scheme.

The STATCOM has been modeled in DlgSILENT PowerFactory thought an element of the library of this software called *static generator*, and it has been selected like current source model (see Fig. 4.3).

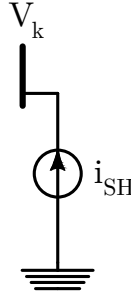


FIGURE 4.3: Equivalent circuit of the STATCOM.

Equations (4.7) - (4.9) represent the dynamic behavior of the STATCOM as a current source model [73]:

$$i_1 = (i_{d.ref} \cos(v) - i_{q.ref} \sin(v)) + j(i_{d.ref} \sin(v) + i_{q.ref} \cos(v)) \quad (4.7)$$

$$\cos(v) = \frac{v_r}{v} \quad (4.8)$$

$$\sin(v) = \frac{v_i}{v} \quad (4.9)$$

where i_1 is the complex current injected by the STATCOM to the power system, $i_{d.ref}$ and $i_{q.ref}$ are the reference currents in dq -axis in the reference frame, $v_1 = v(\cos(v) + j \sin(v)) = v_r + j v_i$ is the complex voltage at the bus connected with the STATCOM, v_r and v_i are the real and complex component of the bus voltage, respectively. Therefore, replacing Eq. (4.8) and (4.9) in (4.7), it can be rewritten as:

$$i_1 = \left(i_{d.ref} \frac{v_r}{v} - i_{q.ref} \frac{v_i}{v} \right) + j \left(i_{d.ref} \frac{v_i}{v} + i_{q.ref} \frac{v_r}{v} \right) \quad (4.10)$$

Base on the apparent power flow S at the connection bus by the STATCOM, the expression that determinate this relationship is:

$$S = VI^* = (v_r i_r + v_i i_i) + j(v_i i_r - v_r i_i) = P + jQ \quad (4.11)$$

where V is the voltage vector, I is the current vector, i_r and i_i are the real and imaginary component of the current. Thus, Eq. (4.11) represents active (P) and reactive (Q) powers, they can be represented as follows:

$$P = v_r i_r + v_i i_i \quad (4.12)$$

$$Q = v_i i_r - v_r i_i \quad (4.13)$$

As the STATCOM is modeled as current source model, there is not exchange of active power ($P = 0$). It is expressed by following expression from Eq. (4.12):

$$i_i = -\frac{v_r i_r}{v_i} \quad (4.14)$$

The STATCOM control signal is i_{SH} , i.e., $i_1 = i_{SH}$, that is the current that the STATCOM injects to the power system, it is expressed as follows:

$$i_{SH}^2 = i_r^2 + i_i^2 = i_r^2 + \left(-\frac{v_r i_r}{v_i}\right)^2 = i_r^2 \left(\frac{v_i^2 + v_r^2}{v_i^2}\right) = \frac{i_r^2 v^2}{v_i^2} \quad (4.15)$$

Equation (4.15) can be rewritten as:

$$i_{SH}^2 = \frac{i_r^2 v^2}{v_i^2} \Rightarrow i_{SH} = \frac{i_r v}{v_i} \quad (4.16)$$

As results of the aforementioned equations, i_r and i_i can be obtained from i_{SH} as follows:

$$i_r = i_{SH} \frac{v_i}{v} \quad (4.17)$$

$$i_i = -i_{SH} \frac{v_r}{v} \quad (4.18)$$

Equations (4.17) and (4.18) allow the relationship between the control signals and the interface with the static generator in DlgSILENT PowerFactory. These expressions are represented as:

$$i_{q.ref} = -i_{SH} \quad (4.19)$$

$$i_{d.ref} = 0 \quad (4.20)$$

4.3.3 Unified Power Flow Controller

The UPFC is a combination of shunt and series converters that are coupled on the DC side via a common link, that allows the bidirectional exchange of active and reactive power between these two devices. This characteristic allows to the UPFC controls simultaneously or selectively, active and reactive power flow, bus voltage and impedance in transmission lines. The basic scheme of the UPFC is shown in Fig. 4.4, which depicts its series and shunt connection with the system. Although Fig. 4.5 shows the circuit equivalent of the UPFC, it is represented by one series voltage source, V_s , and by one shunt current source, i_{sh} .

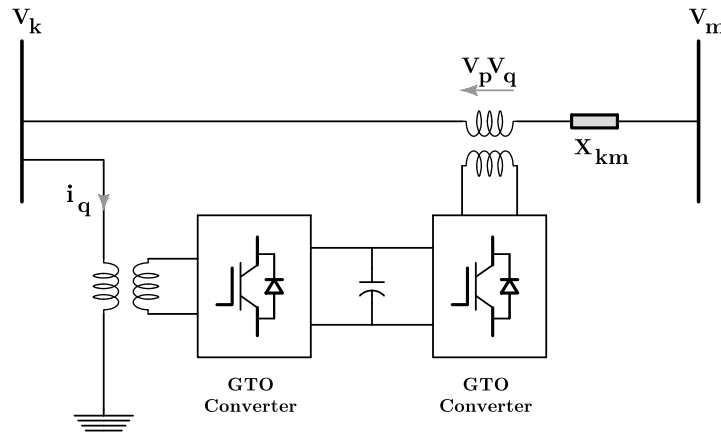


FIGURE 4.4: UPFC scheme.

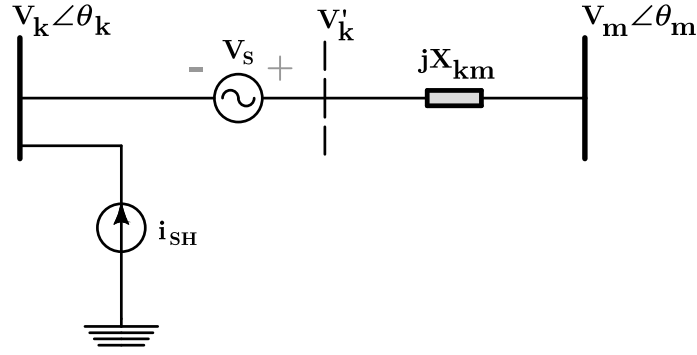


FIGURE 4.5: Equivalent circuit of the UPFC.

Three-output signals are used to control the UPFC: v_p , v_q and i_q . Signal v_p represents the component of the series voltage V_s and it is in phase with the line current. The signal v_q represents the component of the series voltage V_s that is in quadrature with the line current; this signal controls the reactive power to keep a specified value of the voltage in the bus V'_k . The signal i_q represents the component of the shunt current, i_{sh} , which is in quadrature with the bus voltage, this signal controls the bus voltage V_k around a specified level [60]. The corresponding blocks that implement the control signals of the series controller are presented in the Appendix D.

Taking into account the apparent power flow at UPFC series component (S_{series}), the expressions that describes this relationship is:

$$S_{series} = V_{series} I_{series}^* = (v_r \ i_r + v_i \ i_i) + j(v_i \ i_r - v_r \ i_i) = P_{series} + jQ_{series} \quad (4.21)$$

where V_{series} and I_{series} are the voltage and current vectors at series component, respectively, P_{series} and Q_{series} are the active and reactive power at series component, respectively. Thus, Eq. (4.11) represents active and reactive powers, they can be represented as follows:

$$P = v_r \ i_r + v_i \ i_i = v_p i_{series} \quad (4.22)$$

$$Q = v_i \ i_r - v_r \ i_i = v_q i_{series} \quad (4.23)$$

where i_{series} represents the component of the series current. On the other hand, the expression that allows the relationship of the series component voltage and the current of the UPFC is determinate by:

$$\frac{v_p}{v_q} = \frac{v_r i_r + v_i i_i}{v_i i_r - v_r i_i} \quad (4.24)$$

The UPFC uses the constant-voltage mode, this mode considers that the magnitude of voltage v_q is constant in steady-state, and it is independently of the line current ($v_q = v_{q0}$). Hence, applying this relationship in the Eq. (4.23), it can be rewritten as:

$$v_q = v_{q0} = \frac{Q_{series0}}{i_{series0}} \quad (4.25)$$

where v_{q0} , $Q_{series0}$, $i_{series0}$ represent the voltage, reactive power and current, respectively, for constant voltage mode. Now, substituting in the Eq. (4.25) in (4.23), and solving for v_i :

$$v_i = \frac{Q_{series0}}{i_{series0} i_r} i_{series} + v_r \frac{i_i}{i_r} \quad (4.26)$$

Replacing the Eq. (4.26) in (4.24), and solving for v_r :

$$v_r = \frac{Q_{series0} (i_r v_p - i_i v_q)}{i_{series0} i_{series} v_q} \quad (4.27)$$

Finally, replacing Eq. (4.27) in (4.26) and after simplifications:

$$v_i = \frac{Q_{series0} (i_r v_p + i_i v_q)}{i_{series0} i_{series} v_q} \quad (4.28)$$

A consideration for the static generator is that active power losses are neglected ($R=0$), its representation is simplified as follows:

$$v_{1r_in} + jv_{1i_in} = (v_r + jv_i) + (-i_i X + ji_r X) \quad (4.29)$$

Replacing Eq. (4.27) and (4.28) in (4.29) is possible to determinate the static generator as a controlled voltage source (v_{1r_in}, v_{1i_in}) as functions of v_p and v_q . After several simplifications, equations that represent this controller are:

$$v_{1r_in} = \frac{Q_{series0} (i_r v_p - i_i v_q)}{i_{series0} i_{series} v_q} - i_i X \quad (4.30)$$

$$v_{1i_in} = \frac{Q_{series0} (i_r v_p + i_i v_q)}{i_{series0} i_{series} v_q} - i_r X \quad (4.31)$$

On the other hand, the UPFC shunt component operates like the STATCOM, its representation can be seen in Fig. D.10 at the Appendix D. The expressions corresponding to the shunt controller are:

$$i_{qref} = -i_q \quad (4.32)$$

$$i_{dref} = 0 \quad (4.33)$$

4.4 Dynamic studies: implementation of FACTS devices

This Section presents the results of the implementation of FACTS devices in the southeast of the Mexican power system. The objective is to improve problems like congestion in transmission lines and voltage support at the PCC with the WPPs. To carry-out this goal, Fig 4.6, presents the network under study. For this Chapter compensation devices (parallel and series) are connected between bus 2 and 4.

4.4.1 Congestion in transmission lines

One of the present problems in the Istmo of Tehuantepec is the congestion in the transmission lines produced by high penetration of WPPs, these are located between the buses 2 and 4 (JUL-IPO). In contrast with Subsection 2.4.1.1, this Subsection presents the results of dynamic behavior of FACTS devices to improve the congestion in transmission lines.

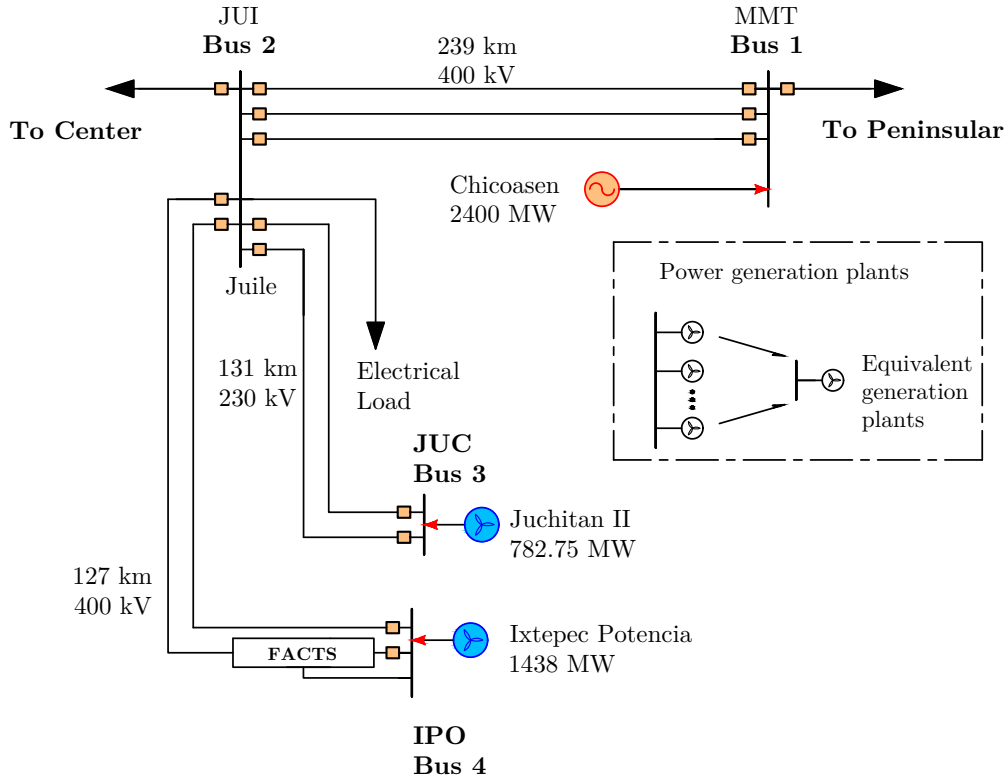


FIGURE 4.6: Southeast region of México equivalent network [5] - [6].

To represent the problem and improvement of the congestion in transmission lines with FACTS devices, three simulations were conducted. In addition, the comparison of performance among FACTS devices is presented. Each simulation represents variations in the load, i.e., active power increases, and the power factor decreases at $t = 10$ s at the same time, while the WPPs of IPO are providing 1,000 MW to the power system, that is, 83.3% of the transmission line capacity [13]. It is important to mention that despite the fact that transmission lines support 1,200 MW, CENACE recommends, for security reasons, do not to exceed 1,000 MW. The variations in the load are shown in Table 4.1.

TABLE 4.1: Active power and power factor in the load for the case studies.

Parameter	Case 1 (C1)	Case 2 (C2)	Case 3 (C3)
Active Power (MW)	500	900	1100
Power Factor	0.95	0.65	0.6

In order to present the dynamic behavior of FACTS devices, case 1 is presented. Figs. 4.7 and 4.8 show the results of the active power in the transmission lines and the voltage at the bus at which the FACTS controllers are connected (bus 4).

In the case of the active power in the transmission line (see Fig. 4.7), it is noticed that when there are not installed FACTS devices, the active power decreases from 1,000 MW to 984.7 MW. With the STATCOM, there is an increment in the active and reactive power in the connection point of this element (because of the principle of parallel compensation [21]), i.e., in bus 4, the active power has a value of 1,034.2 MW. In the case of the TCSC, this device allows to control the active power to keep the same predisturbance active power, in this case, is of 1,000 MW.

With the UPFC, the active power reaches reference value of power in less oscillations compared to the TCSC.

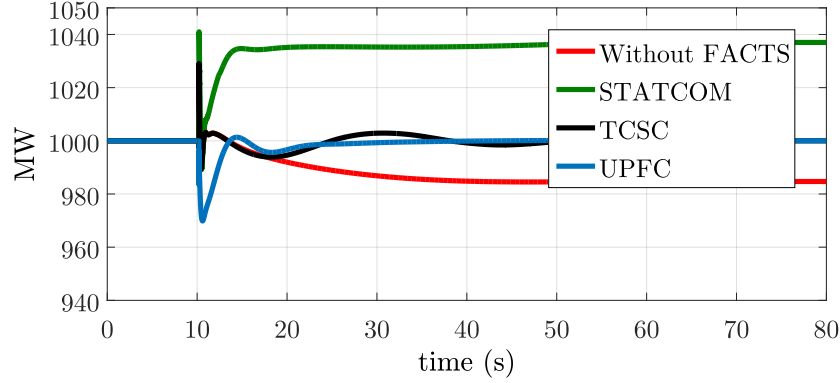


FIGURE 4.7: Active power profile with and without FACTS devices in bus 4.

Figure 4.8 shows the voltage profile in bus 4. Note that when there are not FACTS controllers, the voltage profile is 0.907 p.u., whereas the TCSC controller increases this profile to a value of 0.942 p.u. In the cases of the STATCOM and the UPFC, these devices compensated the voltage to their reference values, that is 1 p.u.; but the responses of the STATCOM and the UPFC in the first oscillation are 0.94 p.u. and 0.99 p.u., respectively. In other words, the UPFC allows a less decrement in the voltage profile, because this device has the objective of compensating the active power in the transmission line and the reactive power in the bus to which it is connected.

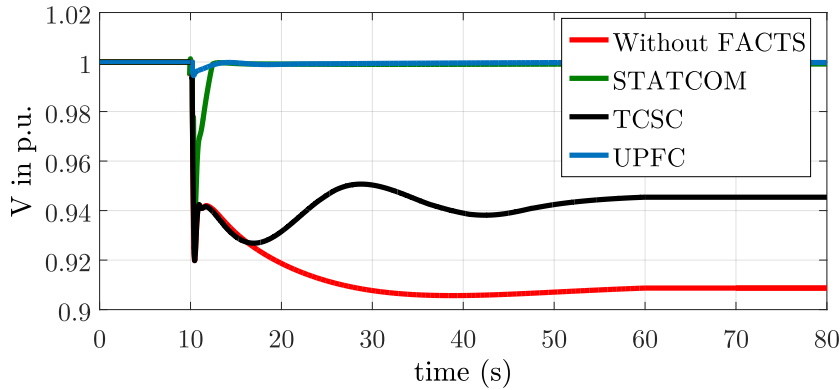


FIGURE 4.8: Voltage in p.u. profile with and without FACTS devices in bus 4.

In the next Figs., the comparative of the performance of FACTS devices for the three case studies is presented, these results belong to steady-state of dynamic simulations (in $t = 60$ s). Fig. 4.9 shows the active power with and without FACTS in the transmission line between the buses 2 and 4 (JUI-IPO). As shown, the TCSC and the UPFC compensate the active power and reach the reference value; therefore, it is worth mentioning that in the three case studies, even if the demand of active and reactive power in the load increases, these devices maintain the value of the active power to the reference without compromising the power capacity of the transmission line. On the other hand, the STATCOM in the three case studies increases the flow of active power in the line. For example, in Case 3, with the STATCOM, the active power in the line represents the 87% of its capacity, whereas without FACTS, the active power represents 82.3% of its capacity.

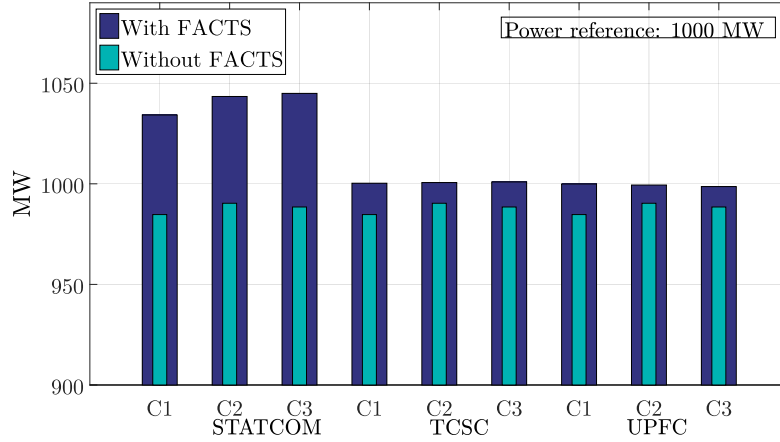


FIGURE 4.9: Active power in the transmission line.

Figure 4.10 shows the results of the voltage profile in bus 4 with and without FACTS controllers. The simulation results show that the shunt controllers (STATCOM and UPFC) compensate the voltage profile near the voltage of reference (1 p.u.). Also, the STATCOM in the case 3 keeps the voltage in bus 4 to 0.995 p.u., whereas the UPFC keeps the voltage to 0.999 p.u. This is because of the operative limits of this device.

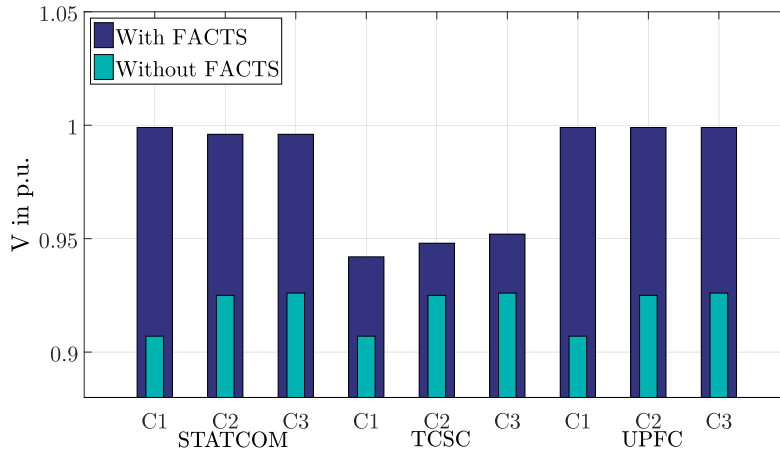


FIGURE 4.10: Voltage in bus 4.

Figure 4.11 shows the reactive power profile in the transmission line with and without FACTS devices. The STATCOM and UPFC, inject reactive power to maintain the reference value, as result of this, reactive power flow in the transmission line is reduced significantly. The STATCOM reduces the reactive power in the transmission line more than the UPFC, because it only has the objective to control the voltage in the bus that is connected (bus 4), whereas the UPFC controls the voltage in shunt compensation, in this case bus 4, while in series compensation, the UPFC controls the active power in the transmission line. In other words, UPFC has a better balance between the compensation of the active and reactive power than the STATCOM and the TCSC. On the other hand, the TCSC compensates in lower magnitude the reactive power than the active power.

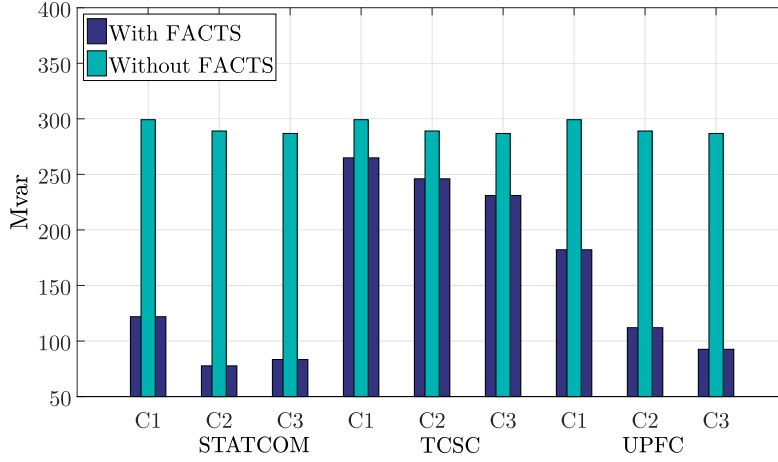


FIGURE 4.11: Reactive power in the transmission line.

In conclusion, in the case of the compensation of the active power in the transmission line, the obtained results of the TCSC and the UPFC show that these devices maintain the reference value, whereas the STATCOM increases the active power and produces congestion problems in the transmission line. In the case of the voltage regulation, the STATCOM and the UPFC keep the voltage near the reference value in the buses to which they are connected. Finally, in the case of the reactive power in the transmission line, the STATCOM and the UPFC reduces this power significantly. On the other hand, the TCSC compensates the reactive power in proportion to the capacity of the capacitor of this device.

4.4.2 Increment of active and reactive power

In this Subsection, two case studies were conducted to compare the impact of the FACTS devices in the voltage of the buses near them. To represent this effect, an increment of the active and reactive power in the electrical load of bus 2 was simulated up to 4,000 MW and 4,000 Mvar. The results are analyzed and compared for bus 2. In case 1, the active power increases, and in case 2, the reactive power increases while the power factor is 0.85 in both cases. For case 1, Fig. 4.12 shows the voltage profile in bus 2 when the active power in the load is increased. In this case, with an increment of 4,000 MW of the active power consumption in the load, the voltage profile when there are not installed FACTS devices is 0.977 p.u.; whereas the profile voltage with the TCSC is 0.981 p.u., and the voltage profile with the STATCOM and the UPFC is 0.985 p.u. and 0.99 p.u., respectively.

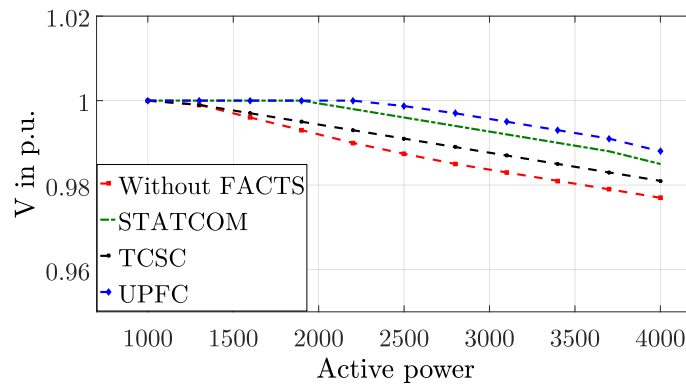


FIGURE 4.12: Voltage profile in bus 2 with changing in active power in the load.

Figure 4.13 shows the voltage profile in bus 2 when there is an increment of reactive power in the load, with and without FACTS devices. For this case, with an increment of 4,000 Mvar of the reactive power consumption in the load, the voltage in bus 2 without FACTS devices is 0.969 p.u.; and in the case of the STATCOM and the UPFC, the voltage profile is 0.993 p.u. and 0.995 p.u., respectively, whereas the TCSC is 0.991 p.u.

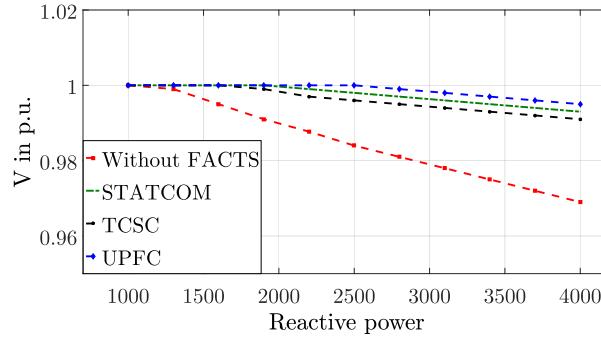


FIGURE 4.13: Voltage profile in bus 2 with changing in reactive power in the load.

In conclusion, according to the case 1, the STATCOM and the UPFC have a better performance in the voltage profile than the TCSC when the active power is increased. This is mainly because the TCSC compensates only active power, whereas the STATCOM and the UPFC inject reactive power that improves the voltage in the buses. In the case 2, the results of the simulations show that all devices have great performance in the voltage profile when the reactive power is increased. For the case of the TCSC, this device does not reduce the flow of reactive power in the transmission line, so that when the reactive power is increased, the voltage in bus 2 is not affected.

4.5 Conclusions

The impact of the application of the FACTS devices for the control of active and reactive power in the southeast area of the Mexican electric system has been analyzed in this Chapter.

In the case of the congestion problem in the transmission lines, the obtained results of the dynamic simulations show the effectiveness of the TCSC and UPFC; these devices allow control the active power in order to keep the same active power when the demand in the load increases. Also, STATCOM produces an increment in active power and congestion problems in the transmission line.

In the case of voltage regulation, shunt devices as the STATCOM and the UPFC provide a great performance and maintain the voltage at its reference (1 p.u.). On other hand, the shunt compensations devices have a better performance in comparison with series devices to improve the voltage profile in buses that are connected and buses near the FACTS controllers.

The simulation results indicate that the operation of the UPFC improves the congestion and voltage problems, this is because this device is a combination of the shunt and series compensators. Finally, the application of the FACTS devices depends on the problem and localization in the power system and its capability to compensate, i.e., its operative limits of compensation.

Chapter 5

Methodology for the inertia constant estimation of wind farms

5.1 Introduction

Wind generation brings benefits [18], [44] but also challenges for power systems [19] - [20], especially when there is a high penetration of wind power plants. Therefore, it is essential to conduct studies about the stability and operation of power systems including this type of plants. Thus, the inertia estimation plays a critical role on frequency stability problems in modern power systems. It can be used as input for control of converters in real-time, modern power processing, energy storage, among others, providing a considerable improvement on swings during transient events.

In this Chapter is presented a methodology for inertia constant estimation of hydropower and WPPs generation units using Phasor Measurement Units (PMUs) [74]. This thesis work improves and evaluates the methodology presented in [74] for the estimation of the inertia available in hydro and wind power plants based on the measurements obtained from PMUs. The methodology was modified using a fourth-order finite-difference approximation to calculate the second-order derivative of the swing equation, and the results obtained are way better. Besides, the methodology is tested using measurements obtained from industrial PMUs in a test power system implemented in an RTDS, to test its practical application, and not only using offline simulations as reported previously. In addition, the methodology is applied to an equivalent of the Mexican southeast power system, where there is high penetration of wind and hydro power generation. This methodology provides great accuracy in the values of the inertia estimation in real-time; it is based on the equation of oscillation and it uses measurements of the bus angle, detection of the disturbance, peak value of the disturbance, and the knowledge of active power flow in the generation units. Afterward, in Section 5.6 the evaluated methodology is applied to the inertia estimation of the hydropower and WPPs of the southeast Mexican equivalent power system.

5.2 Methods for inertia estimation

To address frequency stability issues, some works have been proposed to estimate the inertia in power systems with the purpose to improve the frequency stability and enable higher penetration of wind power plants [75] - [76].

In [76], a virtual inertia is estimated by using the frequency deviations measurements in a Microgrid. The method is based on swing equation, and the value of the inertia is used for tuning load frequency controllers of the generation units, and calculate the active power required for an energy system storage, composed by ultracapacitors (UC), to improve the frequency stability problems.

Reference [77] calculates a synthetic inertia by means of a transfer function that represents the electromechanical behavior of a synchronous generator. The inertia estimation is done considering load changes and frequency deviations of the power system.

In the work reported in [78], a virtual inertia is estimated through the swing equation of synchronous machines. The system is linearized with respect to the speed of the generator and the inertia is determined by the balance between mechanical and active power of the generation units.

Reference [79] estimates the power system inertia through a simulation model and frequency measurements from PMUs. In the inertia estimation the frequency and the total active power at the connection point just after the disturbance are considered.

In [80], the inertia estimation is based on an approximation of the total power change after a disturbance has occurred. This methodology uses the average frequency of the system and the first instant after the application of the disturbance to estimate the inertia.

The aforementioned methodologies are based on the swing equation and transient events, like the Rate Of Change of Frequency ROCOF, and some of them use off-line measurements, such as the power system frequency, which leads to a low inertia estimation accuracy [81]. On the other hand, the method presented in [80] provides low inertia estimation error by employing particle swarm optimization, but the accuracy of this method depends on the load power change model and a large number of parameters such as currents, load impedance, power change measurements after the disturbance and frequency average of the system.

Table 1 shows the differences between the main methodologies proposed in the literature for the inertia estimation and the methodology used in this research. The plus and minus signs indicate if the methodology contains (+) or not (-) the characteristic evaluated in the Table 1, respectively. The principal characteristics used in the comparison are the simplicity of the algorithm, online implementation, accuracy on the inertia estimation on the first oscillation, mean error, a small number of parameters used for the estimation, and the robustness of the algorithm against variations in the system. In contrast with the mentioned methods, the methodology used in this thesis only needs the bus angle deviation at generation buses obtained from PMUs and real power measurements. It has a considerable balance about accuracy on the first oscillation, simplified algorithm, robustness in presence of variations in the system, and low error in the estimation of the inertia in the generation units. However, a disadvantage of this methodology is that the accuracy is reduced when the system is subject to small perturbations such as load variations. The methodology uses the time when the perturbation starts to determinate the peak value of the first angular oscillation. In its current form, this methodology does not include any technique for the detection of perturbations.

TABLE 5.1: Comparison among methodologies for the inertia estimation.

Characteristic	Fifth order polynomial [88]	ROCOF [83]	Optimization methods [84]	Load disturbance and frequency deviation [79]	Methodology used
Simplicity of the algorithm.	+	-	-	-	+
Online implementation.	+	-	-	+	+
Accuracy on inertia estimation on the first oscillation.	-	-	-	-	+
Percentage of error.	<42%	<13%	<5%	<10%	<4%
Less number of parameters used.	+	+	-	-	+
Robustness of the inertia estimation against variations in the system.	+	-	-	-	+

5.3 Methodology for the inertia estimation based on the swing equation and Phasor Measurement Units

Typically, the natural inertia of synchronous generator units responds voluntarily when the system is subject to disturbances, without any control actions [15], [17]. This behavior can be achieved in wind power plants through power electronic converters by wind turbine inertia controls, even when they are decoupled partially or completely from the grid [82] - [83]. This assumption is valid because modern wind turbine controllers can convert the kinetic energy into active power, i.e., control functions achieved by power converter controls can be seen as virtual inertia of wind generators [75], [84]. This is shown in the Fig. 5.1. Through both natural and virtual inertias, active power is released to the power system from kinetic energy of generation units. In the case of wind power plants, it is done through power electronics converters and wind turbine controls that extract the kinetic energy from moving parts and convert into real power output [84] - [85]. This characteristic of inertia response in wind power plants can be described in a format similar to conventional generator units by the swing equation, which is directly derived from the Newton's Law of motion on rotating objects. Due to this correlation between the virtual inertia of wind power plants and real inertia of synchronous generation units, an inertia can be estimated for wind power plants in a format similar of conventional generators [74].

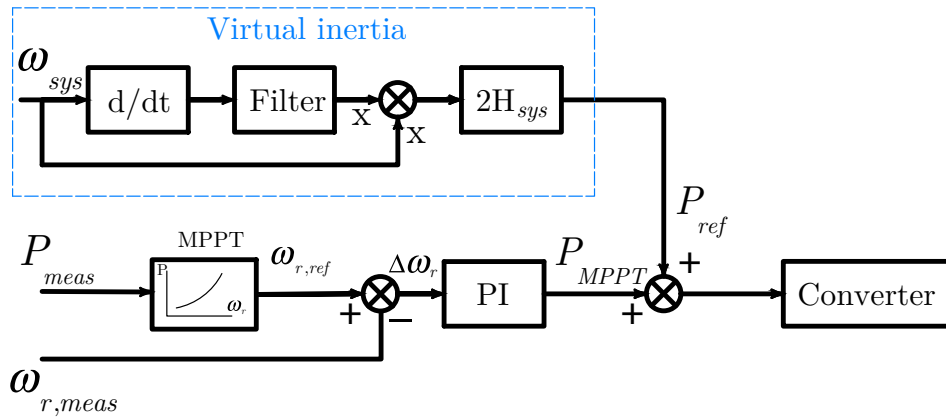


FIGURE 5.1: Virtual inertia concept in wind power plants.

The characteristic inertia response can be represented by the swing equation, which describes the change between the axis of the rotor and the magnetic field. This change is produced when a disturbance occurs in the power system. As a result, the rotor accelerates or decelerates with respect to system synchronous speed [15]. The swing equation is given by the next expression [17], [32] :

$$\frac{2H}{\omega_0} \frac{\partial^2 \Delta\delta}{\partial t^2} = \Delta P_M - \Delta P_E - K_D \Delta\omega \quad (5.1)$$

where ω_0 is the rated speed of the system, δ is the rotor angle, P_M is the mechanical power, P_E is the electrical power, K_D is the damping factor, and $\Delta\omega$ is the derivative of the rotor angle.

Equation (5.1) represents the dynamic response of the inertia of the synchronous machines or a group of synchronous machines. Rotor angle is the rate of change of angular displacement of the rotor, that is, the angular speed of the rotor is equivalent to the derivative of the angle of the rotor with respect to time. This expression can be represented as [74]:

$$\Delta\omega = \frac{\partial \Delta\delta}{\partial t} \quad (5.2)$$

The rotor angle δ cannot be directly measured, however, the angle of the voltage on the bus θ follows closely the rotor angle. Thus, Eq. (5.1) can be rewritten as [74]:

$$\frac{2H}{\omega_0} \frac{\partial^2 \Delta\theta}{\partial t^2} = \Delta P_M - \Delta P_E - K_D \frac{\partial \Delta\theta}{\partial t} \quad (5.3)$$

Real-time measurements, like mechanical power, could be complicated to obtain, especially when there is a change in the mechanical power at the turbine of each generation unit. A consideration can be applied to Eq. (5.3) assuming that the mechanical power has a very large time constant compared with the electrical power. During the first swing of any disturbance, when primary frequency controls are not yet active, it is valid to assume that the mechanical power output remains constant. In addition, the mentioned consideration for this methodology is applied for short-term transient events where the mechanical torque has a higher value in comparison with electromagnetic torque [17], [86].

Assuming that:

$$\Delta P_M = 0 \quad (5.4)$$

$$\Delta P_{E(t)} = P_{E(t)} - P_{E0} \quad (5.5)$$

The swing equation can be developed on [74]:

$$\frac{2H}{\omega_0} \frac{\partial^2 \Delta\theta}{\partial t^2} = P_{E0} - P_E(t) - K_D \frac{\partial \Delta\theta}{\partial t} \quad (5.6)$$

It can be rewritten as:

$$\frac{2H}{\omega_0} \frac{\partial^2 \Delta\theta(t)}{\partial t^2} + K_D \frac{\partial \Delta\theta(t)}{\partial t} = P_{E0} - P_E(t) \quad (5.7)$$

Another consideration is to assume $K_D = 0$ in a short time after a disturbance. Also, as it can be noted this methodology is suitable for discrete measurements, in this way, using finite

difference equations and applying a fourth-order central finite-difference scheme [87], Eq. (5.7) can be expressed as:

$$H = \frac{12h^2 * \omega_0 * (P_{E0} - P_E(t))}{2 * (-\theta_{i+2} + 16\theta_{i+1} - 30\theta_i + 16\theta_{i-1} - \theta_{i-2})} \quad (5.8)$$

where h is the integration step size of the finite-difference approach, θ is the vector of the bus-voltage angles, and i is i -th element of this vector. The implementation of the methodology considers the following conditions: (a) the detection of the beginning of the disturbance, (b) the detection of the peak value of the first angular oscillation, and (c) assume the knowledge of the active power provided by the generation units [74]. Finally, the bus-voltage angle at the generation buses is provided by the PMUs and the total generated active power is directly measured at the generation stations.

5.4 Methodology evaluation

This Section presents the validation of the methodology for the inertia estimation. The main purpose is to evaluate the accuracy and robustness of the results of the inertia estimation obtained with the methodology in comparison with a known given inertia values. In order to carry-out this evaluation, two case studies were implemented in the professional software DIgSILENT PowerFactory and an experimental validation in an RTDS. Afterward, in Section 5.6 the evaluated methodology is applied to the inertia estimation of the hydropower and wind power plants of the southeast Mexican equivalent power system.

For the first case study, the results are produced by a three-phase short-circuit event at the transmission L1 of Fig. 5.2. This event is applied in the middle of the line, at $t=0.3$ s, then at $t=0.4$ s is cleared by opening the breakers at the end of the line, and the inertia of the generation unit G1 is estimated. In this case, the line model used in the RTDS was a distributed parameter model to have a more realistic system representation, while in DIgSILENT PowerFactory was used the lumped parameters PI-model, because DIgSILENT PowerFactory does not support the use of the model of distributed parameters when a three-phase short-circuit is applied at the middle of the transmission line. On the other hand, in the second case study, the PI-model was used in both software, also, it was observed that despite the models used to represent the synchronous machines and their controllers (AVR, governors and excitation systems) are the same in both software, their implementations are slightly different, and this yields different results for the same system under simulation [88] - [89], for that reason, the controllers were tuned in DIgSILENT PowerFactory to obtain the similar behavior that RTDS and be able to compare the obtained results. These changes are to evaluate the robustness of the methodology for the inertia estimation.

5.4.1 System configuration

Figure 5.2 shows the schematic implementation of the system under study in the software RSCAD of RTDS. The system consists of two synchronous generators G1 and G2, and their control systems (Governor PIDGOV, Automatic Voltage Regulator (AVR) EXST1, and Power System Stabilizer (PSS) STAB2A) [27], [90], two three-phase transformers, two transmission lines (L1 and L2) and an electrical load modeled as a constant impedance.

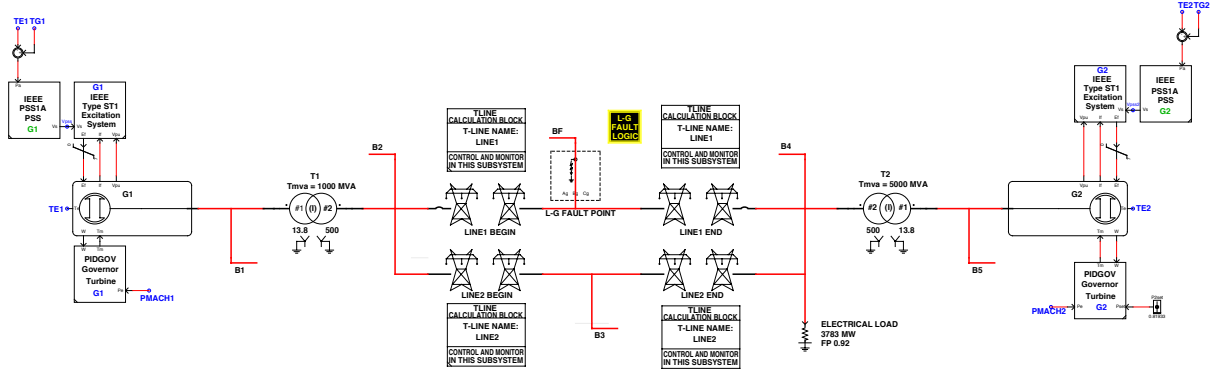


FIGURE 5.2: Implementation in RSCAD-RTDS.

Figure 5.3 presents the experimental setup of the system in RTDS. The measured three-phase voltages of buses 1, 2, 3 and 5 simulated in the RTDS are sent to the PMUs. The estimated synchrophasors are sent via Ethernet in the IEEE protocol C37.118. The sample rate of synchrophasors is 60 cycles/s in protection mode. A GPS satellite clock SEL-2404 is used to timestamp the calculated phasors. All the phasors are received by a computer for further analysis.



FIGURE 5.3: Hardware-in-the-loop implementation in RTDS.

5.4.2 Analysis and comparison of the results

This Section presents the analysis and comparison of the results obtained from the two simulation professional tools. To present this comparison, it has been used the voltages at the all buses of the power system, rotor speed at the generator G1, and the angle θ of the voltage at the bus 1.

Figure 5.4 shows the plots, in both software, of the results of the voltages in the buses of the system. The signals have almost the same behavior, but there are some differences in the values in the first oscillations, whereas in RTDS the value is 1.95 in p.u. at B3, in DIgSILENT PowerFactory is 1.05 p.u. These differences are due to the models used in elements such as the AVR, governors, excitation systems, synchronous machines and transmission lines between the RTDS and DIgSILENT PowerFactory. In addition, the short-circuit produces some oscillations at the beginning and at the end of the event, but as the behavior of the voltages indicated, the system is stable.

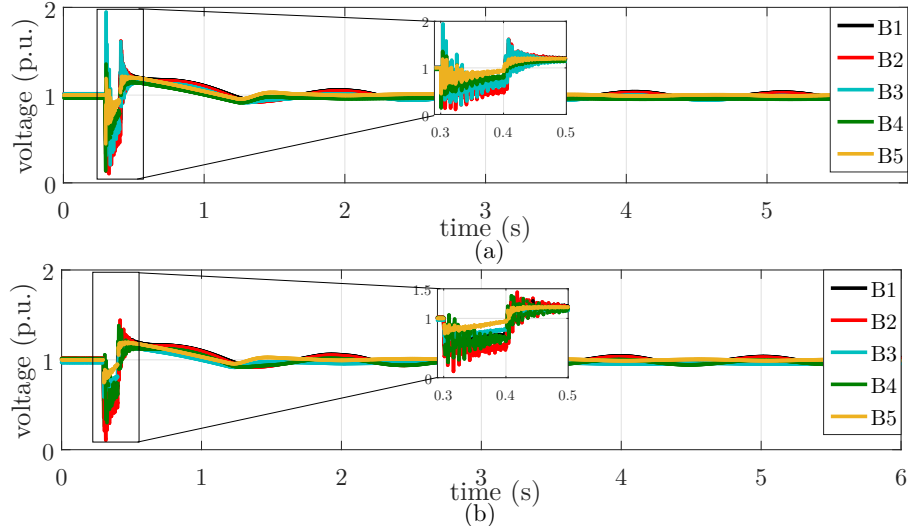


FIGURE 5.4: Voltages in the buses of the power system: (a) RTDS. (b) DIgSILENT PowerFactory.

Figure 5.5 displays the rotor speed of the generator G1. It can be appreciated that both signals in the RTDS and DIgSILENT PowerFactory are almost the same, but in $t = 1.14$ s the speed in the RTDS is 374.1 rad/s, while in DIgSILENT PowerFactory is 374.9 rad/s. In addition, the results suggest that the power system will be able to reach a new steady, without losing of stability after being subjected to a three-phase short-circuit.

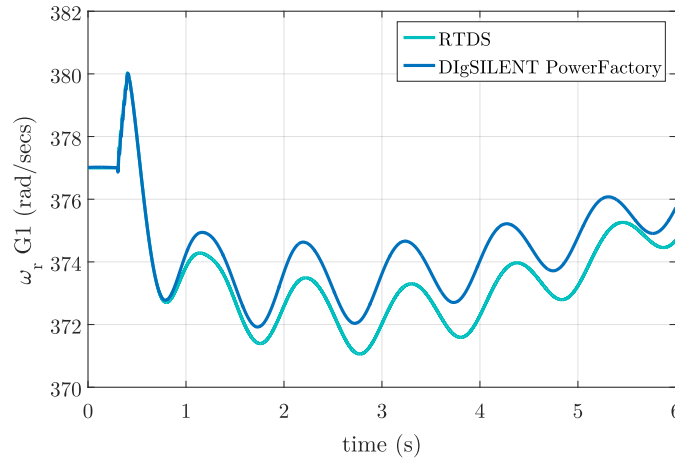


FIGURE 5.5: Rotor speed comparison between two professional tools: (a) RTDS. (b) DIgSILENT PowerFactory.

Figure 5.6 (a) presents the voltage angle θ in bus 1 obtained from the PMUs SEL in radians. While Fig. 5.6 (b), shows the angular difference between bus 1 and bus 5 in degrees and referenced to the generator G1, obtained from the RTDS and the DigSILENT Power Factory, respectively. From Fig. 5.6 (b), it can be observed that signals present the same behavior, but in detail there are some differences. This are because the RTDS waveform was obtained directly from the industrial PMUs, while the DIGSILENT PowerFactory waveform was obtained from the RMS simulation. This signal (Fig. 5.6 (b)) is used to estimate the inertia for the generation unit G1, this because the methodology uses the measurements of the generation bus to be calculated.

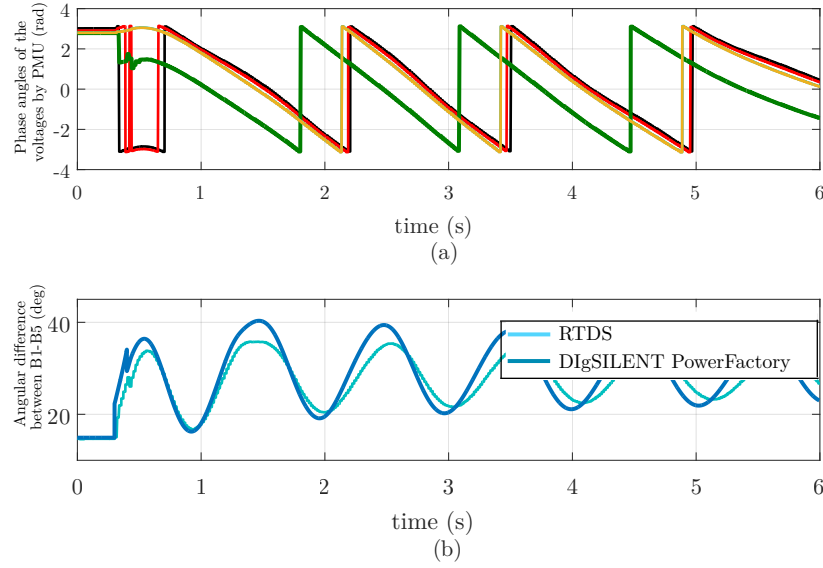


FIGURE 5.6: Voltage synchrophasors: (a) Phase angles of the voltages provided by the PMUs. (b) Angular difference between buses B1 and B5 from RTDS and DigSILENT PowerFactory.

On the other hand, the derivative of the voltage angle θ on the bus follows closely the angular speed of the rotor ω_r as shown in the Fig. 5.7. This signal is used to estimate the inertia value.

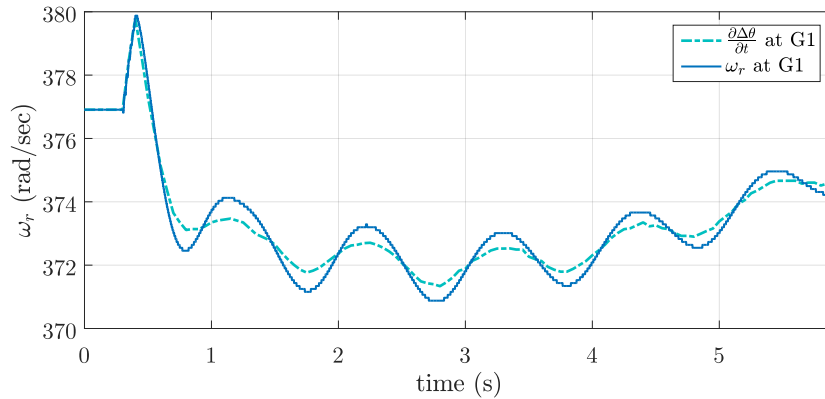


FIGURE 5.7: Rotor speed and derivative of the angle bus in RTDS.

Table 5.2 presents the results of the inertia estimation for this case study. The results obtained demonstrate that there is concordance and are better in comparison with the results reported in [80] - [81], [91], where the error in the estimation is between 0.22% and 41.11%. On

the other hand, reference [74] reports an estimation error of 16%. It is important to mention that is not possible to establish a perfect comparison between the results obtained in this research with the results reported in the literature because the test systems are different; however, the models used and perturbations applied are similar. It is worth mentioning that the estimation errors obtained both in the literature and in this research are compared with previously reported values, and this makes that the comparison is valid and fair and demonstrates that using the methodology presented in this contribution the results obtained are better.

TABLE 5.2: Inertia estimation results in bus 1, three phase short-circuit case.

Simulation tool	H input (s)	H estimated (s)	Absolute Error %
RTDS	3.7	3.8	2.7
DIgSILENT PowerFactory	3.7	3.56	3.78

In order to evaluate the accuracy and robustness of the methodology used in this thesis, another case study was carry-out. In this case study, in the RTDS and in DIgSILENT PowerFactory was used the lumped parameters PI model for the transmission lines. Generator controllers in DIgSILENT PowerFactory were tuning to obtain a similar behavior that RTDS. Table 5.3 provides the results for this case study. The values obtained demonstrate robustness in the methodology to estimate the inertia in the generation units. From the results, it can be noted that the values of the inertia estimated present a considerable accuracy in comparison with the real inertia of the generation units.

TABLE 5.3: Inertia estimation results in bus 1, three phase short-circuit and PI model case.

Simulation tool	H input (s)	H estimated (s)	Absolute Error %
RTDS	3.7	3.79	2.43
DIgSILENT PowerFactory	3.7	3.65	1.35

In agreement with the results obtained in the RTDS and DIgSILENT PowerFactory. It can be observed that the values are similar, this evidence suggests a considerable accuracy of the methodology for the inertia estimation values. Besides, the results validate the performance of the two simulation professional tools. In conclusion, the results and behavior of the signals are slightly different, these are due to the models used in RTDS and DIgSILENT PowerFactory. In the case of the model of the transmission lines, these differences affect the results of the voltages, currents, and the bus angle connected to these elements. Furthermore, the results shown in Table 5.2 and 5.3 show a considerable reliability for the use of the two simulation professional tools.

In addition, the results provided by DIgSILENT PowerFactory offer reasonably performance, due this validation is feasible use this tool to estimate the inertia on large-scale power systems. An example of this affirmation is presented in the next Section.

5.5 Inertia estimation varying P_E

The results obtained using the proposed methodology demonstrate an accurate performance. However, it has been observed that the accuracy of the inertia estimation depends on the increment of the total active power P_E generated by the generation units of the system. In this Section is presented a comparison of the results obtained in DIgSILENT PowerFactory with different values of P_E to estimate the inertia at G1. The results are obtained from the experimental validation of Section 5.4 in the second case study. This procedure uses the measurements prior to a disturbance, using different values of P_E during the first oscillation, hence the inertia can be estimated. Fig. 5.8 shows the behavior of the active power provided by G1 and the inertia estimation when the short-circuit event is applied at the transmission line L1 (Fig. 5.2).

Figure 5.8 presents the results of the inertia estimation when P_E is varying. For this case study, the input inertia at G1 is $H=3.7$ s, the first three approximations are $H=3.57$ s, $H=13.78$ s, and $H=3.13$ s, these results suggest that first approximation has a noticeable accuracy. In addition this Fig. presents the behavior of the inertia-estimation values, but only the first approximation is used. This behavior is due to the changes of P_E in the system. However, it does not mean that the inertia estimation cannot be improved, some factors like the second derivate of the angle at generation bus has an influence on the results, and its value is produced in accordance with the type of the event or disturbance presented in the power system.

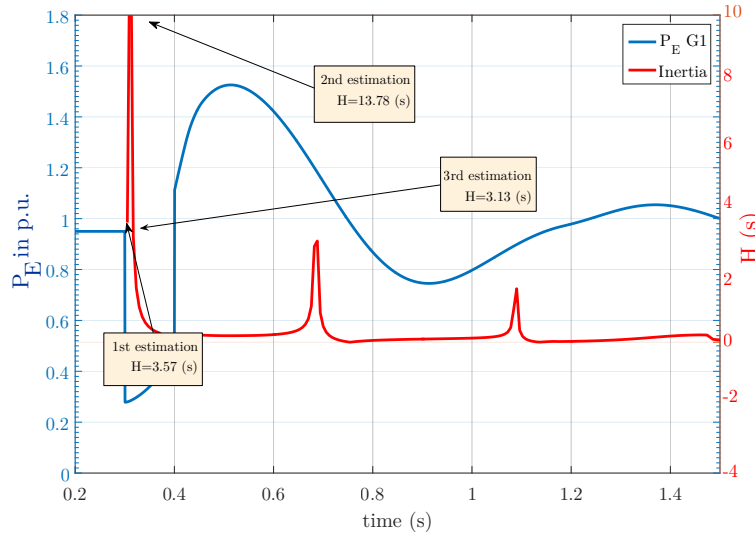


FIGURE 5.8: Active power generated by G1 and behavior of H estimated.

5.6 Inertia estimation of the southeast region of México

An important aspect of this methodology is that it can be applied to estimate the inertia of WPPs. Hence, this Section presents the results of the methodology applied to the Mexican power system, in the area of the Istmo of Tehuantepec, Oaxaca, México, where there is a high penetration of WPPs.

Figure 5.9 shows the system presented in [6], the system is composed of 24 wind farms with the doubly-fed induction generator technology and they are distributed in Ixtepec (14 wind farms, 1,438 MW) and Juchitan (10 wind farms, 782.75 MW), with a total installed capacity of 2,220.75 MW [13].

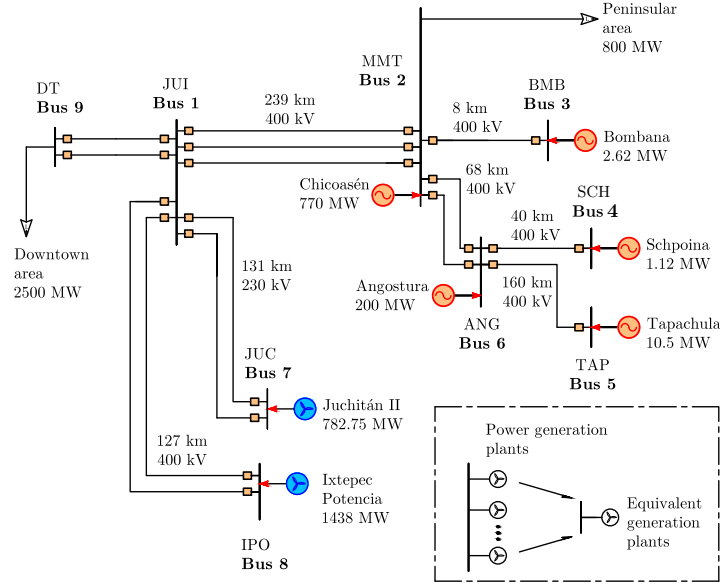


FIGURE 5.9: One-line simplified of southeast zone of México.

Two case studies were carried out in the professional software DigSILENT PowerFactory. In the first case is simulated a generation trip in bus 6, while, the second case presents a load increment in the active power in bus 9.

5.6.1 Generation trip in bus 6

In this case is simulated a generation trip of 200 MW at the bus 6 in $t = 1$ s. The hydropower generation units include their control systems, such as governors [28], AVR [27] and PSS [27]. The WPPs are modeled as reported in [10], [34].

Figure 5.10 shows the active power in p.u. in bus 3 generated by Bombana. For this case study it can be noted that there is an increase in the value of the active power to compensate the trip generation in bus 6. A consideration previously described in the methodology to the inertia estimation, is the detection of the beginning of the disturbance and the peak value of the first angular oscillation (blue window). For this case, the peak value of the active power is 0.52 p.u. in $t = 1.02$ s.

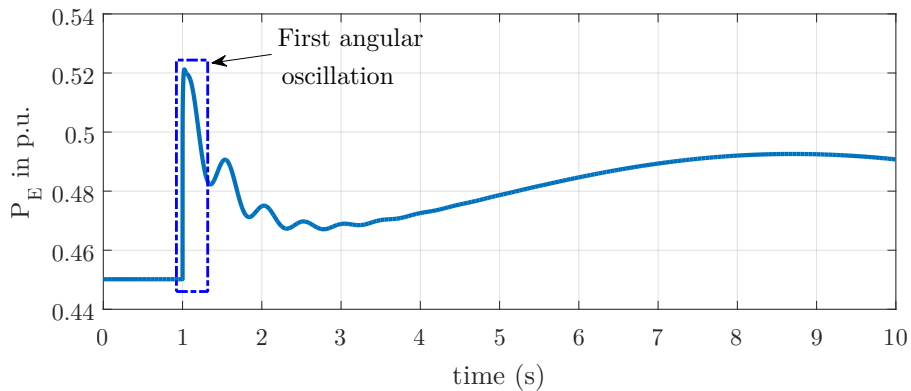


FIGURE 5.10: Active power in p.u. in bus 3 (Bombana): generation trip case.

Table 5.4 summarizes the values of the estimated inertias of the generation units, where H input (s) is the inertia constant which is already known and given by the system operator (CENACE) [28], while H estimated (s) is the inertia obtained using the methodology.

TABLE 5.4: Inertia estimation results, generation trip case.

Power Plants	Generation	H (input)	H (estimated)	Absolute Error %
Bombana	Hydropower	4	3.85	3.75
Chicoasen	Hydropower	4.7	4.62	1.70
Schpoina	Hydropower	3.7	3.71	0.27
Tapachula	Hydropower	4	4.04	1.00
Ixtepec	Wind power	0.00237	0.00236	0.42
Juchitan	Wind power	0.00237	0.00233	1.69

5.6.2 Load increment

In this case study is simulated an increase in the value of the electrical load in bus 9 of 32.5 MW, in $t = 1$ s.

Figure 5.11 illustrates the response of the active power in bus 2 generated by Chicoasen. It can be noted that due the increment of the electrical load, there is an increase from 0.33 p.u. to 0.3392 in p.u. in $t = 1.02$ s, this increment represents 22.5 MW of active power. The peak value is used to the inertia estimation for this generator. Also, there is a minimum of oscillations when the load is increased, as a result mainly of the actions of the control systems of generation units.

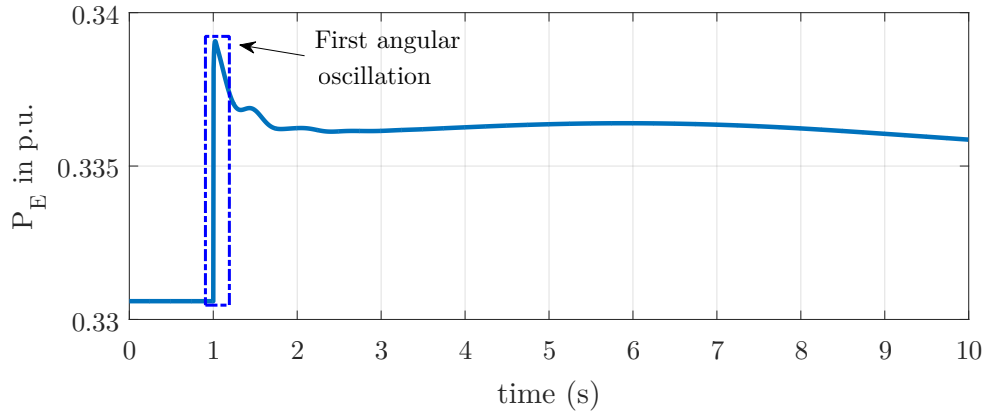


FIGURE 5.11: Active power in p.u. in bus 2 (Chicoasen): load increment case.

Table 5.5 shows the results of the inertia estimation of the generation units. Particularly, it can be observed that there is a few differences in the inertia estimation and the percentage of error has been increased slightly in some power plants in comparison with the case study presented previously.

This is associated to the type of disturbance applied to the power system. For this case, it is a small disturbance. Nevertheless, the results are still good in comparison with the results

reported in the literature, whose values are between 0.22%, 41.11% [80] - [81], [91] , and 16% reported in [74].

TABLE 5.5: Inertia estimation results, load increment case.

Power Plants	Generation	H (input)	H (estimated)	Absolute Error %
Angostura	Hydropower	4	4.08	2.00
Bombana	Hydropower	4	4.03	0.75
Chicoasen	Hydropower	4.7	4.78	1.70
Schpoina	Hydropower	3.7	3.61	2.43
Tapachula	Hydropower	4	4.01	0.25
Juchitan	Wind power	0.00237	0.0023	2.95
Ixtepec	Wind power	0.00237	0.00228	3.80

5.7 Conclusions

This Chapter describes the experimental validation and implementation of a methodology for inertia estimation. This methodology is based on the equation of oscillation and it uses measurements of the angle of bus, detection of the disturbance, peak value of the disturbance, and the knowledge of active power flow in the generation units.

A comparison between the results obtained with two professional tools (RTDS and DIgSILENT PowerFactory) was carried out in order to demonstrate the accuracy, performance and robustness of the methodology. The RTDS is used for the validation of the methodology used, while DIgSILENT PowerFactory is used to calculate the inertia estimation of a large-scale power system, because the RTDS presents a high requirement about the physical components like microprocessors to implement a large-scale power system, in addition, their cost is very expensive.

Also, the results of the inertia estimation of the area of the Istmo of Tehuantepec, México were analyzed and presented. From the obtained results it can be concluded that the methodology can be applied to wind power plants. The estimation of generator inertia is accurate when a generation trip occurs in the system. However, a disadvantage of this methodology is that the accuracy is reduced when small perturbations are applied to the system. This means that the inertia estimation also depends on measurements of the disturbances and their natures.

From the results presented in this Chapter, it can be concluded that despite of the differences between the case studies analyzed in terms of disturbances, network topology, controllers, professional tools, and modeling of the elements, the methodology presents a great robustness to obtain the inertia estimations, i.e., the results of the inertia estimation present a considerable accuracy with respect to the real inertia of the generation units.

With this methodology is possible to estimate the inertia in generation units, such as wind power plants, and set the references of the synthetic inertial controllers to improve frequency stability.

Chapter 6

Conclusions and future work

6.1 General conclusions

Mathematical models of generation units such as hydropower and WPPs, and their controllers have been presented. These models include the dynamic behavior (electric and mechanical) of the generation units. Salient-poles synchronous machine model is used for hydropower plants, while DFIG model is for WPPs. Moreover, specific control systems such as AVR, PSS, turbine-governor model and wind turbine, converters and aerodynamic control are implemented for hydropower and wind power generation units, respectively. These models are used with a network under study and provide relevant information about which type of generation units and their controllers are implemented in a real system.

Besides, all the mathematic models presented have been implemented in an equivalent model of the Mexican electric power system, specifically in the southeast region. This model was implemented in the software DIgSiLENT PowerFactory. It includes the main components such generation units and their controllers, transformers, transmission lines, and electrical loads. The equivalent model has important purposes, firstly, is to reproduce the present problems in the mentioned region such as voltage support, congestion in transmission lines and frequency regulation; moreover, it is used to carry-out all the study cases in this thesis, in steady and dynamic states (RMS simulations); also, implement power electronic devices and methodologies that provide solutions to the mentioned problems. The results obtained can be used in the planning and control strategies to keep the power system stability or determinate if they are around the limits of the Mexican grid code.

A new graphical probability representation has been proposed and used to evaluate the impact of WPPs penetration in the equivalent of the Mexican power system. This representation is a novel expansion of the application of the MPI to evaluate the impact of WPPs in the system, by a probabilistic impact assessment. It provides the region with highest and lowest probability of operating conditions, such as the stochastic behavior of electrical loads and WPPs, it provides the probability of these conditions to be present in the power system, lets to carry-out several analyses in one single graphic, and it can be used as a tool to determinate an optimal location and selection of capacity of FACTS devices, quantification of the probability given an operating condition, among others.

The impact of FACTS devices and the comparative among their performance has been also presented. The simulation results indicate that the application of FACTS devices depends on

the problem and its location in the power system. In the case of the congestion problem in the transmission lines, results demonstrate the effectiveness of the TCSC and UPFC; these devices allow control the active power in order to keep the same active power when the demand in the load increases, however, STATCOM produces an increment in active power and congestion problems in the transmission line. In the case of voltage regulation, STATCOM and the UPFC provide a great performance to keep the voltage in buses in the reference (1 p.u.). Therefore, simulation results about the UPFC show this device improves the congestion and voltage problems, this is because this device is a combination of the shunt and series compensators.

To improve frequency-stability issues in power systems, a methodology for inertia estimation is presented. This methodology is based on the equation of oscillation and it uses measurements of the angle of the bus, detection of the disturbance, peak value of the disturbance, and the knowledge of active power flow in the generation units to estimate an inertia constant in generation units. This methodology was applied in the equivalent model of the Mexican electric power system. From results obtained, the inertia estimation results present good accurate regarding the inertia input, being the high percent of error of 3.75% overall the case studies. According to the case studies, inertia estimation also depends on measurements of the disturbances and their natures.

Finally, all results obtained in this thesis are valuable in the diagnostic, improvement and research to provide solutions in actual and future problems in power systems where there is a high penetration of renewable energies like wind power energy.

6.2 Future work

According to the research work presented in this thesis. The author proposes the following directions:

- DFIG technology is used to represent the WPPs, due this technology is mostly used in the network under study [10], [28]. Although there are few WPPs with FSIG technology in this region, as result of this, in the case to represent a high detail about the technology of WPPs installed, FSIG must be included.
- The main WPPs have been included in the equivalent of the network under study. In the future, more wind power parks will be installed in the different locations of the southeast region [1]. They must be included in the equivalent model with the aim to represent changes in the configuration network.
- The network equivalent is presented for the first time, so that, the information of the topology and the elements of the network can be updated with high detail in the future.
- The GPR can be expanded to any kind of RES, the condition is to include its model with its stochastic behavior (specific-probabilistic distribution).
- In the first stage of this thesis it has been implemented some FACTS devices such as TCSC, STATCOM and UPFC, in the future more FACTS devices such as Static Synchronous Series Compensator (SSSV), Thyristor Controlled Phase Shifting Transformer (TCSPT), Thyristor Controlled Reactor (TCR).
- A High Voltage Direct Current (HVDC) can be modeled and included in the equivalent model of the southeast region of México, the results obtained of this device could be

compared with the protect 303 LT in México, that it is going to be in operation in the 2021 year, and its purpose is transporting the generated power of the mentioned region to network center of the country.

- For purposes of dynamic simulations in this thesis, FACTS devices are modeled by simplified models that reproduce their corresponding controller behavior to the fundamental frequency. Power electronic converters and firing control systems are not modeled due FACTS devices assume simplifications. To represent a high detail behavior in power electronic converters and control systems, FACTS devices must include the detail model of these elements.
- In case of the inertia estimation, all case studies were carried-out with the knowledge of parameters like time of the beginning of the disturbance and peak value of first angular oscillation. Being these areas a gap to research, due to the complexity to obtain these measurements with a high accuracy, as result of the delay time in detection and send of the signals by the measurement instruments. Furthermore, the results are influenced by the second derivate of the angle bus, in this way, alternative methodologies to obtain this approximation can be used to improve the inertia estimation. Finally, a technique for the detection of perturbation can be development, this because the inertia estimation methodology uses the knowledge of the time when the perturbation starts to determinate the peak value of the first angular oscillation.

Appendix A

Parameters of the hydropower and wind power plants controllers

Tables A.1 to A.11, and Fig A.1 show the parameters used in the main components of the test systems.

TABLE A.1: Parameters of the governor water turbine model of the hydropower plant (HYGOV).

Parameter	Value	Parameter	Value
A_t	1 (p.u.)	qNL	0.08 (p.u.)
D_{turb}	0.5 (p.u.)	T_f	0.05 (s)
R	0.1(p.u.)	T_g	0.5 (s)
r	0.3 (p.u.)	T_r	5 (s)
G_{max}	0.95 (p.u.)	T_w	4 (s)
G_{min}	0.76 (p.u.)	$VELM$	0.2 (p.u.)

TABLE A.2: Parameters of the AVR model used in the hydropower plant (IEEET1).

Parameter	Value	Parameter	Value
E_1	2.47 (p.u.)	T_A	0.04 (s)
E_2	4.5 (p.u.)	T_f	1 (s)
K_A	400 (p.u.)	T_E	0.8 (s)
K_E	1 (p.u.)	T_r	0 (s)
K_f	0.03 (s)	Vr_{Max}	7.3 (p.u.)
$SE(E1)$	2.47 (p.u.)	Vr_{Min}	-7.3 (p.u.)
$SE(E2)$	0.47 (p.u.)		

TABLE A.3: Parameters of the PSS model used in the hydropower plant (PSS2A).

Parameter	Value	Parameter	Value
M	5 (-)	T_2	0.03 (s)
N	1 (-)	T_3	0.15 (s)
T_{w1}	2 (s)	T_4	0.03 (s)
T_{w2}	2 (s)	T_6	0 (s)
T_{w3}	2 (s)	T_7	2 (s)
T_{w4}	0 (s)	T_8	0.5 (s)
K_{s1}	10 (p.u.)	T_9	0.1(s)
K_{s3}	1 (p.u.)	VST_{MAX}	0.1 (p.u.)
T_1	0.15 (s)	VST_{MIN}	-0.1 (p.u.)

TABLE A.4: Parameters of the Bii Nee Stipa II wind park.

Parameters of the DFIG	
Model:	G52-800
Type:	Doubly-fed induction generator
Capability:	800 kW
Voltage:	690 V
Frequency:	50-60 Hz
Variable speed:	14.2-26.1 r.p.m.
Poles:	4
Power factor:	0.94_{cap} - 0.94_{ind}
Rotor diameter:	52 m

TABLE A.5: Parameters of the internal transformer.

Internal transformer	
Capability:	900 kVA
Connection:	$\Delta - \Delta$
Cooling:	OA
Voltage:	690 V/34.5 kV

TABLE A.6: PQ control of wind power plants.

Parameter	Value
δ_U	0.1 (p.u.)
K_p	4 (p.u.)
K_q	4 (p.u.)
T_{back} delay	0.001 (s)
T_p	0.1 (s)
T_q	0.1 (s)
T_u delay	0.01 (s)

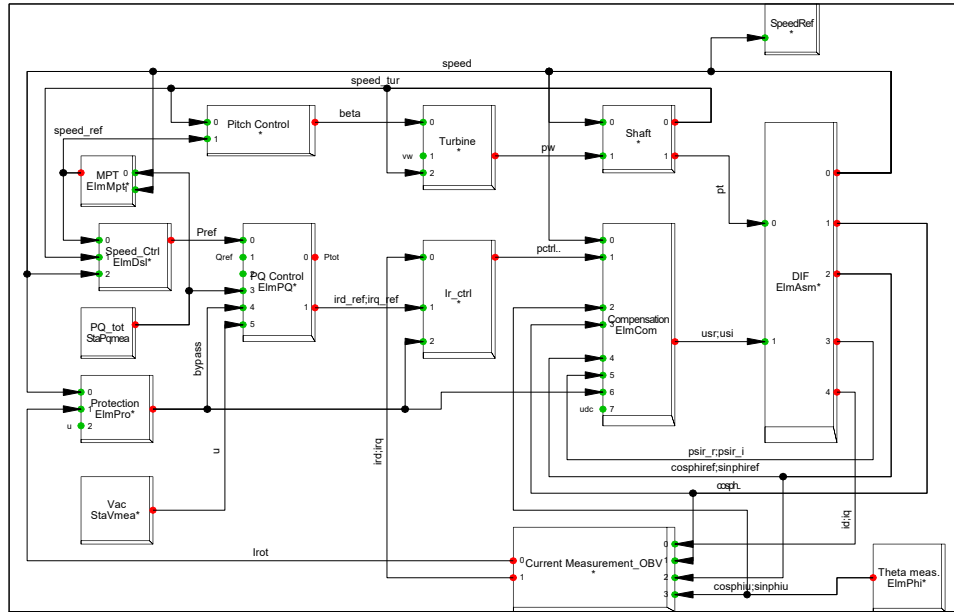


FIGURE A.1: Rotor side converter control.

TABLE A.7: Turbine parameters of the wind power plants.

Parameter	Value
β	0 (deg)
ρA_r	0.00159 (kg/m^3)
R	56 m

TABLE A.8: Pitch control parameters of the wind power plants.

Parameter	Value
β_{max}	27 (deg/s)
β_{min}	0 (deg/s)
$d\beta_{max}$	10 (deg/s)
$d\beta_{min}$	-10 (deg/s)
K_{ip}	25 (p.u.)
K_{pp}	150 (p.u.)
ω_{max}	1.2 (p.u.)
T_p	0.01 (s)

TABLE A.9: Shaft parameters of the wind power plants.

Parameter	Value
D_{tg}	1.5 (Nms/rad)
H	4.02 (s)
K_{tg}	80.27
om_{base}	1.745
Pg_{base}	1.313751 (p.u.)
Pt_{base}	1.5 (p.u.)
RPM_{nom}	18 (rpm)

TABLE A.10: Speed controller parameters of the wind power plants.

Parameter	Value
dp_{max}	99 (p.u./s)
dp_{min}	-99 (p.u./s)
Ki_{trq}	0.1 (1/s)
Kp_{trq}	1
p_{max}	1.1 (p.u.)
p_{min}	0.1 (p.u.)
T_{pc}	0.5 (s)

TABLE A.11: Current controller rotor side parameters of the wind power plants.

Parameter	Value
K_d	0.0496 (p.u.)
K_q	0.0496 (p.u.)
T_d	0.0128 (s)
T_q	0.0128 (s)

Appendix B

Southeast region parameters of the Mexican electric system

Tables B.1 to B.6 show the parameters used in the generation units and transmission lines of the test system.

TABLE B.1: Hydrogeneration system parameters, part I.

Generator	MW	MVA	kV	Power Factor	H (s)	$r_s(\Omega)$	T'_d (s)	T'_q (s)
Angostura	354.96	1000	400	0.9	4.1	0	8.87865	0.98498
Bombana	2.62	5.82	400	0.9	4	0.0504	6	1
Chicoasen	776.16	2667	400	0.9	4.7	0.005	9.10583	0.99226
Malpaso	530.28	1200	400	0.9	4.7	0	8.58344	0.88518
Peñitas	234.36	467	400	0.9	4	0	5.28187	1
Schpoina	1.12	2.5	400	0.9	4	0.0504	6	1
Tapachula	10.5	23.4	400	0.9	2	0	1	1
Temascal II	177.03	394	400	0.9	4	0	8.67146	0.93656

TABLE B.2: Hydrogeneration system parameters, part II.

Generator	T''_d (s)	T''_q (s)	X_d (p.u.)	X_q (p.u.)	X'_d (p.u.)	X'_q (p.u.)
Angostura	0.00738	0.03553	1.74918	1.67508	0.18498	0.39129
Bombana	0.03	0.03	1.5	0.75	0.256	0.3
Chicoasen	0.05808	0.06926	1.60852	1.5432	0.31878	0.46126
Malpaso	0.4931	0.6009	1.53705	1.39304	0.28915	0.41456
Peñitas	0.0681	0.0357	0.8	0.52	0.3	0.3
Schpoina	0.03	0.03	1.5	0.75	0.256	0.3
Tapachula	0.05	0.05	2	2	0.3	0.3
Temascal II	0.01636	0.03757	1.6693	1.59436	0.21067	0.37055

TABLE B.3: Hydrogeneration system parameters, part III.

Generator	X''_d (p.u.)	X''_q (p.u.)
Angostura	0.13874	0.2
Bombana	0.168	0.184
Chicoasen	0.23908	0.2
Malpaso	0.21686	0.2
Peñitas	0.1875	0.2
Schpoina	0.168	0.168
Tapachula	0.2	0.2
Temascal II	0.158	0.2

TABLE B.4: Wind power plants parameters, part I.

Generator	MW	MVA	kV	Power Factor	kgm^2	r_s (p.u.)	X_m (p.u.)	X_s (p.u.)
Ixtepec	1,438	1,598	0.69	0.9	54	0.0159	7.99	0.0922
Juchitan	782.75	870	0.69	0.9	54	0.0159	7.99	0.0922

TABLE B.5: Wind power plants parameters, part II.

Generator	Rra (p.u.)	XrA (p.u.)
Ixtepec	0.0012	0.13
Juchitan	0.0012	0.13

TABLE B.6: Transmission lines parameters.

Bus		Bus	Length (km)	kV	R (Ω/km)	X (Ω/km)	B' ($\mu S/\text{km}$)
1	–	2	220	400	0.003	0.1673	0.00215
1	–	6	160	400	0.000128	0.001673	0.00215
1	–	9	35	400	0.000128	0.001673	0.00215
1	–	10	140	230	0.0017	0.12	0.00215
2	–	3	120	400	0.000128	0.001673	0.00215
3	–	4	104	400	0.000128	0.001673	0.00215
3	–	5	32	230	0.0017	0.12	0.00215
3	–	7	60	400	0.0328	0.001673	0.00215
6	–	7	239	400	0.003	0.1673	0.00215
6	–	9	154	400	0.000128	0.001673	0.00215
6	–	12	131	230	0.02	0.001	0.00175
6	–	13	127	400	0.021	0.12	0.00215
7	–	8	8	400	0.0328	0.001673	0.00215
7	–	14	68	400	0.0328	0.001673	0.00215
14	–	15	40	400	0.0328	0.001673	0.00215
14	–	16	160	400	0.0328	0.001673	0.00215

Appendix C

Graphical Probabilistic Representation: transmission lines parameters

Table C.1 shows the parameters used in the transmission lines of the test system.

TABLE C.1: Transmission line parameters.

Bus		Bus	Length (km)	kV	R (Ω/km)	X (Ω/km)	B' ($\mu S/\text{km}$)
2	–	1	220	400	0.003	0.1673	0.00215
2	–	3	131	230	0.02	0.001	0.00175
2	–	4	127	400	0.021	0.12	0.00215

Appendix D

FACTS devices parameters

Tables D.1 to D.8 and Figures D.1 to D.11 show the parameters and models used in FACTS devices used in test system.

Thyristor-Controlled Series Compensator

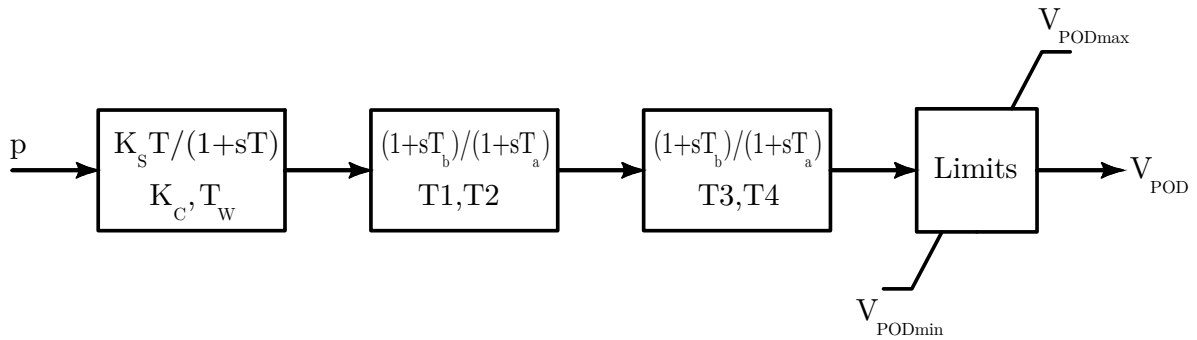


FIGURE D.1: POD scheme controller.

TABLE D.1: Parameters of the V_{POD} controller.

Parameter	Value	Parameter	Value
K_c	10 (p.u.)	$T3$	0.08 (s)
T_w	5 (s)	$T4$	0.5 (s)
$T1$	1.1 (s)	V_{PODmin}	0 (p.u.)
$T2$	0.05 (s)	V_{PODmax}	1 (p.u.)

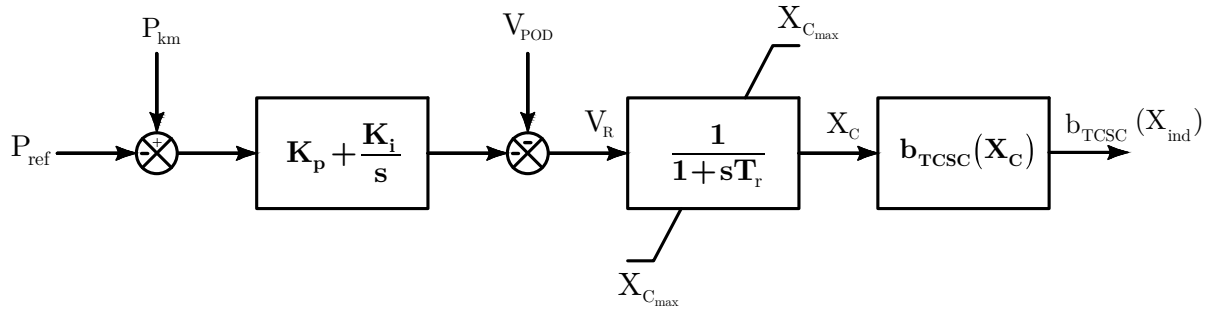


FIGURE D.2: Control block diagram of the TCSC.

TABLE D.2: Parameters of the TCSC controller.

Parameters	Value
E	0.00001 (p.u.)
K_i	1 (p.u.)
K_p	-0.001 (p.u.)
T_r	-0.04 (s)
X_{cap}	0.00276311 (p.u.)
X_{cmax}	0.6801429 (p.u.)
X_{cmin}	0.3662308 (p.u.)
X_{km}	0.4761 (p.u.)
Z_b	80 (Ω)

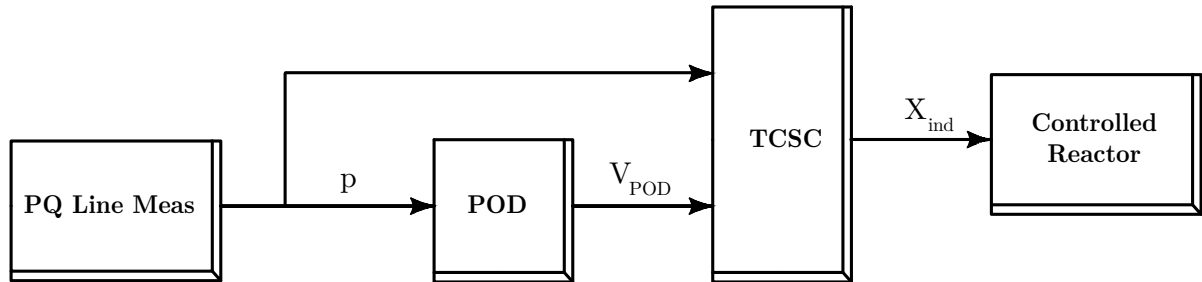


FIGURE D.3: Implementation of control blocks of TCSC in DigSILENT.

Static Synchronous Compensator

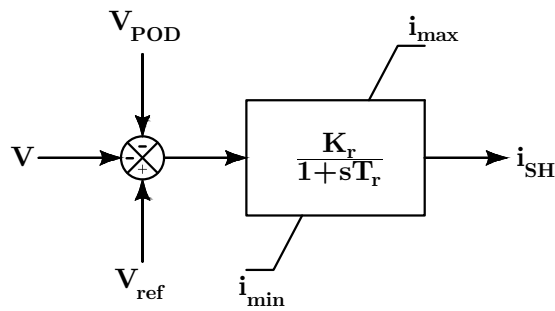


FIGURE D.4: Control block diagram of the STATCOM.

TABLE D.3: Parameters of the STATCOM controller.

Parameter	Value
i_{max}	1 (p.u.)
i_{min}	-1 (p.u.)
K_r	100 (p.u.)
T_r	0.05 (s)

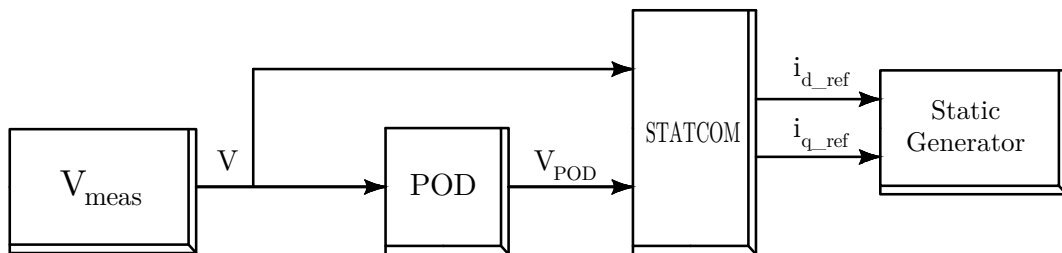
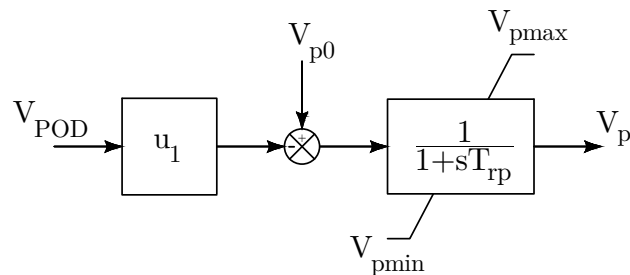


FIGURE D.5: Implementation of control blocks of STATCOM in DIgSILENT.

Unified Power Flow Controller

FIGURE D.6: Implementation of the series controller V_p of the UPFC in DIgSILENT.TABLE D.4: Parameters of the series controller V_p of the UPFC.

Parameters	Units
T_{rp}	-500 (s)
u_1	1 (1=on, 0=off)
$v_{p,max}$	1 (p.u.)
$v_{p,min}$	0 (p.u.)

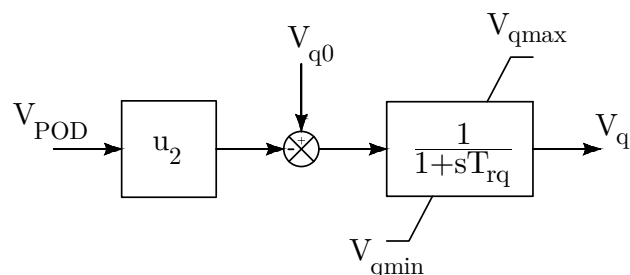
FIGURE D.7: Implementation of series controller V_q of the UPFC in DIgSILENT.

TABLE D.5: Parameters of the series controller V_q of the UPFC.

Parameters	Units
T_{rq}	-5,678 (s)
u_2	1 (1=on, 0=off)
v_{q_max}	1 (p.u.)
v_{q_min}	-1 (p.u.)

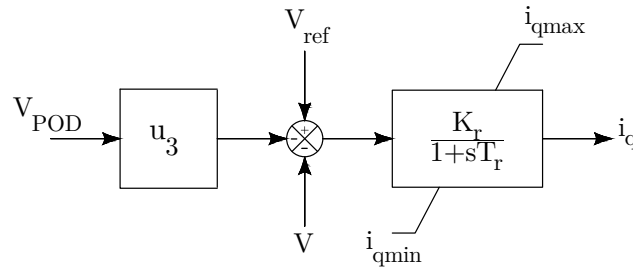


FIGURE D.8: Implementation of shunt controller of the UPFC in DIgSILENT.

TABLE D.6: Parameters of shunt controller of the UPFC.

Parameter	Value
i_{qmax}	1 (p.u.)
i_{qmin}	-1 (p.u.)
K_r	200 (p.u.)
T_r	1 (s)
u_3	1 (1=on, 0=off)

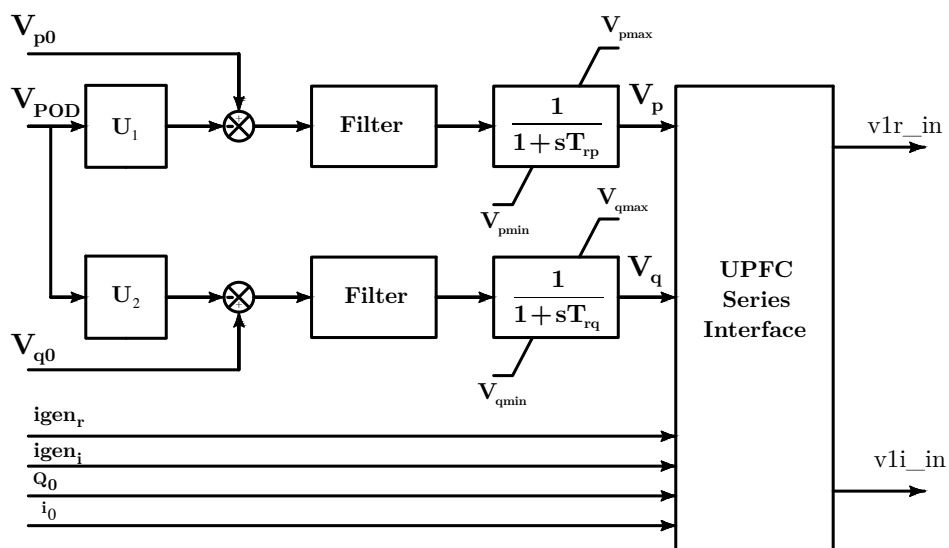


FIGURE D.9: Control block diagram of the series converter of the UPFC.

TABLE D.7: Parameters of the series converter of the UPFC.

Parameter	Value	Parameter	Value
T_{rp}	-500 (s)	v_{pmax}	1 (p.u.)
T_{rq}	-5,678 (s)	v_{pmin}	0 (p.u.)
u_1	1 (1=on, 0=off)	v_{qmax}	1 (p.u.)
u_2	1 (1=on, 0=off)	v_{qmin}	-1 (p.u.)
		X	0.0001 (p.u.)

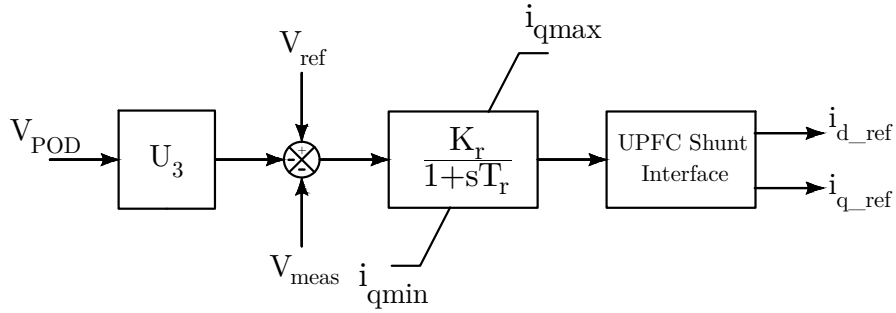


FIGURE D.10: Control block diagram of the shunt converter of the UPFC.

TABLE D.8: Parameters of shunt converter of the UPFC.

Parameter	Value
i_{qmax}	1 (p.u.)
i_{qmin}	-1 (p.u.)
K_r	200 (p.u.)
T_r	1 (s)
u_3	1 (1=on, 0=off)

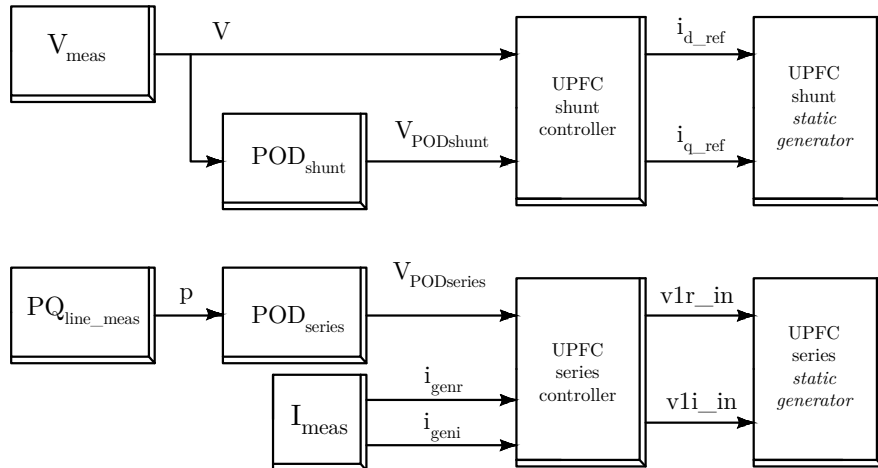


FIGURE D.11: Implementation of control blocks of UPFC in DIgSILENT.

Appendix E

RTDS power system parameters

Tables E.1 to E.6 show the parameters and models used in the RTDS used in test system.

TABLE E.1: Parameters of the governor (PIDGOV) used in the RTDS.

Parameter	Value	Parameter	Value
A_{tw}	1 (p.u.)	P_2	0.5 (p.u.)
D_{turb}	0 (p.u.)	P_3	1 (p.u.)
G_0	0 (p.u.)	P_N	0 (p.u.)
G_1	0.25 (p.u.)	R_{perm}	0.05 (p.u.)
G_2	0.5 (p.u.)	T_a	0.000001 (s)
G_{max}	1.2 (p.u.)	T_b	0.3 (s)
G_{min}	0.01 (p.u.)	T_{reg}	0 (s)
K_d	0 (p.u./s)	T_w	3 (s)
K_i	0.105 (p.u./s)	Vel_{max}	0.1 (p.u./s)
K_p	1.163 (p.u./s)	Vel_{pmin}	-0.1 (p.u./s)
P_1	0.25 (p.u.)		

TABLE E.2: Parameters of the AVR model (EXST1) used in the RTDS.

Parameter	Value	Parameter	Value
K_a	200 (p.u.)	T_f	0.1 (s)
K_c	0 (p.u.)	T_r	0.02 (s)
K_f	0.001 (p.u.)	Vi_{max}	10 (p.u.)
T_a	0.001 (s)	Vi_{min}	-10 (p.u.)
T_b	0 (s)	Vr_{max}	20 (p.u.)
T_c	0 (s)	Vr_{min}	0 (p.u.)

TABLE E.3: Parameters of the PSS model (STAB2A) used in the RTDS.

Parameter	Value	Parameter	Value
H_{lim}	0.05 (p.u.)	K_4	0.1 (p.u.)
inv	-1 (cs)	K_5	1 (p.u.)
IPB	1 (MVA)	T_2	2 (s)
K_2	1 (p.u.)	T_3	0.01 (s)
K_3	0.2 (p.u.)	T_5	0.01 (s)

TABLE E.4: Parameters of the synchronous generators.

Parameter	Value	Parameter	Value
H	3.7 (s) G1/G2	T'_{d0}	4.452871 (s)
kVA	13.8	X''_d	0.252 (p.u.)
MVA	1,000 G1/5,000 G2	X''_q	0.253 (p.u.)
$P.F.$	0.94 (p.u.)	X'_d	0.296 (p.u.)
$rstr$	0.0028544 (p.u.)	X_d	1.305 (p.u.)
T''_{d0}	0.06225397 (s)	X_l	0.18 (p.u.)
T''_{q0}	0.1 (s)	X_q	0.474 (p.u.)

TABLE E.5: Parameters of the transmission lines.

Parameter	Value	Parameter	Value
R	0.0175 (Ω/km)	B'	5.025292 ($\mu S/km$)
R'_0	0.2758 (Ω/km)	B'_0	3.127895 ($\mu S/km$)
X'	0.329377 (Ω/km)	Length	350 (km) L1/L2
X'_0	1.213911 (Ω/km)	kV	500

TABLE E.6: Electrical load parameters.

MW	MVar
3783	1585

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