Optimal Voltage and Frequency Control in Solar Integrated Power Network

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Abstract

This study presents the modelling and simulation of a single area power system network containing three different generating sources, solar thermal power plant (STPP), thermal, and diesel power plants. The simultaneous frequency and voltage control problem has been investigated using Linear Quadratic Regulator (LQR) and State Feedback based Sliding Mode Control (SF-SMC) design. Also, the integration of Particle Swarm Optimization (PSO) has been considered for the selection of LQR cost function weight matrices and SMC control parameters. Proper selection of LQR and SF-SMC parameters allows the controllers to handle the complexities involved in a very efficient manner and also augments necessary robustness in the controller design. The transient performance of the PSO based LQR and SF-SMC controlled system has been assessed in terms of time-domain performance indices, and it has been compared with the conventional PID and 2-DOF PID controllers. Additionally, the robustness of the proposed controllers has been tested and verified after contemplating variation in model parameters.

Keywords: Frequency control, automatic voltage control, linear quadratic, optimal control, robustness.

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Nomenclature

Parameters	Description	Values
K_{si}	Gain of solar field	1.0
T_{si}	Time constant of solar collector	1 sec
T_{gs}	Time constant of governor for STPP	1.0
T_{ts}	Turbine time constant for STPP	3.0 sec
K_{di}	Gain of the diesel plant	16.5
T_g	Time constant of the governor in thermal plant	0.08 sec
T_t	Turbine time constant of thermal plant	0.3 sec
B_i	Frequency-bias coefficient	0.425 pu MW/Hz
R	Governor droop characteristic	2.4 pu Hz/MW
D	Percentage change in load caused by percentage change in frequency	0.00833 pu MW/Hz
H	Load inertia constant	5 sec
f	Nominal frequency of the system	60 Hz
K_A	Amplifier gain in	10
T_A	Amplifier time constant	0.1 sec
K_e	Gain of exciter	1
T_e	Time constant of exciter	0.4 sec
K_f	Field circuit gain	0.8
T_f	Time constant of field circuit	1.4 sec
K_s	Sensor gain	1
T_s	Sensor time constant	0.05
K_1, K_2, K_3, K_4	Coupling coefficients between AVR and LFC	1, −0.1, 0.5, and 1.4, respectively
P_s	Synchronizing power coefficient	0.425

1 Introduction

Power industries around the world are facing a major challenge of keeping frequency and voltage stability in the system, as it is desired for the secure and safe operation of the power system network. Unceasingly changing load demand is one of the major factors responsible for causing a difference between real power demand and generation, which leads to the variation in system frequency [1, 2]. On the other hand, a sudden surge or decline in reactive loads causes the terminal voltage to change. Therefore, it is desirable to have a certain feasible prearrangement so that these oscillations in voltage and frequency can be minimized or eliminated within a very short time interval. But the abrupt increase in energy demand and also the need for carbon free renewable sources have ensured that the conventional load frequency and voltage regulation methods are not sufficient for effective neutralization of frequency and voltage oscillations. Therefore, advanced control strategies are required that can allow LFC (Load Frequency Control) and AVR (Automatic Voltage Regulator) loops to handle effectively the renewable integration as well as sudden variation in the load. In past, various authors have studied the LFC control problem, where PID controllers have been employed for the secondary control loop [3–5]. Some authors have studied advanced controllers like MPC and SMC for bringing betterment in the transient properties of the LFC loop [6–8]. While a reasonable level of research in the voltage control area involves PID and its other variants as the controller [9–13], few authors have studies AVR loop using modern control tools [14]. The minor interaction between voltage and frequency control loop has forced the researchers to study these loops independently. Recently, authors [15] have demonstrated that the LFC loop dynamics get significantly affected by the presence of AVR loop and hence these interactions between the said loops cannot be ignored. The major research in the combined AVR-LFC problem includes work from [16], where renewable integrations have been considered for combined voltage and frequency control problem. Further, meta-heuristically tuned PID controllers have been adopted by various authors for simultaneous LFC and AVR loops [17, 18].

In this work a single area power system model containing three different generation sources (thermal, diesel, and STPP) have been considered for combined voltage and frequency control. An optimal control scheme has been implemented for simultaneous control of two different loops. LQR can handle MIMO problems effectively, but it requires an appropriate selection of cost function weights. Therefore, this study proposes an optimal methodology where LQR cost function matrices have been adjusted using the PSO algorithm for balanced and efficient control of said loops. Furthermore, the State Feedback based Sliding Mode Control scheme has been implemented for securing improvements in the frequency and voltage profile of the system. The controller parameters of SF-SMC have been tuned using the PSO algorithm and the obtained response has been compared with PSO tuned LQR, PID, and 2-DOF PID control methods. The technical contributions and highlights of this research are given as:

- To study and model a combined AVR and LFC model for a power system network containing three generating units, thermal, diesel, and solar thermal power plant.
- An initial endeavour has been rendered to implement PSO based LQR and SF-SMC controller schemes for combined voltage and frequency management problem.
- The performance evaluation of the above-mentioned controllers has been carried out in terms of transient response parameters and fitness function values. The validity of controllers' efficacy has been established after comparing it with PSO tuned PID and 2-DOF PID controllers. Furthermore, the effectiveness of the proposed method has been validated after comparing the results with exiting methods available in literature.

The remaining manuscript is structured as follows: basic introduction of AVR and LFC loops is given in 2nd section, LQR, SF-SMC and PSO algorithm have been discussed in Section 3, followed by the results and conclusions in following sections.

2 System Under Consideration

The combined AVR-LFC model for a single area renewable integrated power system model has been given in Figure 1. LFC loop mainly contains the governor and turbine modelling for each generating unit, where the primary loop is responsible for making necessary changes in the prime mover power with respect to varied load demand, and the secondary loop is employed for getting zero steady-state error in the frequency of the system. The secondary loop requires an additional control action to make necessary changes in the speed reference of the governor.

A non-reheat style steam turbine has been considered for a thermal power plant in this study because it is flexible against any type of steam environment. In order to model STPP, a constant irradiance of 0.4 was used in each field, with a transport delay of 1 second. With the aid of a solar collector, a solar thermal power plant transforms solar irradiance into heat energy [7]. A thermal engine translates the obtained thermal energy into mechanical energy, which is then converted into electricity with the aid of a turbine. STPPs can produce electrical power in the range of 5 MW to 200 MW. Figure 1 shows

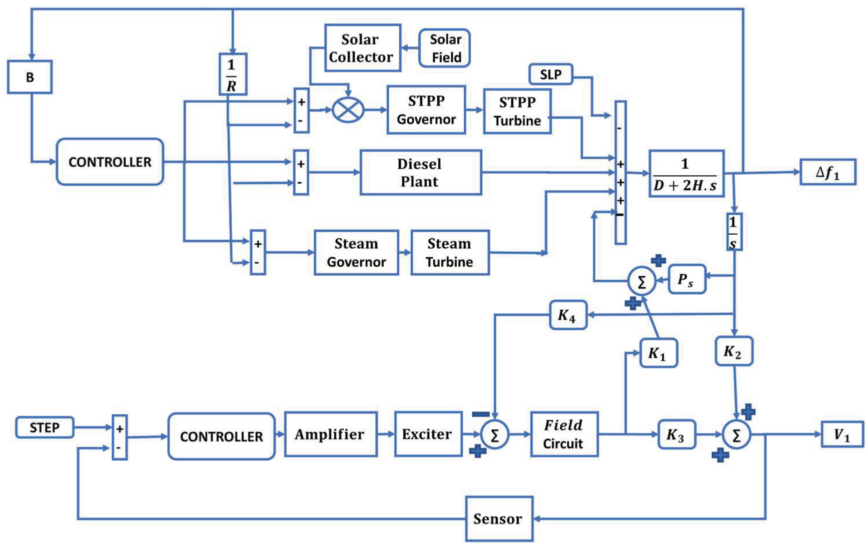

Figure 1 Block diagram of combined AVR-LFC model.

the comprehensive transfer function modelling of each variable involved in the LFC loop. The transfer function of each component involved is given as,

Steam Plant: Steam power plant has governor and turbine modelled as,

$$\text{Steam Governor} = \frac{1}{1 + T_g.s}; \quad \text{Steam Turbine} = \frac{\mathbf{1}}{\mathbf{1} + \boldsymbol{T_t} \cdot \boldsymbol{s}}$$

Solar Thermal Power Plant: STPP includes solar collector, turbine and governor as its main components.

$$\text{Solar Collector} = \frac{\boldsymbol{K_{si}}}{\mathbf{1} + \boldsymbol{T_{si}} \cdot \boldsymbol{s}}; \quad \text{STPP Governor} = \frac{\mathbf{1}}{\mathbf{1} + \boldsymbol{s} \cdot \boldsymbol{T_{gs}}};$$

$$\text{STPP Turbine} = \frac{\mathbf{1}}{\mathbf{1} + \boldsymbol{s} \cdot \boldsymbol{T_{ts}}}$$

Diesel Plant: The diesel plant is modelled using 2nd order Transfer Function model,

$$\frac{K_{di}(1 + s)}{0.025s^2 + s}$$

The AVR loop is incorporated in the system to make sure that the terminal voltage remains fixed irrespective of variations in reactive power demand, AVR loop comprises of amplifier, exciter, generator field, and sensor model. All the components of the AVR and LFC model have been modelled using first-order transfer function with parameter values listed in the beginning of this paper. The transfer function of each component is given as,

$$\text{Amplifier} = \frac{\boldsymbol{K_A}}{\boldsymbol{1 + T_A \cdot s}}; \quad \text{Exciter} = \frac{\boldsymbol{K_e}}{\boldsymbol{1 + T_e \cdot s}};$$
$$\text{Field Circuit} = \frac{\boldsymbol{K_f}}{\boldsymbol{1 + T_f \cdot s}}; \quad \text{Sensor} = \frac{\boldsymbol{K_s}}{\boldsymbol{1 + T_s \cdot s}}$$

Also, the coupling between two said loops have been considered in this study, the detailed analysis and modelling of coupling coefficients are provided in [15, 16]. The LFC loop will have a very negligible effect on the AVR loop. But, as the real power in the system is directly related to the terminal voltage in the system, hence the AVR loop will have a substantial effect on the LFC loop. Since a small variation in frequency is caused by the shift in rotor angle. The slight change in real power (ΔP_e) is a function of variation in rotor angle ($\Delta\delta$) and the generator internal EMF [2].

$$\Delta P_e = P_s \Delta\delta + K_1 E^1 \tag{1}$$

Similarly, the terminal voltage can be articulated in terms of rotor angle variation and internal EMF.

$$\Delta V_i = K_2 \Delta\delta + K_3 E^1 \tag{2}$$

Also, since the generator internal EMF (E^1) is affected by the change in rotor angle, it is important to include this effect in generator internal EMF equation,

$$\mathrm{E}^1 = \frac{K_f}{1 + T_f}[V_{field} - K_4 \Delta\delta] \tag{3}$$

K_f and T_f are the values of generator field circuit gain and time constant, V_{field} is the exciter output. P_s is the synchronizing power coefficient, and K_1, K_2, K_3, and K_4 have been considered as the coupling coefficients between the AVR and LFC loops [1, 2].

3 PSO Based LQR/SMC Control Methodology

Linear Quadratic Regulator is a very well-known and widespread method for designing optimal control strategy for linear systems. This optimal control method is based on the concept of full state feedback where control input is acquired through an optimally calculated state feedback gain matrix (*K*). This feedback matrix is calculated after solving an Algebraic Matrix Riccati Equation (AMRE) backwards in time using final boundary conditions. This AMRE is obtained after minimizing a performance index (*J*) which contains weighted input and state vectors, these weight matrices must be selected properly for obtaining desired performance. Additionally, LQR also supports reference tracking with the aid of the input scaling factor (*N*).

$$J = \frac{1}{2}\int_0^\infty x(t)^T Q x(t) + u(t)^T R u(t)]dt \tag{4}$$

The selection of weight matrices is a very challenging task as no proper method for the same is given in the existing literature. In this work, the system order is 13 with two inputs, hence *Q* matrix and *R* matrix will have 13 and 2 diagonal elements, respectively. Most of the researchers have preferred trial and error method for the selection of *Q* and *R* matrices, which may not yield good results for higher-order systems. Therefore, a meta-heuristic optimization method has been selected for the tuning of LQR cost function weights [19–21].

Because of the unmodeled dynamics and external disruptions in any real-world complex system, there will always be some inaccuracies in the model. As a result, having a control structure that can yield a decent transient response even when the design parameters are critically altered. The SMC is a renowned control method for its high robustness concerning parameter changes and external turbulences. The SMC controller is constructed on the formulation of a sliding manifold such that the process output contained within it behaves as anticipated. To guarantee the passage of system trajectories on this hypersurface, the discontinuous feedback control rule must be designed after the sliding surface has been designed. The SMC is based on variable structure control, in which a high frequency switching control rule is utilized to change the dynamics of a system. The SMC has two stages: a reaching phase and a sliding phase. The reaching method defines the movement of machine trajectories to the sliding manifold from any non-zero initial state. The controller ensures that the trajectories stay on the hypersurface for a extended time and reach their final value rendering to the sliding surface's stated dynamics during the sliding phase [22, 23].

LQR methods gives excellent transient response for linear systems, but it often fails to provide necessary robustness in the case of complex dynamical

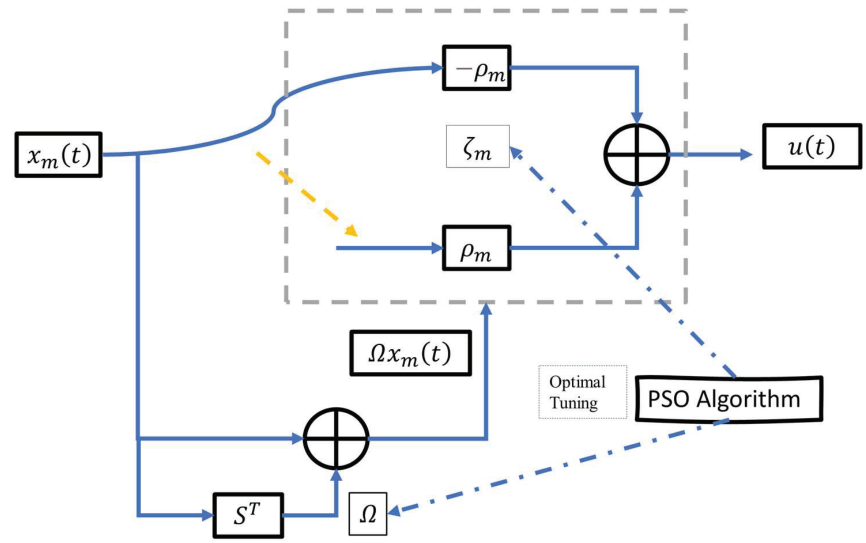

Figure 2 Block diagram illustrating proposed PSO based SMC methodology.

systems. Therefore, in this study State Feedback based SMC has been discussed. The switching law in SF-SMC would be a linear feature of system states, with state feedback control regulation is calculated to navigate the system states to their ultimate position. It is written as,

$$u(t) = -\sum_{m=1}^{n} \zeta_m x_m(t) \tag{5}$$

$x_m(t)$ is the state vector having m elements, and ζ_m is the SF gain matrix, it is written as,

$$\zeta_m = \begin{cases} \rho_m & \text{if, } \Omega x_m(t) > 0 \\ -\rho_m & \text{if, } \Omega x_m(t) < 0 \end{cases} \tag{6}$$

Here, Ω is the sliding hypersurface, which is characterized as, $\Omega = S^T x_m(t)$.

S^T is the switching vector. ρ_m and S^T can be derived with the assistance of meta-heuristic optimization approaches. Traditional state-feedback control procedures such as pole-placement and LQR can be used to obtain an initial solution for the problem [6].

PSO is nature-based methodology for encountering different complicated optimization problems. Historically, PSO was introduced by Kennedy and

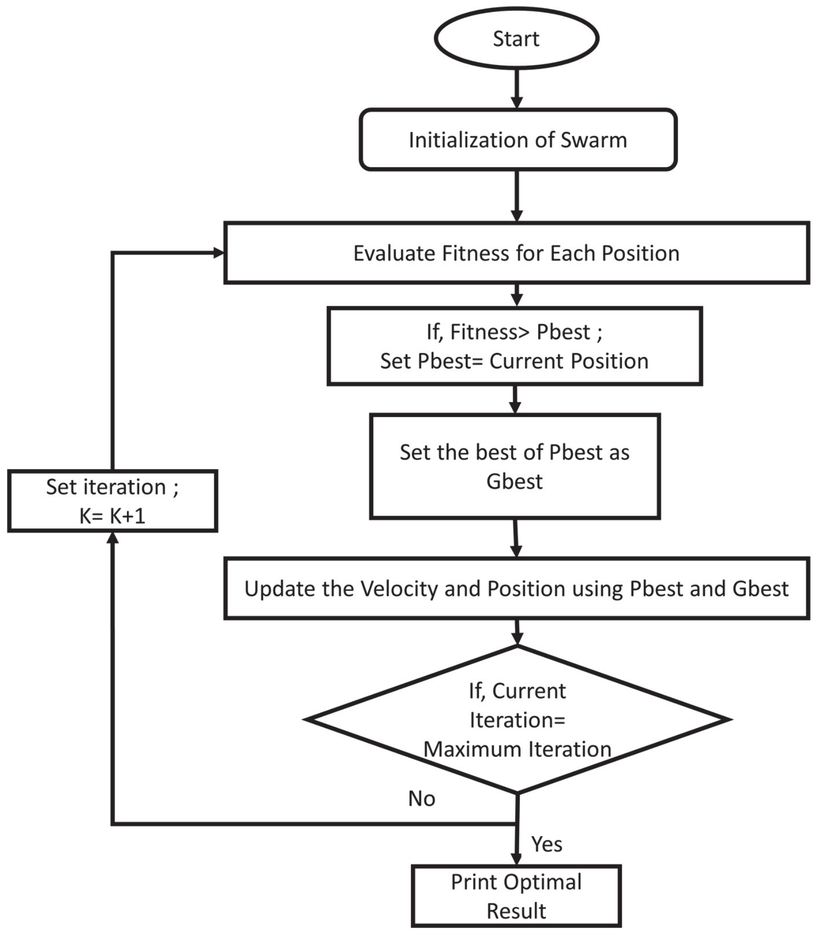

Figure 3 Algorithmic flow of PSO.

Eberhart in 1995, PSO is a metaheuristic approach that imitates the swarm conduct of various particles to evaluate optimum solution. PSO starts the solution with a randomly generated initial solution within the bounds of problem dimension, further, the velocity and position of each search agent gets swayed by their own knowledge of optimum position along with the understanding of adjacent particles [24–27]. The process flow of PSO is demonstrated in Figure 3. Each agent's optimum status within the search area is identified as P_{best}, and the status of search agent with best cost function is termed as G_{best}. The velocity and position updates of search agents are made using below given equations.

$$X_i(K+1) = X_i(K) + V_i(K+1) \quad (7)$$

$$V_i(K+1) = \omega * V_i(K) + C_1 rand(\,) * (P_{best,i}(K) - X_i(K)) + C_2 rand(\,) * (G_{best,i}(K) - X_i(K)) \quad (8)$$

4 Results and Discussion

4.1 Basic Analysis

Firstly, the PSO algorithm has been successfully implemented for the optimal tuning LQR cost function weights using ISE (integral squared error) function corresponding to the errors in voltage and frequency. For reduced complexity, the off-diagonal terms of *Q* and *R* matrices have been taken as zero, i.e., the penalty is imposed on the square of states and input values. Also, the state-feedback reference tracking parameter (*N*) is 4.25514. The obtained diagonal entries of *Q* matrix and *R* matrix are given as,

$$Q_{Diag} = [20, 20, 1.3648, 7.9886, 0, 8.9113, 0, 1.9383, 0, 0, 0, 0.5073, 6.6442]$$

$$R = \begin{bmatrix} 4.7244 & 0 \\ 0 & 1.015 \end{bmatrix}$$

Further, State Feedback based SMC control design has been implemented using PSO tuned optimal surface and control parameters.

$$S^T = \begin{bmatrix} -0.908\ -5.6452 - 9.13\ 0.9619\ 5.0681\ 5.8937\ 1.3201 \ldots \\ \ldots - 2.8386\ 1.53 - 8.12 - 1.609\ 10.5439 - 8.9956 \\ -7.2147 - 11.5747 - 2.9594\ 2.8350 - 5.7241\ 8.1814\ 1.28 \ldots \\ \ldots - 8.58\ 11.5943 - 1.222\ 14.11\ 0.6473\ 2.9897 \end{bmatrix}$$

$$\rho_m = \begin{bmatrix} 42.8937\ 22.3013 - 0.3455\ 38.8704\ 6.4041\ 24.7142 \ldots \\ \ldots 12.3201\ 6.8448\ 8.8085\ 0\ 0\ 14.5841\ 17.7199 \\ -12.386 - 23.9623\ 0 - 20.6243 - 10.5361 - 28.3954 \ldots \\ \ldots - 11.545\ 18.7964 - 40.9183\ 4.76\ 39.08 - 34.6866 - 29.08 \end{bmatrix}$$

Using these parameters, the LQR and SF-SMC have been applied on a combined AVR-LFC model where a step load perturbation (SLP) of 1% has

Table 1 Comparison of time domain performance obtained from SF-SMC, LQR, PID, and 2-DOF PID controlled systems

Controller		Overshoot	Undershoot	Settling Time	Fitness Value
SF-SMC	LFC	0.0073	−0.0115	4.75	0.000027
	AVR	2.3%	0%	1.15	0.1677
LQR	LFC	0.0434	0	4.90	0.00041
	AVR	8.2%	0%	1.2	0.2699
PID	LFC	0.006	−0.024	18.0	0.00061
	AVR	6.1%	0%	10.0	0.4746
2 DOF-PID	LFC	0.0054	−0.024	15.0	0.00055
	AVR	2.9%	0%	7.5	0.4389

Table 2 Comparison of performance with exiting methods available in literature

Controller		Overshoot	Undershoot	Settling Time
SF-SMC [proposed]	LFC	0.0073	−0.0115	4.75
	AVR	2.3%	–	1.15
FGPI [29]	LFC	–	−1.35	25
	AVR	11 %	–	6
Hybrid NN+FTF [30]	LFC	–	−0.045	9
	AVR	–	–	–
Fuzzy PID [31]	LFC	–	−0.0025	24
	AVR	0.25 %	–	22

been measured, and the transient performance has been evaluated in terms of overshoot, undershoot, settling time, and fitness function (ISE) values. The effectiveness of PSO tuned LQR and SF-SMC methods have been confirmed after comparing its performance with that of PSO tuned PID and 2-DOF PID controllers.

Further, the obtained results from proposed PSO-SMC method have been compared with existing methodologies available in literature [29–31]. Table 2 shows that the proposed method provides better results than existing methodologies in terms of transient response specifications. Reduced settling time and oscillations in frequency and voltage are necessary for effective and efficient operation of power system network. The cost function (ISE) value for SMC-PSO controlled system is minimum for both frequency and voltage control loops. The conventional methods for calculation of SMC controller gain and surface variables requires very hight computational efforts. The proposed control method uses meta-heuristic algorithm for the computation of its control parameters, which saves a lot of computational effort and cost.

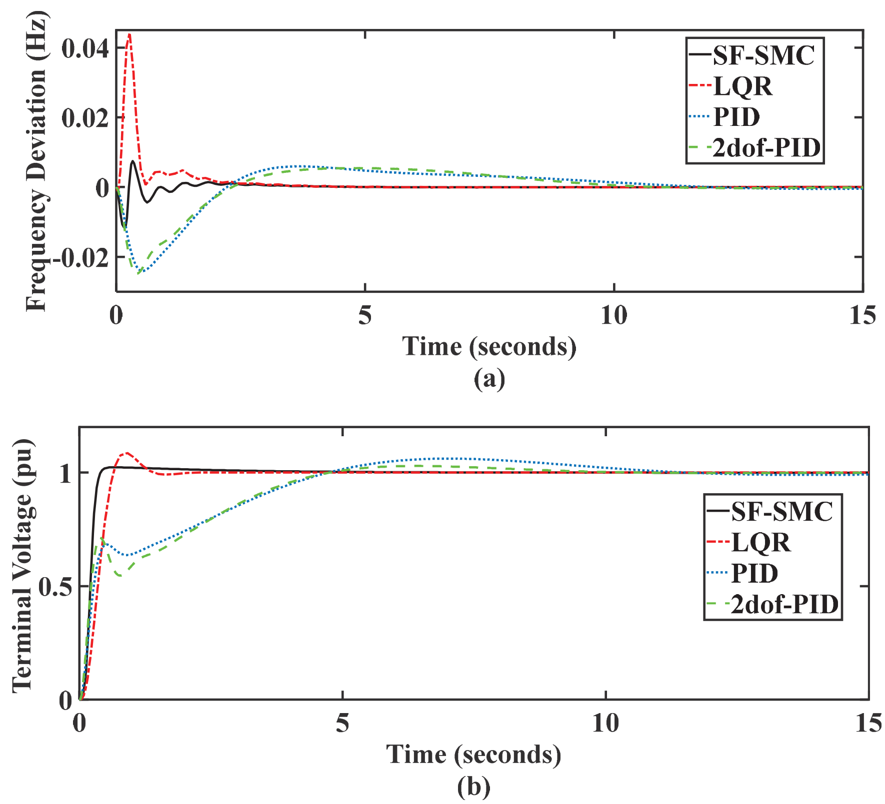

Figure 4 Transient response plots obtained after using LQR, SF-SMC, PID, and 2-DOF PID controllers for; (a) frequency deviation, (b) terminal voltage.

4.2 Parameter Sensitivity Analysis

In this assessment, the robustness of the proposed LQR and SF-SMC methods have been investigated after introducing variations in the parameters of the AVR-LFC model. Under the first subcase the step load perturbation has been varied from 1% to 5% and 10% and corresponding transient response characteristics have been plotted in Figure 5, the terminal voltage profile remains unaltered when the SLP value is varied.

Further, the parameter sensitivity has been considered in the AVR loop when the time constant parameters of the exciter model have been differed from −20% to +20% of its original value in the intervals of 10%. To study the effect of sensitivity, the resulting voltage and frequency characteristic plots have been evaluated for each case and have been plotted in Figure 6.

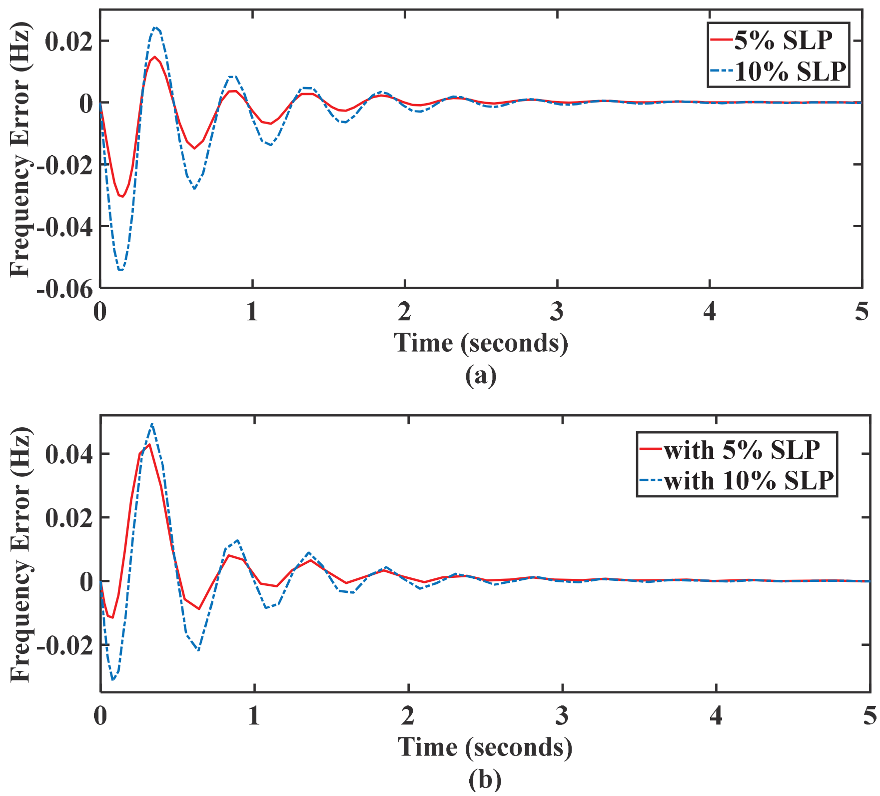

Figure 5 Transient response plots of frequency error obtained after varying the SLP value of LFC loop using; (a) SF-PID, (b) LQR.

From the obtained characteristics plots, it can be observed that sensitivity in step load perturbation (SLP) degrades the transient characteristics of the frequency profile while terminal voltage remains unaffected. Additionally, the sensitivity in exciter parameters have affected the performance of the AVR loop and is demonstrated in Table 3.

4.3 Nonlinearity Analysis

In this case, various nonlinearities involved in the power system model have been considered with nominal controller parameters. This case study helps in validating the robustness of the proposed SF-SMC and LQR controller schemes. Here, generation rate constraint (GRC) and governor dead-band (GDB) have been considered in the turbine and governor modelling of the

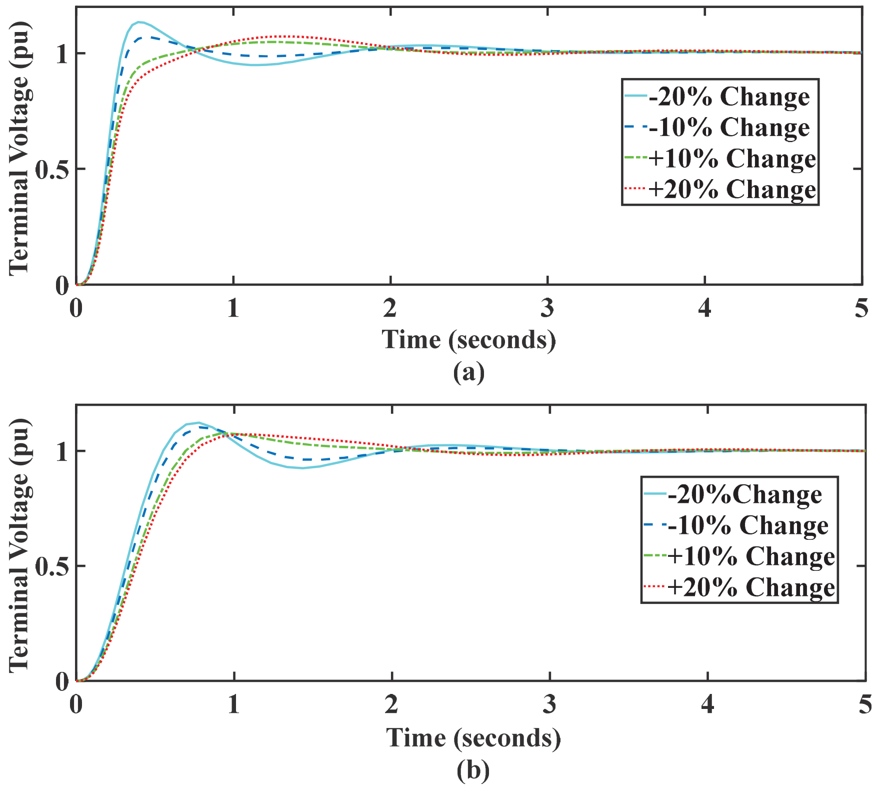

Figure 6 Transient response plots obtained after varying exciter time constant values of; (a) SF-SMC controlled system, (b) LQR controlled system.

Table 3 Transient response of voltage and frequency profile of the system under parameter variation cases

		Frequency Error (Using SMC)			Frequency Error (Using LQR)		
Parameter Variation		ST (sec)	US	OS	ST (sec)	US	OS
SLP	5%	4.3	−0.0308	0.0145	8.25	−0.0112	0.0426
	10%	4.5	−0.0541	0.0244	8.45	−0.0309	0.0491
		Terminal Voltage (Using SMC)			Terminal Voltage (Using LQR)		
		ST (sec)	US	OS	ST (sec)	US	OS
Percentage	−20%	2.65	5.13%	13.4%	2.57	7.5%	12.1%
Change in	−10%	2.51	1.3%	6.8%	1.90	3.8%	10.0%
Exciter Time	+10%	1.93	0%	4.8%	1.60	0%	7.5%
Constant	+20%	2.0	0%	7.2%	2.0	1.85%	7.2%

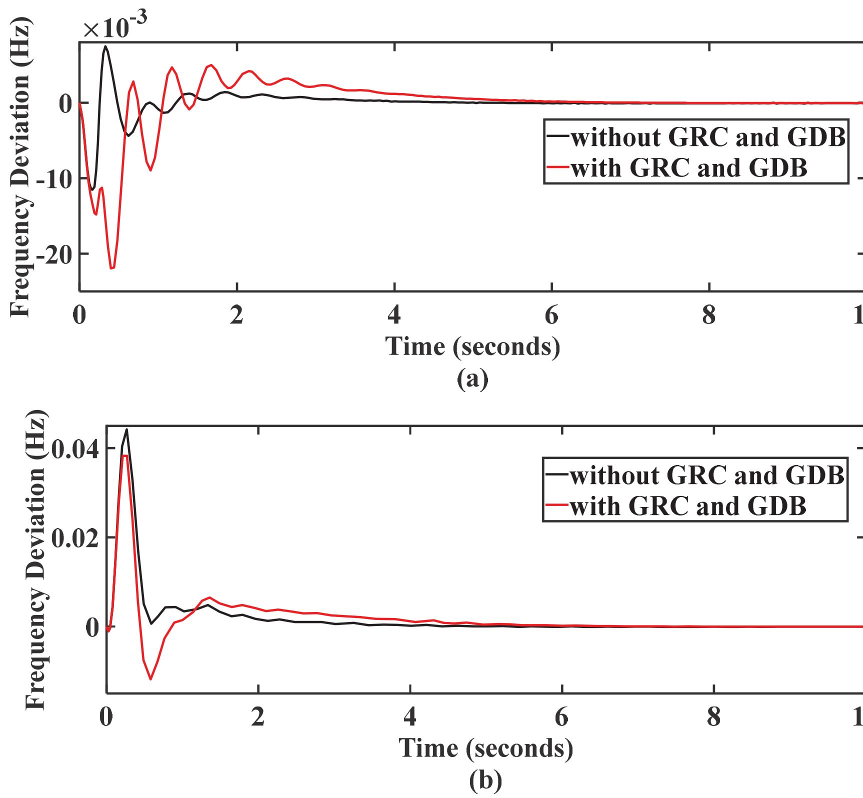

Figure 7 Transient response plots obtained after considering nonlinearities in; (a) SF-SMC controlled system, (b) LQR controlled system.

thermal generating unit. The transient characteristics plots of the system including nonlinearities have been plotted in Figure 7.

5 Conclusions

This paper investigated the collective voltage and frequency regulation problem for a single area power system network with the aid of MATLAB/SIMULINK software. Further, the PSO optimized Linear Quadratic Regulator (LQR) and State Feedback based Sliding Mode Control (SF-SMC) methods have been successfully implemented for effective control of voltage and frequency in renewable (solar) integrated thermal and diesel power plants. The controller performance has been verified by determining its transient state specifications with that of PSO tuned PID and 2-DOF PID controllers. Furthermore, the validation of robustness has been established by varying the parameter values of AVR and LFC loops and re-evaluating the transient profile of the renewable integrated system. From the results obtained, both LQR and SF-SMC methods give qualitative transient and robustness performance for the collective voltage and frequency management of the system. Further, from the results it is evident that the PSO tuned SF-SMC method provides better functioning as compared to the optimal LQR method.

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