A Simple Lyapunov Function Based Control Strategy for Coordinated Transient Stability Enhancement of Power Systems

Fombu Andrew Muluh[1], Clotaire Thierry Sanjong Dagang[2], Pesdjock Mathieu Jean Pierre[3], Sonfack Lionel Leroy[2], Kenne Godpromesse[2]
[1]Department of Electrical and Electronic Engineering, National Higher Polytechnic Institute, University of Bamenda, P.O. Box 39 Bambili, North West Region, Cameroon
[2]Department of Electrical and Power engineering, Research Unit of Automation and Applied Computer Science, IUT-FV Bandjoun, University of Dschang, P.O. Box 134, West Region, Cameroon
[3]Cameroonian Association for Research and Innovation in Energy, Technology and Environment, P.O. Box 59 Ebolowa, South Region, Cameroon

Article Info

Article history:

Received Mar 13, 2024
Revised Apr 22, 2024
Accepted Apr 30, 2024

Keywords:

Lyapunov Function
Multi-Machine Power System
Global Stability
Coordinated Control

ABSTRACT

Transient stability is still a serious impediment in power system operation due to their highly nonlinear nature. Over the last decades, a vast number of diverse nonlinear control algorithms for sub-controllers located at the generator subsystem and transmission lines have been developed to boost power system stability. However, for an effective and feasible operation of these power systems, coordination of these sub-controllers is very essential. In this paper, a simple direct Lyapunov based approach for coordinated control is proposed for global enhancement of power system stability. The proposed control scheme is achieved through the coordination of Lyapunov based decentralized steam valve, excitation and SSSC adaptive controllers. To test the efficacy of the proposed scheme, several comparisons in multi-machine fault scenarios with other design coordinated approaches are presented. Numerical simulations demonstrate the swiftness and efficacy of the proposed control scheme in boosting global stability.

Corresponding Author:

Fombu Andrew Muluh,
Department of Electrical and Electronic Engineering,
National Higher Polytechnic Institute, University of Bamenda,
P.O. Box 39 Bambili, North West Region, Cameroon
Email: fombuandrewmuluh@yahoo.com

1. INTRODUCTION

Power systems are highly nonlinear structural systems with multiple control objectives, which mainly include voltage and frequency regulation, adequate damping of oscillations, and maintaining synchronization in the presence of large disturbances. These multiple control objectives have so far been partially achieved through the application of control schemes to sub-controllers located at different positions within the power system. For stability evaluation, Lyapunov method is still a crucial mathematical theory that provides direct stability assessments with strict theoretical guarantees. This method is still widely used for both stability analysis and control synthesis.

For the improvement of transient stability, generator control using excitation and turbine governing systems are the major control implements of power systems when financial limitations restrict the exploitation of FACTS devices [1–6]. Thus, a more affordable solution based on the existing electrical installations is achieved. However, as a result of the physical constraints on the excitation signal and power control input of the turbine, global power system stability boosting with generator control alone is constrained [7, 8]. To further boost power system stability and equally optimize the utilization of available transmission resources, the current trend is the use of FACTS devices [9–12].

The application of FACTS equipments to boost power system stability and transfer capacity is a viable option when deregulations and environmental factors restrict the setting up of new electrical lines. The Static Synchronous Series Compensator (SSSC), among the different variants of FACTS equipments, is particularly appealing for power stability and transmission applications due to its operating characteristics [13–15].

Future smart grids will require the coordinated operation of both generator controllers (excitation and steam valve) and FACTS equipments for optimal performance. Global control helps to achieve the coordinated operation of these sub-controllers throughout the system under all operating conditions. For the coordinated control of generator controllers and FACTS devices, various advanced nonlinear control algorithms are found in the literature [16–23]. Nevertheless, in most cases, these geographically dispersed sub-controllers are designed separately due to the difficulty in obtaining control signals. Hence their dynamic interconnection which are not taking into consideration may induce instability and limits the power operating range of the system [24]. Thus these interactions must be taken into account in other to ameliorate the stability of the overall system.

The coordination of FACTS and generator excitation controllers have been achieved through a vast number of control strategies proposed in the literature [17–19, 25–29]. However, most of these solutions cannot withstand large perturbations because they are conceived from approximate linearized power system models. A coordinated STATCOM and excitation controller based on a nonlinear control algorithm is designed in [18] to boost transient stability. In [17] and [29], coordinated generator excitation and FACTS robust nonlinear controllers (TCPS and SVC respectively) are designed using direct feedback linearization to boost the transient stability of a multi-area interconnected power system. In [30], a comprehensive assessment of the effects of the PSS and SVC based control when applied independently and also through coordinated application has been carried out. The design problem of the proposed controller was formulated as an optimization problem and simulation results showed the superiority of the coordinated control scheme to both the uncoordinated controller of the PSS and the SVC damping controller. Several other optimization techniques have equally been proposed in the literature for improving the performance of coordination of FACTS and generator excitation controllers [31, 32]. However, in these contributions, voltage regulation which is very important in the stability of the power system has not been addressed and the inherent system nonlinearity has been reduced in some works using direct feedback linearization. Hence, the control schemes cannot achieve satisfactory results in the presence of large disturbances.

Using a framework for managing dissimilar controllers at diverse positions within a power system, a new global control algorithm is conceived in [28] to boost transient stability. However, linearized model-based classical controllers are used and a commutating control strategy which produces discontinuity of system behavior is used to achieve the coordination between the generator excitation, PSS, FACTS devices and capacitor switching. Within the same frame work stated above, a coordinated control strategy of SVC and generator excitation is proposed in [19] to ameliorate both transient and voltage stability of power systems. Nevertheless, the implementation on a multi-area interconnected power system is not considered and the control laws are conceived from direct feedback linearization. Furthermore, the aforementioned control algorithms have not equally examined how the turbine control affects the power system’s transient stability, making them inappropriate for current power systems given that the introduction of modern governors, such as digital governors, has lead to close mutual interaction between the excitation and governor loops [7, 8]. For the coordination of turbine governing system and a FACTS device, in [33], a novel quasi-decentralized sliding mode control-based strategies using turbine governor control and FACTS device is developed for boosting the frequency and voltage stability of a multi-area interconnected power systems. However, the authors of this paper did not consider the contributions of the excitation control.

In view of the above challenges, it can be observed that so much work has been done on the coordinated control of the excitation and turbine governing systems, excitation and FACTS devices, and turbine governing systems and FACTS devices. However, very little attention has been given to global simultaneous coordinated control of the turbine governing system, excitation and FACTS devices. Hence, in this paper, we are proposing a simple approach to design a global nonlinear decentralized steam valve, excitation and SSSC adaptive control based on the direct Lyapunov’s method. This simple approach is the extension of the concept of simultaneous transient stability and voltage regulation enhancement using coordinated steam valve and excitation control developed in [4]. Several numerical simulation comparisons in multi-machine fault scenarios have been performed to evaluate and validate the performance of the new global nonlinear adaptive control scheme.

Overall, the remainder of the paper is structured thus: Section 2. presents the power system model and elaborates the proposed global control design technique. In Section 3., simulation results are presented to illustrate the performance, effectiveness, robustness and feasibility of the proposed scheme. Concluding remarks are given in Section 4.

2. METHODOLOGY
2.1. Power System Model
The classical mathematical model of an extensive power system with a FACTS device (SSSC), can be expressed using the following equations [4, 7, 34, 35]:

$$\frac{d\delta_i}{dt} = \omega_i, \tag{1}$$

$$\frac{d^2\delta_i}{dt^2} = -\frac{1}{M_i}\left[D_i\frac{d\delta_i}{dt} + \omega_s(P_{ei} - P_{mi})\right], \tag{2}$$

$$\frac{dP_{ei}}{dt} = \frac{1}{T'_{doi}}\left(-P_{ei} + U_{fi}\right), \tag{3}$$

$$\frac{dP_{mi}}{dt} = -\frac{1}{T_{mi}}[P_{mi} + K_{mi}T_{mi}\xi_{ci}], \tag{4}$$

$$\frac{d\xi_{ci}}{dt} = -\frac{1}{T_{ei}}[\frac{K_{ei}}{R_i\omega_s}\frac{d\delta_i}{dt} + \xi_{ei} - U_{gi}]. \tag{5}$$

Where

$$U_{fi} = [E_{fi} - (x_{di} - x'_{di})I_{di}]I_{qi} + T'_{doi}\frac{P_{ei}}{I_{qi}}\frac{dI_{qi}}{dt} \tag{6}$$

From Fig.1, the SSSC output ac voltages are U_dV_{dc} and U_qV_{dc}. Following Fig.1, the nonlinear dynamics of the SSSC is given by [35]:

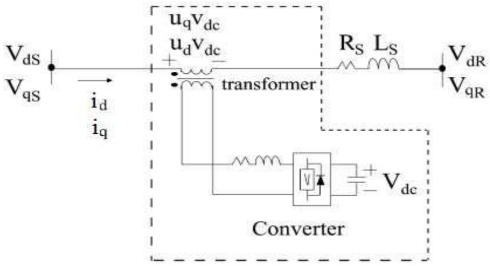


Figure 1. SSSC single-line diagram

$$\frac{1}{\omega_o}\frac{di_d}{dt} = -\frac{R_s}{L_s}i_d + i_q - \frac{1}{L_s}(U_dV_{dc}) + \frac{1}{L_s}(V_{dS} - V_{dR}) \tag{7}$$

$$\frac{1}{\omega_o}\frac{di_q}{dt} = -\frac{R_s}{L_s}i_q - i_d - \frac{1}{L_s}(U_qV_{dc}) + \frac{1}{L_s}(V_{qS} - V_{qR}) \tag{8}$$

$$\frac{C_{dc}}{\omega_o}\frac{dV_{dc}}{dt} = (i_dU_d + i_qU_q - \frac{V_{dc}}{R_{dc}}) \tag{9}$$

With $U_d = K\cos(\alpha + \theta_s)$ and $U_q = K\sin(\alpha + \theta_s)$.

In the above mathematical model, and for the i^{th} generator, δ_i is the power angle in radians, ω_s is the synchronous machine speed in rad/s, ω_i is the relative rotor speed in rad/s, M_i is the inertia constant in seconds, D_i is the damping constant in p.u, E_{fi} is the equivalent EMF in the excitation coil in p.u, T'_{doi} is the direct axis transient short-circuit time constant in seconds, P_{ei} and P_{mi} are the active electric and mechanical power input respectively in p.u, I_{di} and I_{qi} are the direct and quadrature axis currents respectively in p.u, x_{di} is the direct axis reactance in p.u, x_{di}' is the direct axis transient reactance in p.u, ξ_{ei} is the steam valve opening in p.u, U_{gi} is the generator power control input in p.u, T_{mi} and T_{ei} are the turbine and speed governor time constant respectively in seconds, K_{mi} and K_{ei} are the turbine gain and speed governor gain respectively, R_i is the turbine regulation constant, i_d and i_q are the injected SSSC dq-axis currents in p.u, R_s and L_s are the resistance and inductance of the coupling transformer in p.u, V_{dc} is the voltage across the dc capacitor in p.u, ω_0 is the synchronous speed in rad/s, V_{dS} and V_{qS} are the sending end dq-axis voltages of the SSSC, V_{dR} and V_{qR} are the receiving end dq-axis voltages of the SSSC, θ_s is the phase angle of the sending end voltage, C_{dc} is the capacitance of the dc side capacitor in p.u, R_{dc} is the converter losses in p.u, and K and α are the modulation ratio and phase shift respectively.

In the above mathematical model, E_{fi}, U_{gi} and $V_{se} = \sqrt{(V_{dc}U_d)^2 + (V_{dc}U_q)^2}$ are the control inputs of the excitation, steam turbine and SSSC control loops respectively. The measurable outputs are P_{ei}, ω_i, I_{qi}, I_{di}, ξ_{ei}, i_d, i_q and V_{dc}.

2.2. Global Nonlinear Control Design Methodology
To achieve voltage stability and provide the utmost damping of oscillation in the presence of various multi-machine fault scenarios, we aim at designing sub-controllers for each machine, i.e., E_{fi} and U_{gi} for the generator control loops and coordinate their actions with the stabilizing signal V_{se} obtained from the SSSC

controller. The robust controllers compensate for the interactions between sub controllers, which are viewed as perturbations.

The second (direct) method of Lyapunov will be used in the following analysis to design coordinated adaptive nonlinear excitation, steam valve, and SSSC controllers. In this analysis, the system outputs are assumed to be continuous and bounded.

2.2.1. Generator Control

Lets define the following active electric power tracking error:

$$\varepsilon_{P_e} = P_{ei} - P_{ei}^*, \tag{10}$$

Where $P_{ei}{}^*$ is the reference active electric power. Using the concepts developed in [4] and applying Lyapunov's direct method on the candidate function

$$W_{1i} = \frac{(\varepsilon_{P_e})^2}{2}, \tag{11}$$

the excitation control law can be computed as [4]:

$$E_{fi} = \frac{1}{I_{qi}}\left[U_{fi} + (x_{di} - x'_{di})I_{di}I_{qi} - T'_{doi}\frac{P_{ei}}{I_{qi}}\frac{dI_{qi}}{dt}\right] \tag{12}$$

Where

$$U_{fi} = P_{ei} + T'_{doi}[-\frac{\gamma_{1i}^2 M_i}{\lambda_{oi}\omega_s}\eta_i - \frac{(1-\lambda_{oi}\frac{D_i}{M_i})}{\lambda_{oi}\omega_s}[D_i\omega_i + \omega_s(P_{ei} - P_{mi})] + \frac{dP_{mi}}{dt}] - \lambda_{1i}(\varepsilon_{P_e}) \tag{13}$$

and

$$P_{ei}^* = \frac{M_i}{\lambda_{oi}\omega_s}[\gamma_{1i}\eta_i + \omega_i(1 - \lambda_{oi}\frac{D_i}{M_i})] + P_{mi}, \tag{14}$$

with the design parameters $\lambda_{oi} > 0$, $\lambda_{1i} > 0$ and $\gamma_{1i} > 0$.

Similarly, given the following tracking error on the steam valve opening

$$\varepsilon_{\xi_e} = \xi_{ei} - \xi_{ei}^*, \tag{15}$$

where $\xi_{ei}{}^*$ is the reference steam valve opening. Applying Lyapunov's direct method on the candidate function

$$W_{2i} = \frac{(\varepsilon_{\xi_e})^2}{2}, \tag{16}$$

the steam valve control law can be computed as [4]:

$$U_{gi} = \frac{K_{ei}}{R_i\omega_s}\omega_i + \xi_{ei} + T_{ei}\frac{d\xi_{ei}^*}{dt} - \lambda_{2i}(\varepsilon_{\xi_e}). \tag{17}$$

where

$$\xi_{ei}^* = \frac{1}{K_{mi}}[P_{mi} + T_{mi}\frac{dP_{mi}^*}{dt} - T_{mi}\gamma_{2i}(P_{mi} - P_{mi}^*)] \tag{18}$$

with the design parameters $\lambda_{2i} > 0$ and $\gamma_{2i} > 0$

2.2.2. SSSC Control

Let's rewrite the mathematical model of the dc bus voltage in the form:

$$\frac{dV_{dc}}{dt} = \frac{\omega_o}{C_{dc}}(i_{dc} - \frac{V_{dc}}{R_{dc}}) \tag{19}$$

where the dc bus current i_{dc} is the sum of two terms. That is:

$$i_{dc} = i_d U_d + i_q U_q \tag{20}$$

To simultaneously achieve both dc bus regulation and transient stability enhancement within a single control law, the dc bus current will be considered as a supplementary control to the dc bus voltage. Hence, let's consider the following dc bus voltage tracking error

$$\varepsilon_{V_{dc}} = V_{dc} - V_{dc}^*, \tag{21}$$

where V^*_{dc} is the reference dc bus voltage. For ε_{Vdc} to exponentially converge to zero, we take:

$$\frac{d\varepsilon_{V_{dc}}}{dt} = -\gamma_{3i}\varepsilon_{V_{dc}}, \quad \text{with the design parameter } \gamma_{3i} > 0 \tag{22}$$

and compute the reference i_{dc}^*which is the unique solution of (22) as:

$$i_{dc}^* = \frac{V_{dc}}{R_{dc}} - \frac{C_{dc}}{\omega_o}\gamma_{3i}\varepsilon_{V_{dc}}. \tag{23}$$

To indirectly control the dc bus voltage, the reference real currents of the FACTS device are used because the amount of real current entering the converter determines the dc voltage in the capacitor. Hence if the supplementary control signal i_{dc}^* is taken into consideration in the exponential convergence of the FACTS currents towards their reference values, then dc bus voltage regulation will be achieved. To this end, the real and reactive current reference values will be expressed as:

$$i_d^* = i_d^{ref} + i_{dc}^* \tag{24}$$

$$i_q^* = i_q^{ref} \tag{25}$$

With [36]:

$$\begin{bmatrix} i_d^{ref} \\ i_q^{ref} \end{bmatrix} = \frac{1}{V_R}\begin{bmatrix} Cos\theta_R & Sin\theta_R \\ Sin\theta_R & -Cos\theta_R \end{bmatrix}^{-1}\begin{bmatrix} P_{eR}^{ref} \\ Q_{eR}^{ref} \end{bmatrix} \quad (26)$$

where P_{eR}^{ref} and Q_{eR}^{ref} are the active and reactive power references of the receiving end of the SSSC, θ_R is the phase angle of the receiving end voltage and V_R is the voltage at the receiving end.

To achieve the SSSC current regulation, let's define a new Lyapunov candidate function as:

$$W_{3i} = \frac{(\varepsilon_{i_d})^2}{2} + \frac{(\varepsilon_{i_q})^2}{2} \quad (27)$$

where

$$\varepsilon_{i_d} = i_d - i_d^*, \quad (28)$$

$$\varepsilon_{i_q} = i_q - i_q^* \quad (29)$$

The time derivative of (27) is given by:

$$\begin{aligned} \frac{dW_{3i}}{dt} &= (\varepsilon_{i_d})\left(\frac{di_d}{dt} - \frac{di_d^*}{dt}\right) + (\varepsilon_{i_q})\left(\frac{di_q}{dt} - \frac{di_q^*}{dt}\right) \\ &= (\varepsilon_{i_d})\left[-\frac{\omega_o R_s}{L_s} i_d + \omega_o i_q - \frac{\omega_o}{L_s(U_d V_{dc})} + \frac{\omega_o}{L_s(V_{dS} - V_{dR})} - \frac{di_d^*}{dt}\right] \\ &+ (\varepsilon_{i_q})\left[-\frac{R_s}{L_s} i_q - i_d - \frac{1}{L_s(U_q V_{dc})} + \frac{1}{L_s(V_{qS} - V_{qR})} - \frac{di_q^*}{dt}\right] \end{aligned} \quad (30)$$

By choosing the control signals as:

$$\begin{aligned} V_{dc} U_d &= -R_s i_d + L_s i_q + (V_{dS} - V_{dR}) - \lambda_{3i}(\varepsilon_{i_d}) \\ V_{dc} U_q &= -R_s i_q - L_s i_d + (V_{qS} - V_{qR}) - \lambda_{4i}(\varepsilon_{i_q}) \end{aligned} \quad (31)$$

we can compute the time derivative of W_{3i} as:

$$\frac{dW_{3i}}{dt} = -\lambda_{3i}(\varepsilon_{i_d})^2 - \lambda_{4i}(\varepsilon_{i_q})^2 \text{ with the design parameters } \lambda_{3i} > 0 \text{ and } \lambda_{4i} > 0 \quad (32)$$

The controllers developed in (12), (17), and (31) are feasible and can easily be implemented since they are all decentralized controllers and can be realized using only local measurements of (I_{qi}, I_{di}, ξ_{ei}, ω_i, P_{ei}, i_d, i_q and V_{dc}). The time derivatives of I_{qi}, P_{mi}, ξ_{ei}, i_d^* and i_q^* are obtained using the technique proposed in [4, 37]. From the separation principle theorem [38], the global convergence and stability of the control scheme taking into account the interconnections between the nonlinear controllers (12), (17), and (31) depends only on the fact that the system states should be bounded within the operational domain. Complete schematic diagrams of the steam valve, excitation and SSSC controllers are shown in Fig. 2

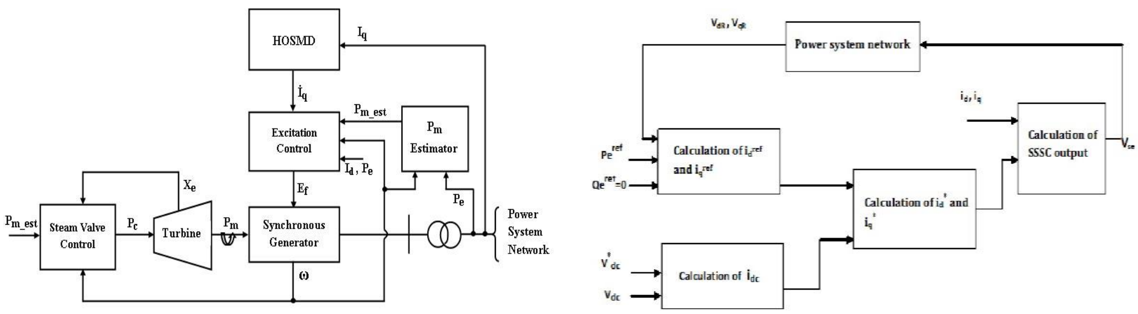


Figure 2. (a) Schematic of steam valve and excitation control (b) Schematic of SSSC control

3. SIMULATION RESULTS AND DISCUSSION

The proposed control strategy is implemented on the Kundur 4-machine 2-area power system of Fig.3 whose parameters are given in Table 1 and Table 2 of Appendix B. Simulations have been performed in Matlab/Simulink.

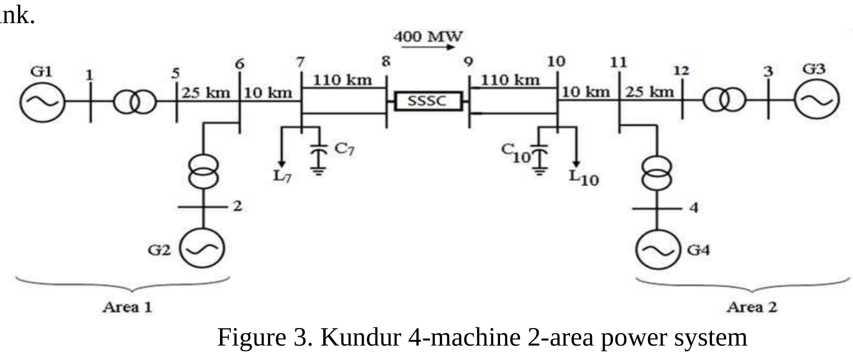


Figure 3. Kundur 4-machine 2-area power system

To make the simulations more feasible, limiters have been used on the integral control part to prevent excessive control action and also on the governor system (with values of ±0.5) to implement the effect of the generation rate constraint (GRC). The physical constraints on the excitation signal and steam valve opening are $-3\ p.u \leq E_f \leq 6\ p.u$ and $0 \leq \xi_e \leq 1.55\ p.u$ respectively. The measured stator currents are equally subjected to noise conditions. The proposed nonlinear controllers were mounted only on machines 1 and 3 while machines 2 and 4 were equipped with classical controllers in order to examine the interaction of the global nonlinear scheme with other classical controllers. The optimal tuning parameters for the proposed control scheme reported in Appendix D were obtained by the trial and error approach. In order to compare simulation results, two other schemes were used; a global linear control scheme made up of a traditional AVR/PSS for the excitation and PI regulators for the steam valve and SSSC, and a nonlinear coordinated excitation and steam valve adaptive control presented in [4]. Schematics of the classical controllers are shown in Appendix C. The parameters obtained from tuning these conventional controllers using optimal control methods are listed in Appendix D. The following multi-machine fault scenarios were used to evaluate and validate the efficacy of the proposed global nonlinear control scheme.

Scenario 1: A severe 200 *ms* symmetrical three phase short-circuit fault which takes place near bus 8 on the line between bus 7-8. The system response for this scenario is displayed in Figs. 4–8 between 0*s* and 3*s*. An inspection of the signals of these results shows that the proposed global nonlinear scheme rapidly mitigates oscillations and converges the system to it pre-fault state. Fig. 4 shows that the power angles of generator 1 and 3 and the relative rotor speeds are all maintained at their pre-fault values with these controllers but the proposed scheme settles rapidly with improved damping. The terminal voltages and active electrical powers also both converge to their reference values with reduced settling times and overshoots. Figs. 6 and 7 show the control signals and the excellent performance of the SSSC in providing an adequate stabilizing signal which helps to achieve voltage regulation. The power flow at bus 8 and 9 are displayed in Figs. 8. From the dynamic performance shown between 0*s* and 3*s*, we can see that the designed global nonlinear scheme can significantly ameliorate the transient and voltage stability of the power system.

Scenario 2: A 20% temporal signal loss (terminal voltage) of all machines. The comparative results for this scenario are illustrated in Figs. 4–8 between 4*s* and 8*s*. The results shown in the figures visibly indicate that synchronism is maintained since the relative rotor speeds, power angles, terminal voltages and active electric powers of generators 1 and 3 all converge to their pre-fault values. However, the signals from the proposed control scheme settle rapidly with a significant improvement in damping. These results shows that some modes of small signal oscillations can also be effectively mitigated and increase stability.

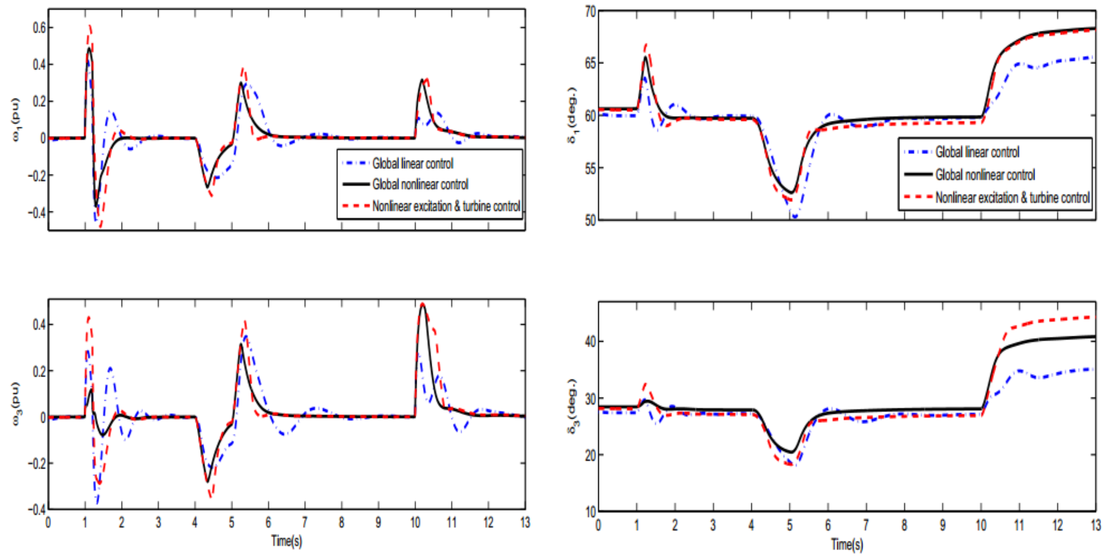
Scenario 3: A 30% permanent decrease in load demand at bus 7 and 10. The comparative results shown in Figs. 4–8 between 9*s* and 13*s* show that the proposed controller exhibits improved damping and faster convergence rates. Although from Fig. 4, it is observed that the global nonlinear algorithm presents a slightly greater overshoot than the global linear scheme, it quickly converges to its post-fault value. Similar results are obtained for the terminal voltage and active electric power. A general observation of Figs. 8 shows that the system remains stable despite the change in operating point observed. The variation in power flow at bus 8 and 9 is an adaptation to the needs of the loads that vary in the power system.

Scenario 4: A parameter variation is performed by increasing the values of M_i and T'_{doi} of all machines by 40%. That is $M_{1,2} = 9.1\ s$, $M_{3,4} = 8.65\ s$ and $T'_{doi} = 11.2\ s$. Simulation results produced the following values: $\Delta\delta_1 = 0.89^o$, $\Delta\delta_2 = 0.95^o$, $\Delta\delta_3 = 1.02^o$, $\Delta\delta_4 = 1.039^o$ for the power angle deviations and $\Delta\omega_1 = 0.0000415$, $\Delta\omega_2 = 0.000307$, $\Delta\omega_3 = 0.0000432$, $\Delta\omega_4 = 0.000464$ for the relative rotor speed deviations. The results show that smaller variations are obtained from $G_{1,3}$ which are designed with the proposed algorithm. Therefore, the response of the proposed algorithm can still be consistent with different models of power system.

From all the dynamic simulation results, a global observation shows that the proposed global nonlinear control scheme has an improved response in terms of convergence rate, overshoots and attenuation of oscillations. Hence, it can swiftly and satisfactorily ameliorate the stability of the power system.

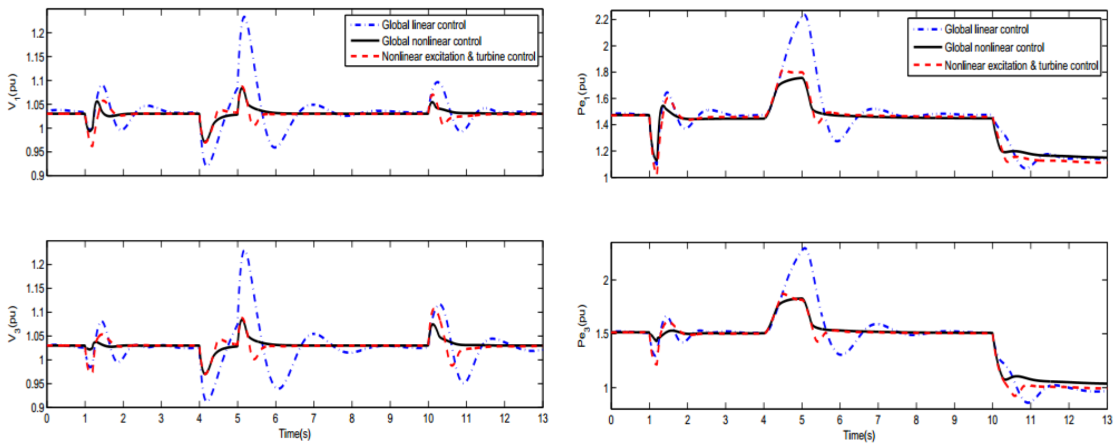
4. CONCLUSION

This paper presented a simple approach to conceive a global nonlinear coordinated control scheme for simultaneous transient and voltage regulation boosting of multi-area power systems. The proposed global control scheme was made up of nonlinear decentralized steam valve, excitation and SSSC adaptive controllers designed based on Lyapunov direct method. The proposed scheme is feasible since all the state variables required for its implementation are easily measurable or computable. Simulation analysis and comparisons in four multi-machine fault scenarios with another benchmark nonlinear coordinated algorithm proposed in [4] and the combined traditional AVR/PSS and PI regulators visibly demonstrate the effectiveness, robustness and superiority of the proposed strategy in providing good damping to system oscillations, reduced overshoots and enhanced transient and voltage stability over a wide range of disturbances and parameter variations. As future work, a laboratory realization and testing of the proposed strategy is envisaged.



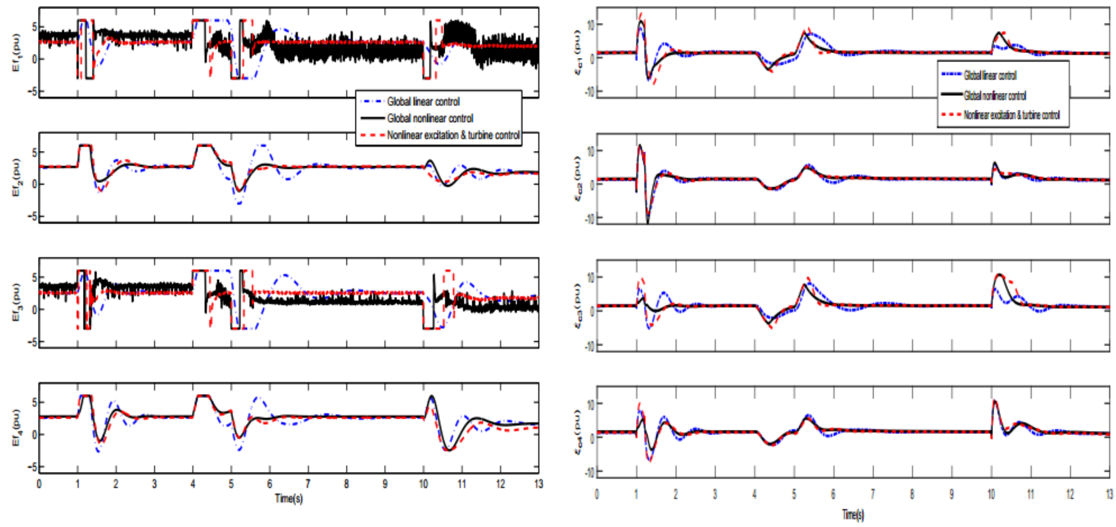
(a) (b)

Figure 4. Robustness test (a) Relative rotor speed of $G_{1,3}$ (b) Power angle of $G_{1,3}$



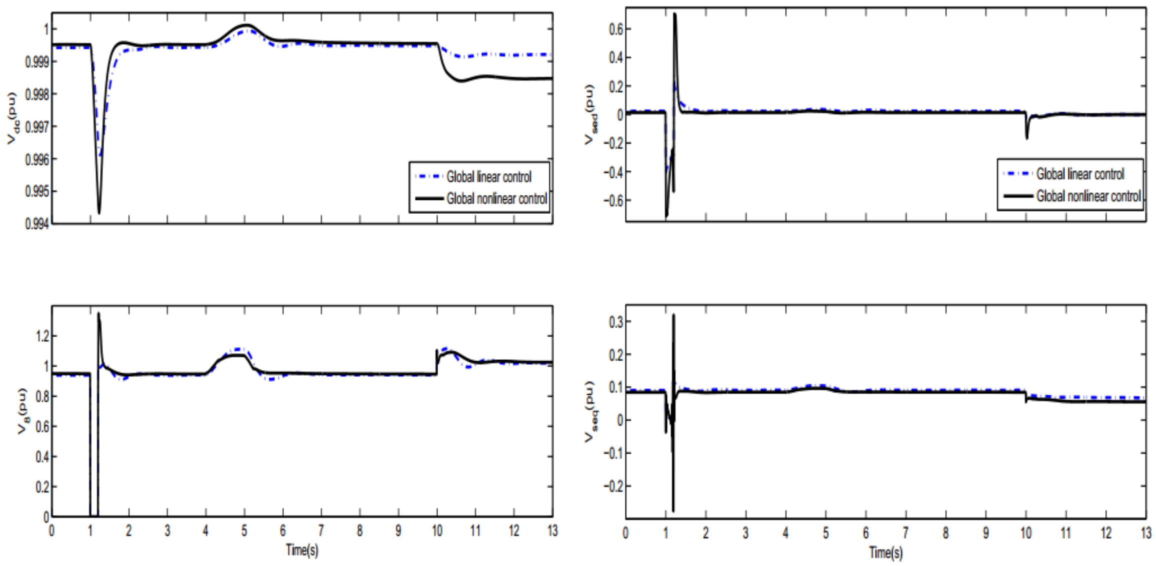
(a) (b)

Figure 5. Robustness test (a) Voltage signal at bus 1 and 3 (b) Active power signal at bus 1 and 3



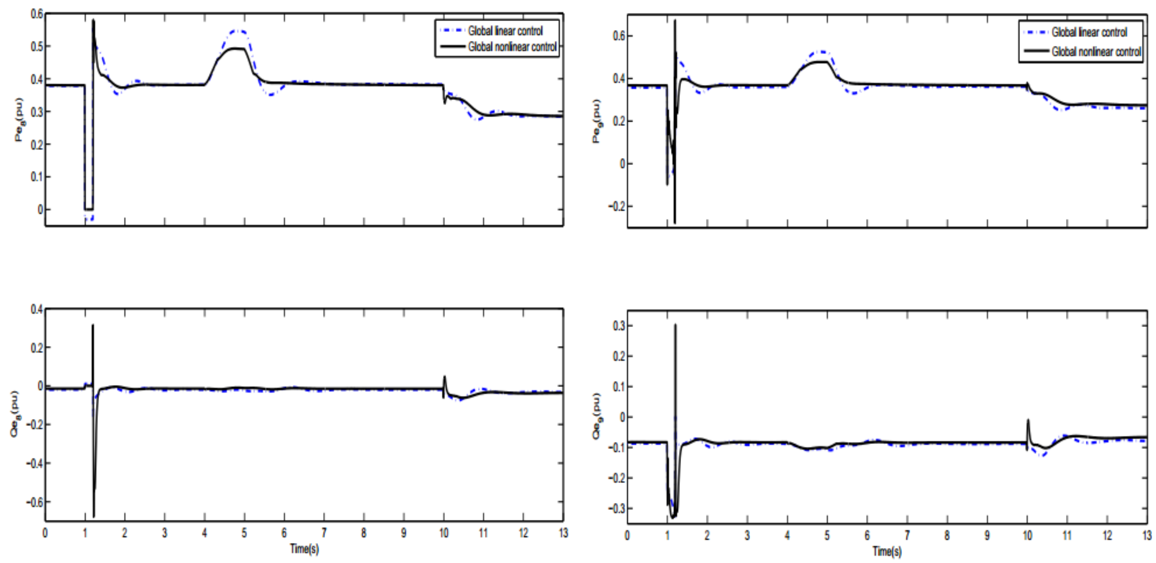
(a) (b)

Figure 6. Robustness test (a) Excitation control signals (b) Turbine control signals



(a) (b)

Figure 7. Robustness test (a) Dc bus voltage and voltage at bus 8 (b) SSSC control signals



(a) (b)

Figure 8. Robustness test (a) Power flow at bus 8 (b) Power flow at bus 9

APPENDIX

Appendix A: Power systems nomenclature

δi Power angle of the i^{th} generator in radians valid over the region defined by $0 < \delta i < \pi$
α Phase shift
ω_s Synchronous machine speed in rad/s
K Modulation ratio
ω_i Relative rotor speed of the i^{th} generator in rad/s
θ_s Phase angle
M_i Inertia constant of the i^{th} generator in s
R_{dc} Converter losses in p.u
D_i Damping constant of the i^{th} generator in p.u
C_{dc} Capacitance of the dc side capacitor in p.u
E_{fi} Equivalent EMF in the excitation coil in p.u
ω_0 Synchronous speed in rad/s
T'_{doi} Direct axis transient short-circuit time constant in s

V_{dc} Voltage across the dc capacitor in p.u
P_{ei} Active electrical power in p.u
L_s Inductance of the coupling transformer in p.u
Q_{ei} Reactive power in p.u
R_s Resistance of the coupling transformer in p.u
P_{mi} Mechanical power input in p.u
i_q Injected SSSC q-axis currents in p.u
I_{di} Direct axis current in p.u
i_d Injected SSSC d-axis currents in p.u
I_{qi} Quadrature axis current in p.u
R_i Regulation constant of the i^{th} machine in p.u
x_{di} Direct axis reactance in p.u
k_{ei} Gain of the i^{th} machine's speed governor
x'_{di} Direct axis transient reactance in p.u
K_{mi} Gain of the i^{th} machine's turbine
x_{adi} Mutual reactance between the excitation coil and the stator coil in p.u
T_{ei} Time constant of speed governor in s
T_{mi} Time constant of the i^{th} machine's turbine in s
ξ_{ei} Steam valve opening of the i^{th} generator in p.u
U_{gi} Power control input of the i^{th} generator in p.u

Appendix B: System Parameters

Table 1 and table 2 contain the per unit data of the power system and SSSC respectively [36, 39]:

Table 1. Power system nominal parameters

Parameters	$Gen_{1,2}$	$Gen_{3,4}$
$\omega_s(pu)$	1	1
$T_m(pu)$	0.35	0.35
$K_m(pu)$	1.0	1.0
$D(pu)$	0.8	0.8
$T'_{d0}(s)$	8.0	8.0
$M(s)$	6.5	6.175
$X_d(pu)$	1.8	1.8
$x'_d(pu)$	0.3	0.3
$T_e(pu)$	0.1	0.1
$K_e(pu)$	1.0	1.0
$R(pu)$	0.05	0.05

Table 2. SSSC nominal parameters

SSSC parameters	Value
$R_{dc}(pu)$	100
$C_{dc}(pu)$	325
$R_s(pu)$	0.073
$L_s(pu)$	0.22

Appendix C: Block Diagrams of Classical Controllers

The block diagrams of the classical controllers used in the global linear scheme are given in Fig. C1, C2 and C3

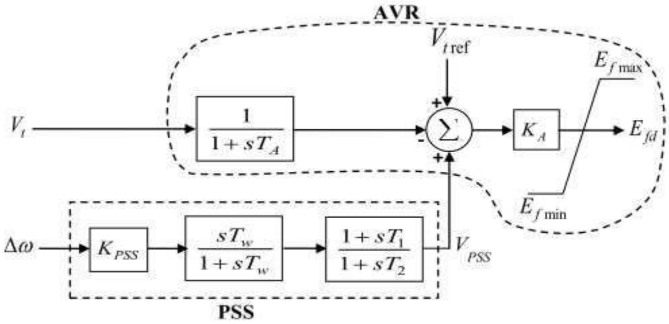


Figure C.1: Schematic of AVR/PSS

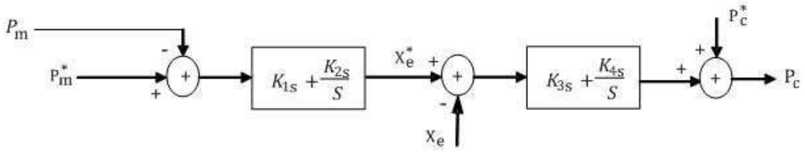


Figure C.2: Schematic of Steam Valve PI Regulator

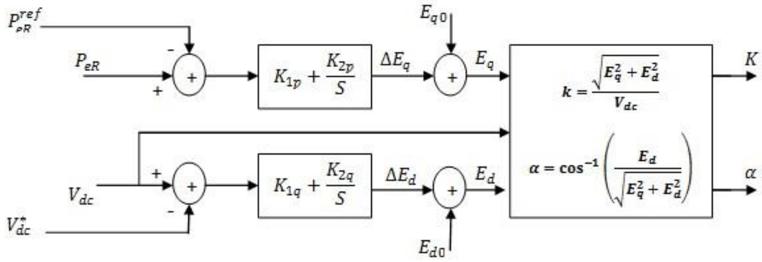


Figure C.3: Schematic of SSSC PI Regulator

Appendix D: Control Parameters

The optimal parameters used in the nonlinear and linear control schemes are given in table 3

Table 3. Control Parameters

Observer/Controller	Parameter
Nonlinear excitation controllers	$\gamma_{1i} = 3$; $\lambda_{0i} = 0.005$; $\lambda_{1i} = 15$
Nonlinear steam valve controllers	$\gamma_{2i} = 0.30$; $\lambda_{2i} = 0.9$
Nonlinear SSSC controllers	$\gamma_{3i} = 100$; $\lambda_{3i} = 0.1$ $\lambda_{4i} = 0.0005$
AVR/PSS controllers	$K_{PSS} = 0.9$; $T_w(s) = 4$; $T_1(s) = 0.05$ $T_2(s) = 0.07$; $K_A = 450$; $T_A(s) = 0.0$
SSSC PI regulator	$K_{1p} = 0.013$; $K_{2p} = 0.07$; $K_{1q} = 0.013$; $K_{2q} = 0.7$
Steam valve PI regulator	$K_{1s} = 3$; $K_{2s} = 3$; $K_{3s} = 1.2$; $K_{4s} = 2.5$

REFERENCES

[1] Kanchanaharuthai, “Immersion and invariance-based nonlinear dual-excitation and steam-valving control of synchronous generators,” *International Transactions on Electrical Energy Systems*, vol. 24, Issue 12, pp. 1671–1687, 2013.
[2] W. Y. Wan, J. Zhao, and G. M. Dimirovski, “Nonlinear adaptive control for multi-machine power systems with boiler-turbine-generator unit,” *International Transactions on Electrical Energy Systems*, vol. 25, Issue 5, pp. 859–875, 2015.
[3] G. Yi, H. David, J., and W. Youyi, “Nonlinear decentralized control of large power systems,” *Automatica*, vol. 36, pp. 1275–1289, 2000.
[4] A. M. Fombu, G. Kenne, J. d. D. Nguimfack-Ndongmo, and R. Kuate-Fochie, “Decentralized nonlinear coordinated excitation and steam valve adaptive control for multi-machine power system,” *Electrical Power and Energy Systems*, vol. 75, pp. 117–126, 2016.
[5] G. Kenne, A. M. Fombu, and J. d. D. Nguimfack-Ndongmo, “Coordinated excitation and steam valve control for multimachine power system using high order sliding mode technique,” *Electrical Power Systems Research*, vol. 131C, pp. 87–95, doi:10.1016/j.epsr.2015.10.003, 2016.
[6] S. Li, X. Liu, and X. Liu, “The coordinated immersion and variance control of power systems with excitation and steam-valve,” *Journal of Dynamic Systems, Measurement, and Control*, vol. 140, 2017.
[7] L. Qiang, *Nonlinear control system and power system dyanamics*. Kluwer Academic Publishers, 2001.
[8] M. Jin, W. Hu, F. Liu, S. Mei, and Q. Lu, “Nonlinear co-ordinated control of excitation and governor for hydraulic power plant,” *IEE Proc. Gener. Transm. Distrib.*, vol. 152, pp. 544–548, July 2005.
[9] E. Zhou, “Application of static var compensator to increase power system damping,” *IEEE Trans. Power Syst*, vol. 8, N0.2, pp. 655–61, 1993.
[10] X. Zairong and L. James, “Stabilization of generalized hamiltonian systems with internally generated energy and application to power systems,” *Nonlinear Analysis: Real World Application*, vol. 9, pp. 1202– 1223, 2008.
[11] W. Du, H. Wang, J. Cao, and L. Xiao, “Robustness of an energy storage system-based stabiliser to suppress inter-area oscillations in a multi-machine power system,” *IET Generation, Transmission* & *Distribution*, vol. 6, Issue 4, pp. 339–351, 2012.

[12] B. Singh, S. Murthy, R. Chilipi, S. Madishetti, and G. Bhuvaneswari, "Static synchronous compensator variable frequency drive for voltage and frequency control of small-hydro driven self-excited induction generators system," *IET Generation, Transmission* & *Distribution*, vol. 8, Iss. 9, pp. 1528–1538, 2014.

[13] H. F. Wang, "Static synchronous series compensator to damp systems oscillations," *Electrical Power Systems Research*, vol. 54, pp. 113–119, 2000.

[14] J. d. D. Nguimfack-Ndongmo, G. Kenne, R. Kuate-Fochie, A. Cheukem, F. H. Bertrand, and F. Lamnabhi Lagarrigue, "A simplified nonlinear controller for transient stability enhancement of multimachine power systems using SSSC device," *Electrical Power and Energy Systems*, vol. 54, pp. 650–657, 2014.

[15] M. Khalilian, M. Mokhtari, S. Golshannavaz, and D. Nazarpour, "Distributed static series compensator (DSSC) for subsynchronous resonance alleviation and power oscillation damping," *European Transactions on Electrical power*, vol. 22, Issue 5, pp. 589–600, 2011.

[16] L. Kang and J. Wang, "Nonlinear multi-index coordinated control of generator excitation and battery energy storage system," *European Transactions on Electrical power*, vol. 22, Issue 6, pp. 758–770, 2011.

[17] A. A. Hashmani, Y. Wang, and T. Lie, "Enhancement of power system transient stability using a nonlinear coordinated excitation and TCPS controller," *Electrical Power and Energy Systems*, vol. 24, pp. 201–214, 2002.

[18] G. Lihong and J. Wang, "Nonlinear coordinated control design of excitation and STATCOM of power systems," *Electric Power Systems Research*, vol. 77, pp. 788–796, 2007.

[19] L. Cong, Y. Wang, and D. Hill, "Transient stability and voltage regulation enhancement via coordinated control of generator excitation and SVC," *Electrical Power and Energy Systems*, vol. 27, pp. 121–130, 2005.

[20] G. Zhang and Y. Wang, "Global control of power system for transient stability enhancement and voltage regulation," *15th* PSCC, *Liege*, pp. 22–26, August 2005.

[21] T. Nguyen and R. Gianto, "Optimal design for control coordination of power system stabilisers and flexible alternating current transmission system devices with controller saturation limits," *IET Generation, Transmission* & *Distribution*, vol. 4, Issue 9, pp. 1028–1043, 2010.

[22] T. Nguyen and R. Gianto, "Neural networks for adaptive control coordination of PSSs and FACTS devices in multimachine power system," *IET Generation, Transmission* & *Distribution*, vol. 2, Issue 3, pp. 355–372, 2008.

[23] T. Nguyen and R. Gianto, "Optimisation-based control coordination of PSSs and FACTS devices for optimal oscillations damping in multi-machine power system," *IET Generation, Transmission* & *Distribution*, vol. 1, Issue 4, pp. 564– 573, 2007.

[24] X. Lei, E. Lerch, and D. Povl, "Optimization and coordination of damping control for improving system dynamic performance," *IEEE Trans. Power Syst*, vol. 16, N0.3, pp. 473–80, 2001.

[25] E. Ali and S. Abd-Elazim, "Stability improvement of multimachine power system via new coordinated design of PSSs and SVC," *Inc. Complexity*, vol. 21, Issue 2, pp. 256–266, 2015.

[26] A. R. Mahran, B. W. Hogg, and M. L. El-Sayed, "Co-ordinated control of synchronous generator excitation and static var compensation," *IEEE Trans. Energy Convers*, vol. 7, N0.4, pp. 615–21, 1992.

[27] P. Pourbeik and M. J. Gibbard, "Simultaneous coordination of power system stabilizers and FACTS device stabilizer in a multimachine power system for enhancing dynamic performance," *IEEE Trans. Power Syst*, vol. 13, N0.2, pp. 473–9, 1998.

[28] S. Joseph, J. David, and N. Yixin, "Global power system control using generator excitation, PSS, FACTS devices and capacitor switching," *Electrical Power and Energy Systems*, vol. 27, pp. 448–464, 2005.

[29] Y. Wang, L. Yoke, and G. Guoxiao, "Robust nonlinear coordinated generator excitation and SVC control for power systems," *Electrical Power and Energy Systems*, vol. 24, pp. 187–195, 2000.

[30] S. Abd-Elazim and E. Ali, "Coordinated design of PSSs and SVC via bacteria foraging optimization algorithm in a multimachine power system," *International Journal of Electrical Power Energy Systems*, vol. 41, no. 1, pp. 44–53, 2012.

[31] S. Abd Elazim and E. Ali, "Optimal SSSC design for damping power systems oscillations via gravitational search algorithm," *International Journal of Electrical Power Energy Systems*, vol. 82, pp. 161–168,2016.

[32] E. Ali and S. Abd-Elazim, "Coordinated design of PSSs and TCSC via bacterial swarm optimization algorithm in a multimachine power system," *International Journal of Electrical Power Energy Systems*, vol. 36, no. 1, pp. 84–92, 2012.

[33] S. Yu, T. Chau, T. Fernando, A. V. Savkin, and H. H. C. Iu, "Novel quasi-decentralized SMC-based frequency and voltage stability enhancement strategies using valve position control and facts device," *IEEE Access*, vol. 5, pp. 946–955, 2017.

[34] Y. Yu, *Electric power system dynamics*. Academic Press, 1983.

[35] L. Bin and O. Boon-Teck, "Nonlinear control of voltage-source converter systems," *IEEE Transactions on power electronics*, vol. 22, N0.4, pp. 1186–1195, 2007.

[36] L. Bangjun and F. Shumin, "A brand new nonlinear robust control design of SSSC for transient stability and damping improvement of multi-machine power systems via pseudo-generalized Hamiltonian theory," *Control Engineering Practice*, vol. 29, pp. 147–157, 2014.

[37] G. Kenne, J. d. D. Nguimfack-Ndongmo, R. F. Kuate, and H. B. Fotsin, "Online simplified nonlinear controller for transient stabilization enhancement of DFIG in multi-machine power systems," *IEEE Transactions on Automatic control*, vol. 60, pp. 2464–2469, 2015.

[38] A. Levant, "Robust exact differentiation via sliding mode technique," *Automatica*, vol. 34, pp. 379–384, 1998.

[39] P. Kundur, *Power systems stability and control*. NewYork: McGraw-Hill Inc, 1994.

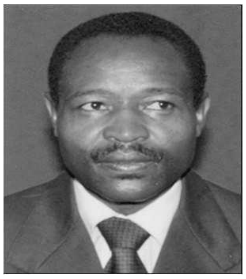
BIOGRAPHY OF AUTHORS

Fombu Andrew Muluh obtained his B.Sc., M.Sc., and Ph.D. degrees in Applied Physics Option: Electronics, Electrotechnics and Automation (EEA) from the University of Dschang in 2010, 2013, and 2017, respectively. He is presently working at the National Higher Polytechnic Institute of the University of Bamenda as a lecturer and research fellow. His research interests include nonlinear control, renewable energy, power quality, power system stability, artificial intelligence applied power system and applications of control theory to industrial systems, such as large-scale power systems. He can be contacted at email: fombuandrewmuluh@yahoomail.com.

Clotaire Thierry Sanjong Dagang received his BTech degree in Electrical and Power Engineering from the Fotso Victor University Institute of Technology, University of Dschang, Cameroon, in 2009, and the MSc and PhD degrees in Applied Physics Option: Electronics, Electrotechnics and Automation (EEA) from the University of Dschang in 2013 and 2017 respectively. He is presently working at the Fotso Victor University Institute of Technology, University of Dschang as a lecturer and research fellow. His research interests include nonlinear control, renewable energy, power quality, artificial intelligent with applications in renewable energy and power system. He can be contacted at email: sanjongthierry@yahoo.fr

Pesdjock Mathieu Jean Pierre received his BTech degree in Electrical and Power Engineering from the Fotso Victor University Institute of Technology, University of Dschang, Cameroon, in 2013, and the MSc and PhD degrees in Applied Physics Option: Electronics, Electrotechnics and Automation (EEA) from the University of Dschang in 2017 and 2021 respectively. He is a member of the Cameroonian Association for Research and Innovation in Energy Technology and Environment. He is equally a holder of a DIPET II obtained for the University of Yaounde I in 2019. His research interests include nonlinear control, artificial intelligent and optimization with applications in renewable energy and power system. He can be contacted at email: mathieuthales@gmail.com.

Lionel Leroy Sonfack received his BTech degree in Electrical and Power Engineering from the Fotso Victor University Institute of Technology, University of Dschang, Cameroon, in 2009, and the MSc and PhD degrees in Applied Physics Option: Electronics, Electrotechnics and Automation (EEA) from the University of Dschang in 2015 and 2019 respectively. His research interests include adaptive control, nonlinear control, and intelligent control with applications in FACTS Devices and power system. He can be contacted at email: liosonfack@yahoo.fr.



Godpromesse Kenne received the BEng degree in Electromechanical Engineering in 1991, M.Sc. degree in Mechanical Engineering in 1994, both from ENSP, University of Yaounde I, Ph.D. degree in Control Theory and HDR in Applied Physics from University of Paris XI, France, in 2003 and 2012, respectively. Since 1996, he has been with the University of Dschang (Fotso Victor University Institute of Technology), Cameroon, where he was Head of Department of Electrical Engineering from 2007 to 2014. He is currently a Professor and Head of Division in charge of initial training program and research. He was Guest Researcher at L2S, CNRS, University of Paris XI, and the Departement Energie, SUPELEC, in 2005, 2006, 2008, and 2012. Since April 2006, he is founding member of Unite de Recherche d'Automatique et d'Informatique Appliquee (LAIA). His research interests include identification and control of nonlinear systems using modern control technique with applications in electro-mechanical systems. He can be contacted at email: gokenne@yahoo.com.