Observer–based Damping Low Frequency Oscillations for a SMIB system

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Abstract: Low-frequency oscillations can provoke serious stability problems in power systems. Therefore the generation units are equipped with several auxiliary controls like the Automatic Voltage Regulators and the Power System Stabilizers. Unfortunately, the operation of these devices relies on the knowledge of some variables that usually are not available for measurement, leading to the necessity to include dynamic state estimators into the scheme. In this paper, a novel nonlinear observer for a Single Machine Infinite Bus system is proposed whose design is based on the well–known third order (Flux Decay) model for the synchronous generator. Although the main contribution is the establishment of the formal proof for its convergence (stability) properties, this result is complemented by showing the usefulness of the proposed scheme in a numerical evaluation, illustrating that a classical Power System Stabilizer fed with the estimated variables achieves the objective of damping low frequency oscillations for the aforementioned system.

Keywords: Electromechanical oscillations, transient stability, non-linear observer, power system stabilizer, automatic voltage regulator.

1. INTRODUCTION

Nowadays low frequency power system oscillations represent a classical stability problem due to the fact that these small magnitude disturbances can induce serious transient instability problems, even when the system operates in steady–state since this undesirable behavior is invariably present in every operation condition (Sánchez Tello (1988)).

The modern way to deal with the aforementioned problem considers the use of Flexible AC Transmission Systems (FACTS), like the Static VAR Compensator (SVC); the aim is to take advantage of the capability of these power electronic based devices to exhibit high speed responses that allow to quickly compensate the disturbances (Wang and Swift (1997)). Indeed, the power electronic technology evolution makes of this alternative a profitable option to establish new solutions for power system stability problems.

In spite of the advantages of the power electronic based solution, its implementation still imposes some problems. Thus, the traditional method to damp the power system oscillations appears as the more viable and reliable option to deal with this problem. It is based on the traditional synchronous machines regulators given by the Power System Stabilizer (PSS) which is an ancillary control to the Automatic Voltage Regulator (AVR) that, in its turn, defines the primary voltage control for synchronous machine.

Concerning the control schemes currently used for both, the AVR and the PSS, the usual approach is based on the use of classical linear controllers (Gomes Jr et al. (2018), Guesmi et al. (2018), Yu and Li (1990)) which are tuned using techniques as pole assignment or those based in the frequency response of the system. Due to hierarchical structure considered for the operation of the different controllers (Ilic and Liu (2012)), they have the necessity to use local measurements that must be available for a proper operation. The main topic approached in this paper refers to this situation, in particular the considered problematic refers to the case when some signals which are necessary to know for the operation of the controllers are not available for measurement.

Several attempts can be found in the literature to deal with the lack of measurements problem for damping the power system oscillations. Just to mention a couple that illustrate the most recurrent solutions, in (Zolotas et al. (2007)) it is proposed a LQG control for a Thyristor-Controlled Series Compensator (TCSC) Single Machine Infinite Bus (SMIB) system using a Kalman filter to estimate the system state, and in (Rivera et al. (2018)) a dynamic state estimator for a PSS implementation is presented to approach the damping of inter-area oscillations. In both cases, linear models of the considered system are used for the design, making the solution a valid alternative only around a given operation condition.

One alternative that can be used in order to enhance the operation conditions for a given dynamic state estimator is the use of nonlinear models for the considered power system. Evidently, the design becomes more complicated, in particular if the convergence (stability) properties of the scheme are formally (mathematically) established. Fortunately, the available design techniques for nonlinear observers from the dynamical nonlinear systems literature make possible to propose new observation schemes to deal with the damping oscillations problem.

In this paper a novel nonlinear observer for a SMIB system is proposed. For its design it is considered the well–known third order (flux decay) model of the synchronous generator and is assumed that only one state, the rotor angle, is available for measurement leaving to the observer the task of estimating both the angular velocity and quadrature voltage states. In addition to formulate the mathematical stability properties of the proposed scheme, its usefulness is illustrated by showing, in a numerical context, that a classical PSS achieves its objective when is fed with the estimated states provided by the reported contribution.

The rest of the paper is organized in the next way: First, some preliminary theory that is necessary to understand the main result is presented. Later on, some oscillation theory, synchronous machine regulators structure and power system stability concepts are discussed to continue with the description of the main result of the paper, namely, the observer design that is used to estimate the synchronous machine non-measurable states. Finally, the numerical evaluation results are introduced. The paper is ended with some concluding remarks.

2. PRELIMINARIES

In this section some concepts required for the proper development of the main contribution of the paper are presented.

2.1 Oscillations in power system.

In this paper the considered oscillations that may cause instability in the power systems correspond to the electromechanical kind. These can be divided into two types, namely, local and inter-area oscillations. The former is associated to the generator units, in this case, the rotor angle of the machines oscillates with respect to the whole electric power system and are known as local mode oscillation because the disturbance effect can be seen in the specific generators. These oscillations do not affect the power system, they are usually present in SMIB systems with a frequency around $1-2[Hz]$ depending on the transmission line impedance. The latter kind is more complex since its effect involves several generator units that are connected by transmission lines. The oscillation frequency goes from 0.1 to $0.5[Hz]$.

The power system stability analysis is based on in the effect that the disturbances have into the power system variables, in (Kundur et al. (2004)) is presented a classification about the electric power system stability. In particular, for rotor angle stability case the following definition is established

Definition 1. (Rotor angle stability). It refers to the power system ability to keep on synchronised after some disturbance effect. In other words, the power system has rotor stability if it is able to reconstruct the equilibrium between the electromagnetic and mechanic torque in every machine that is connected in a power system.

The rotor angle instability is a problem that occurs when the power system does not have the enough damping to absorb the electromechanical oscillations This damping may be better achieved through some control application and compensation techniques.

2.2 Single machine infinite bus (SMIB) power system

An electric power system represents the generator units interconnection with load areas through transmission lines. The power system structure can be represented by a SMIB which is showed in the Figure 1. The infinite bus is the Thevénin reduction of the whole electric network and it is represented with a constant frequency and magnitude voltage source.

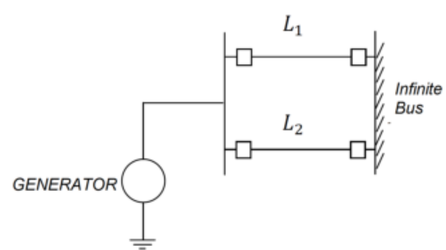

Fig. 1. Single machine infinite bus, where L_1 and L_2 are the transmission lines.

For this work it is used a third-order mathematical model of a SMIB system given by Sauer and Pai (1998)

$$\begin{aligned}\dot{\delta} &= \omega_s v - \omega_s \qquad (1)\\ \dot{v} &= \frac{T_m}{2H} - b_1 E_q' \sin(\delta) + b_2 \cos(\delta)\sin(\delta) - b_3(v-1)\\ \dot{E}_q' &= -b_4 E_q' + b_5 \cos(\delta) + \frac{E_{fd}}{T_{d0}'}\end{aligned}$$

where the state variables are $x_1 = \delta$ which is the rotor angle, $x_2 = v$ that is the normalized angular speed and $x_3 = E_q'$ is the quadrature-axis component of internal voltage, the model parameters are given by the next expressions

Parameter	Definition
b_1	$\frac{1}{2H}\left(\frac{E_B}{X_q+X_{ep}}+\frac{(X_q-X_d')E_B}{(X_d'+X_{ep})(X_q+X_{ep})}\right)$
b_2	$\frac{1}{2H}\left(\frac{(X_q-X_d')E_B^2}{(X_d'+X_{ep})(X_q+X_{ep})}\right)$
b_3	$\frac{D\omega_s}{2H}$
b_4	$\frac{1}{T_{d0}'}\left(1+\frac{X_d-X_d'}{X_d'+X_{ep}}\right)$
b_5	$\frac{1}{T_{d0}'}\left(\frac{(X_d-X_d')E_B}{X_d'+X_{ep}}\right)$

which are assumed known and positive. It is also assumed that the mechanical power is constant and the field voltage is separated in two terms, a constant voltage E and an additional signal u which stands for the control signal used to deal with the perturbantion. In the next table are presented the SMIB's physical parameters

Parameters	Symbol
Inertia	H
Nominal frequency	ω_s
Synchronous reactance	X_d
Transitory reactance	X_d'
Transitory time	T_{d0}'
Mechanical torque	T_m
Damping factor	D
Infinite bus voltage	E_B
Line reactance	X_E

3. OBSERVER DESIGN

In this section the main result of the paper is presented, namely: The design of a nonlinear observer for a class of nonlinear dynamical systems which is specialized in the SMIB system presented in the last section.

To explain the methodology followed for the observer design, consider systems whose mathematical model can be represented by

$$\begin{aligned}\dot{\eta} &= A(y,u)\eta + B(y,u) \\ \dot{y} &= \psi_0(y,u) + \psi_1(y,u)\eta\end{aligned} \tag{2}$$

where $[\eta, y] \in \mathbf{R}^n \times \mathbf{R}^p$ is the system state, $\eta \in \mathbf{R}^{n-p}$ is the unmeasured state, $y \in \mathbf{R}^p$ is the measured output and $u \in \mathbf{R}^m$ is the control input.

The system (2) can be represented as

$$\dot{\eta} = A(y,u)\eta + B(y,u) \tag{3}$$

$$z = \psi_1(y,u)\eta \tag{4}$$

where $z = \dot{y} - \psi_0(y,u)$.

Notice that one possible observer is given by

$$\dot{\hat{\eta}} = A(y,u)\hat{\eta} + B(y,u) + K_0(z - \hat{z}) \tag{5}$$

where

$$\hat{z} = \psi_1(y,u)\hat{\eta} \tag{6}$$

Substitution of (5) into (6) leads to the equivalent representation

$$\begin{aligned}\dot{s} &= (A(y,u) - K_0\psi_1(y,u))\hat{\eta} + B(y,u) - K_0\psi_0(y,u) \\ \hat{\eta} &= s + \beta(y)\end{aligned} \tag{7}$$

If it is defined the observation error by

$$\varepsilon = s + \beta(y) - \eta, \tag{8}$$

then the error derivative follows that

$$\dot{\varepsilon} = \left(A(y,u) - \frac{\partial\beta(y)}{\partial y}\varphi_1(y,u)\right)\varepsilon \tag{9}$$

if $A_e = \left(A(y,u) - \frac{\partial\beta(y)}{\partial y}\varphi_1(y,u)\right)$ then the error dynamic is given by the next expression

$$\dot{\varepsilon} = A_e\varepsilon \tag{10}$$

Proposition 2. There is a mapping $\beta(y) : \mathbb{R}^q \to \mathbb{R}^{n-q}$ so that the matrix A_e is continuous, differentiable and non singular□.

If A_e is continuous, bounded and non singular matrix, there is an only equilibrium point that is $\varepsilon = 0$. In order to prove Lyapunov stability it is proposed the next candidate Lyapunov function

$$V(\varepsilon,t) = \varepsilon^\top P(t)\varepsilon \tag{11}$$

where $V(\varepsilon,t) : \mathbb{R}^{n-p} \times \mathbb{R} \to \mathbb{R}$ also there is a matrix $P(t) \in \mathbb{R}^{n-p}$ that is a positive symmetric defined continuously differentiable and bounded matrix. The derivative of $V(\varepsilon,t)$ along to the system trajectories is given by

$$\dot{V}(\varepsilon,t) = \varepsilon^\top(A_e^\top P(t) + \dot{P}(t) + P(t)A_e)\varepsilon \tag{12}$$

as A_e is continuous and bounded, the matrix $P(t)$ meets the following

$$\dot{P}(t) + A_e^\top P + PA_e = -Q(t)$$

where $Q(t)$ is a positive symmetric continuous matrix, therefore the Lyapunov derivative function along of the system trajectories is presented by the next equation

$$\dot{V}(\varepsilon,t) = -\varepsilon^\top Q(t)\varepsilon \tag{13}$$

Theorem 3. Let $\varepsilon = 0$ an equilibrium ponit of the system (10) and $D \subset \mathbb{R}^{n-p}$ a domain which contains $\varepsilon = 0$. Let a function $V : [0,\infty) \times D \to \mathbb{R}$ that is a continuously differentiable function so that

$$k_1||\varepsilon||^a \le V(t,\varepsilon) \le k_2||\varepsilon||^a \tag{14}$$

$$\frac{\partial V}{\partial t} + \frac{\partial V}{\partial \varepsilon}f(t,\varepsilon) \le -k_3||\varepsilon||^a \tag{15}$$

$\forall t \ge 0$ and $\forall \varepsilon \in D$ where k_1, k_2, k_3 and a are positive constants. Then $\varepsilon = 0$ is exponentially stable;

if the assumptions hold globally, then $x = 0$ is globally exponentially stable.$\diamond$

The purpose is to design the gain $A(y,u) - \frac{\partial \beta(y)}{\partial y}\psi_1(y,u)$ in such a way that the time derivative of the function V fulfills (14) and (15).

3.1 Observer design for SMIB system

Concerning the application of the presented result for the system (1), it must be considered that if x_1 is the measurable state, the goal is to design an observer in order to reconstruct the states x_2 and x_3. In this case, the SMIB model can be represented in the form (2) given by

$$\dot{x}_1 = -\omega_s + [\omega_s \;\; 0]\begin{bmatrix} x_2 \\ x_3 \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -b_3 & -b_1 sen(x_1) \\ 0 & -b_4 \end{bmatrix}\begin{bmatrix} x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{T_m}{2H} + b_2\sin(x_1)\cos(x_1) + b_3 \\ b_5\cos(x_1) + \frac{E_{fd}}{T'_d0} \end{bmatrix}$$

According to the described methodology, the proposed observer takes the form

$$\dot{s} = \begin{bmatrix} -b_3 - \omega_s\frac{\partial \beta_1(y)}{\partial y} & -b_1\sin(x_1) \\ -\omega_s\frac{\partial \beta_2(y)}{\partial y} & -b_4 \end{bmatrix}\begin{bmatrix} \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} + \begin{bmatrix} \frac{T_m}{2H} + b_2\sin(x_1)\cos(x_1) + b_3 + \omega_s\frac{\partial \beta_1(y)}{\partial y} \\ b_5\cos(x_1) + \frac{E_{fd}}{T'_{d0}} + \omega_s\frac{\partial \beta_2(y)}{\partial y} \end{bmatrix} \tag{17}$$

$$\hat{\eta} = s + \begin{bmatrix} \beta_1(y) \\ \beta_2(y) \end{bmatrix} \tag{18}$$

Then, in order to achieve that η tends $\hat{\eta}$, the mapping $\beta(y)$ must accomplish the restrictions of the Theorem 3, for that reason, the mapping $\beta(y)$ is given by

$$\beta(y) = \begin{bmatrix} K_1(x_1 - x_{1\star}) \\ K_2 b_1(\cos(x_1) - \cos(x_{1\star})) \end{bmatrix}$$

4. FUNDAMENTALS OF POWER SYSTEM CONTROLLERS

Since one of the main problems approached in this paper is to show that a proper operation of classical control schemes is achieved when they are fed with estimated states, it is important to introduce the structure of these devices. Thus, in this section the AVR control and the PSS compensator considered for the evaluation are presented.

4.1 Automatic voltage regulator

The AVR has different versions in the power systems literature. For this work it is considered the AVR Type *III* (Lee (1992)) which is defined by the next mathematical model

$$\dot{v}_r = \left(K_0\left(1 - \frac{T_1}{T_2}\right)(v_{ref} - v_m) - v_r\right)T_2^{-1}$$
$$\dot{v}_f = \left(\left(v_r + K_0\frac{T_1}{T_2}(v_{ref} - v_m)\right)\left(1 - \frac{v_m}{v_0}\right) - v_f\right)T_e^{-1}$$

where v_m is the voltage in terminals, v_f is the field voltage, corresponding to u in model (1), and T_1, T_2, T_e, K_0 are design parameters that must be assigned by a tuning procedure.

The AVR presented above is usually implemented together with two phase shifters given by

$$G_1(s) = \frac{T_1 s + 1}{T_2 s + 1}; \quad G_2(s) = \frac{1}{T_e s + 1} \tag{19}$$

where the AVR's input is a lineal combination of a reference voltage, a PSS's voltage and machine's voltage while the output is the field machine voltage.

4.2 Power system stabilizer

It is also possible to find different versions of PSS. In this work a PSS Type *II* (Larsen and Swann (1981)) is considered which is described by three transfer functions, namely, a filter that is called *watch out*, a feedforward-feedback control and a phase shifter. Those transfer functions are described by

$$G_3(s) = K_w\frac{T_w s}{T_w s + 1}; \quad G_4(s) = \frac{T_1 s + 1}{T_2 s + 1};$$
$$G_5(s) = \frac{T_3 s + 1}{T_4 s + 1} \tag{20}$$

where K_w is the PSS's gain and T_w,T_1,T_2,T_3,T_4 are variables that must be properly tuned. The input of PSS is the machine's speed and the output is a voltage that modifies the AVR's reference voltage.

5. MODAL ANALYSIS FOR A SMIB

With the aim to clearly state the conditions and criteria used in the evaluation of the proposed observer, it is important to recognize some features of the system operation. In this sense, a proper operation of a power system from the small stability approach is characterized by the next two features

F.1 The mechanical power satisfies the next constraint

$$0 \le P_m \le \frac{E_b E'_q}{X'_d + X_E} \tag{21}$$

F.2 There exists a compact invariant set D so that

$$D = \{x \in \mathbf{R}^2 : \quad 0 \le x_1 \le \frac{\pi}{2} - \varepsilon\} \tag{22}$$

where x is the variable state vector that contains the electric and mechanical variables.

Under the conditions above, in order to achieve rotor angle stability it is enough to guarantee a steady state operation such that the previous conditions hold.

In order to further characterize the presented operation conditions, a local analysis can be carried out. Thus, in the SMIB case there are only two generators so this power system has only one electromechanical oscillation. Moreover, it is well known that the system temporal response depends on the system's eigenvalue in such a way that

- If one eigenvalue corresponds to a non-oscillatory mode, then it is negative. In this case the response exponentially decreases in function with the eigenvalue magnitude.
- If a pair of eigenvalues are complex conjugated, the corresponding behavior is an oscillation mode. The real component is a damping constant while the imaginary part is associated to the oscillation frequency.

As a consequence of the previous analysis, the eigenvalue $\lambda_A = \beta + j\omega$ has oscillation frequency given by

$$f = \frac{\omega}{2\pi} \tag{23}$$

and damping constant is defined by

$$\xi = \frac{-\beta}{\sqrt{\beta^2 + \omega^2}}. \tag{24}$$

The principal objective of PSS control designed is decreased the damping system constant and the frequency oscillation in some oscillatory mode.

6. EVALUATION FOR A SMIB SYSTEM

In this section the results obtained from the evaluation of the system composed by the SMIB system equipped with an AVR, a PSS and the proposed observer are presented. To carry this evaluation out, the regulators were tuned using a linearized model of fourth-order transient SMIB system with a simple exciter and the classical root locus method. However, it must be worth noticed that the implementation of the whole control system was developed considering the original nonlinear model in order to show its usefulness under more realistic conditions.

The numeric experiment considered that the system stars in a stable condition until a three-phase fault occurs, the fault condition was modeled by a very large impedance which is added to X_e, the fault duration is six cycles of synchronous frequency (0.1s), the fauilre causes the loss of a transmission line and for that reason the equivalent reactance for pos-fault condition is $X_e = 0.5[pu]$. The parameters for the synchronous machine are included in Table 1 while the considered interconnection among the sub-systems is presented in Figure 2.

Table 1. SMIB parameters

f the synchronous frequency	$60[Hz]$
T_m The mechanic torque	$1[pu]$
X'_d is the transitory reactance on the axe d	$0.245[pu]$
D is the damping coefficient	0
$E_b$is the infinite bus voltage	$1.08103[pu]$
X_E is the equivalent reactance on the line	$0.3[pu]$
H is the machine's inertia	$2[pu]$

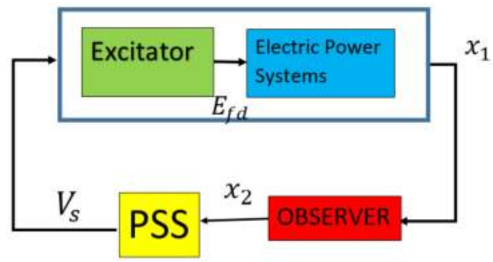

Fig. 2. Control scheme, where V_s is the PSS' voltage, x_1 is the angular position and x_2 is the angular speed.

The experiment that was designed to validate the observer is to implement a classic PSS for a forth linear SMIB system with a first order linear exciter; the PSS that is used in this case needs the measurement of the angular speed generator, this variable can not usually be measured, to solve this problem it is implemented an nonlinear observer presented in previous sections. The observer that is used to reconstruct the angular speed generator was designed for a third order model (flux decay).

The linearization of a power electric system was done considering the stable equilibrium point $x^\star = [1.2406, 1, 0.7437$ $, 0.6895, 2.0099]$ when the states of this linear system are $[\delta, \omega, E'_q, E'_d, E_{fd}]$, giving as a result the matrix

$$A = \begin{bmatrix} 0 & 376.9911 & 0 & 0 & 0 \\ -1.9025 & 0 & -1.8763 & 0.4868 & 0 \\ -0.6586 & 0 & -0.8440 & 0 & 0.2 \\ 1.099 & 0 & 0 & -4.6506 & 0 \\ 1.3396 & 0 - 5.2308 & -6.1725 & -2.5 & \end{bmatrix}$$

where A is the state matrix of the power system. Therefore the system's eigenvalues are

$$\lambda_{1,2} = -0.4620 \pm j26.7545; \quad \lambda_3 = -4.2670;$$
$$\lambda_4 = -2.1272; \quad \lambda_5 = -0.6765$$

leading to a mechanical oscillation characterized by the eigenvalues $\lambda = -0.4620 \pm 26.7545j$. Hence its frequency is $f = 4.2581[Hz]$ while its damping factor is $\xi = 0.01726$.

The transfer function of the PSS is

$$PSS = 20.07 \left(\frac{5s}{5s+1} \right)$$

In Figure 3 is presented a comparisson among the delivered power by the generator in three cases. The first case is the generator in open loop, the second is the case when it is considered the control of the generator with measured variables and finally in the third case it is considered the case when the variables that the control uses are the observed ones.

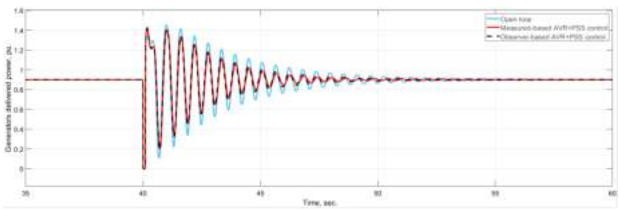

Fig. 3. Delivered electric power.

In this studied case is possible to note that both control cases, when the variables are measured and observed, the action control is achieved its target which is to damp the oscillation in the SMIB system. The principal difference of SMIB control response with observed variables with respect to the SMIB control response with measured ones is that the former takes about $5[ms]$ longer to reach steady state.

In Figure 4 there is a comparison among the open loop system, system speed response with control based on measured variables and system speed response with control based on observed variables.

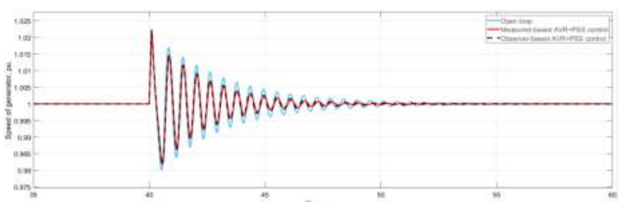

Fig. 4. System whit control based on measured and observed speed.

In this studied case it can be noted that the control system achieves its target. In the same case that the delivered power, the SMIB control speed response has the same behavior that the previous case.

7. CONCLUSION

In this paper a novel nonlinear observer for a SMIB system equipped with a classical AVR and a PSS was presented. Formal stability properties of the observer were established and its usefulness was illustrated in a numerical setting showing that even when the PSS is fed with the estimated state, the purpose of damping low frequency rotor angle oscillations is achieved.

REFERENCES

Gomes Jr, S., Guimarães, C., Martins, N., and Taranto, G. (2018). Damped nyquist plot for a pole placement design of power system stabilizers. *Electric Power Systems Research*, 158, 158–169.

Guesmi, T., Farah, A., Abdallah, H.H., and Ouali, A. (2018). Robust design of multimachine power system stabilizers based on improved non-dominated sorting genetic algorithms. *Electrical Engineering*, 1–13.

Ilic, M. and Liu, S. (2012). *Hierarchical power systems control: its value in a changing industry.* Springer Science & Business Media.

Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., Hatziargyriou, N., Hill, D., Stankovic, A., Taylor, C., Van Cutsem, T., and Vittal, V. (2004). Definition and classification of power sys stability. *IEEE Transactions on Power Systems*, 19(2), 1387–1400.

Larsen, E. and Swann, D. (1981). Applying power system stabilizers part i: general concepts. *IEEE Transactions on Power Apparatus and systems*, (6), 3017–3024.

Lee, D. (1992). Ieee recommended practice for excitation system models for power system stability studies (ieee std 421.5-1992). *Energy Development and Power Generating Committee of the Power Engineering Society*, 95(96).

Rivera, I.L.O., Vittal, V., Heydt, G.T., Fuerte-Esquivel, C.R., and Angeles-Camacho, C. (2018). A dynamic state estimator based control for power system damping. *IEEE Transactions on Power Systems*, 33(6), 6839–6848.

Sánchez Tello, F. (1988). *Oscilaciones electromecánicas en sistemas de potencia.* Ph.D. thesis, Universidad Auónoma de Nuevo León.

Sauer, P.W. and Pai, M.A. (1998). *Power system dynamics and stability*, volume 101. Prentice hall Upper Saddle River, NJ.

Wang, H. and Swift, F. (1997). A unified model for the analysis of facts devices in damping power system oscillations. i. single-machine infinite-bus power systems. *IEEE Transactions on Power Delivery*, 12(2), 941–946.

Yu, Y.N. and Li, Q.H. (1990). Pole-placement power system stabilizers design of an unstable nine-machine system. *IEEE transactions on power systems*, 5(2), 353–358.

Zolotas, A.C., Chaudhuri, B., Jaimoukha, I.M., and Korba, P. (2007). A study on lqg/ltr control for damping inter-area oscillations in power systems. *IEEE Transactions on Control Systems Technology*, 15(1), 151–160.