Mitigation of Uncertainty in an Islanded Microgrid Using Robust Voltage Controller

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Abstract

In microgrid, a severe problem occurs in terms of voltage oscillations due to mismatch between synchronizing and damping torque. In this study, a centralized nonlinear sliding mode voltage controller proposes to minimize the rotor and DC voltage oscillations issue in an islanded microgrid. The linear matrix inequality (LMI) technique has been applied for bounding the state error. Lyapunov criteria is utilized for assurance of asymptotic convergence and LMI optimization approach is used for obtaining the controller parameters. The proposed controller is able to tackle the parametric uncertainties of diesel generator, oscillations of rotor and voltage fluctuation as well as the closed-loop system responses also improves both transient responses and steady state responses simultaneously. The simulation results authenticate

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that the proposed controller confirms speedy recovery of nominal frequency without any oscillations and reduced the limitation of chattering notably without any loss in control accuracy. The performance and robustness of the proposed controller is also compared with conventional controllers.

Keywords: Microgrid voltage control, nonlinear sliding mode controller, linear matrix inequality optimization, system uncertainty.

1 Introduction

Due to limited sources of fossil fuels and environmental pollution are basic cause to find an alternative solution of power generation. As results, renewable energy resources are utilized as an alternative source of power. Recent studies have been shown that renewable energy has a remarkable share of future electricity need even after consideration of several limitations [1]. The renewable energy resources are freely available in nature and can be used to generate electricity. The microgrid concept-based power generation is more economical compared to fossil fuel-based generation and also it is environment friendly. This idea brings the concept of microgrid which became an interesting technology in the several renewable plant integrations based centralized control nowadays [2].

Thus, continuous localize increased power demand can be managed using a community Microgrid [3]. In a distribution type system, if high renewable penetration is considered then it faces too many technical and operational problems just like quality of power, stability and voltage of network as well as frequency deviation. In order to solve this issue by using concept of microgrid was developed by researchers [4, 5]. In [6], several functional and technical problems such as ownership, coordinated equipment control, frequency control etc. are highlighted effectively. With the help of two methodology of microgrid named as grid connected mode, which is connected to utility grid by a static stitch, while another one named as islanding mode, which is not giving any power to microgrid [7]. Very basic parameters of distinct type microgrid described as a single controllable entity from grid and generate frequency and reference voltage in an islanded operation mode [8].

For generation of electricity by renewable energy resources like photovoltaic, tidal, wind etc. the controller is playing the key role for proper generation and distribution of energy resources and mitigating the effect of disturbances/uncertainties in parameters. Thus, in the literature, several controllers such as proportional-integral-derivation (PID) controller [9, 10] were used to minimize the effect of disturbances/uncertainties in parameters. Due to static nature, PID controller is not capable to sustain closed loop performance against disturbances/uncertainties in parameters [11]. As results, microgrid is affected from the frequency deviation or even leads to system instability. However, the frequency deviation in an isolated mode of operation of microgrid is still formidable task due to intermittent nature of distributed energy resources.

Sliding mode controller is utilized to extract maximum power from wind even in presence of wind speed uncertainties [12]. The microgrid frequency is regulated even in presence of stochastic uncertainties and disturbances using several optimization such as two dimensional Sine Logistic map based chaotic sine cosine algorithm (2D-SLCSCA) based PID controller [11], grasshopper algorithmic technique based PI controller [12], fast frequency response optimized power point tracking method [13], h-infinity optimization based PID controller [14], genetic algorithms based PI controller [15], genetic algorithm based grid-forming droop control [16] etc. Thus, islanded microgrid frequency and voltage deviations against uncertainties, outage of power or load and load disturbances in distributed generations are still required further developments.

In this study, diesel generator and DC voltage solar PV based DC to AC converter has been considered and its state-space model is developed with assumption of mechanical torque for small perturbations. The performance of automatic voltage regulator (AVR) associated with diesel generator models are not sufficient to reduce frequency and voltage deviations against load disturbances and parametric uncertainties. Hence, parametric uncertainties are taken in rotor angle feedback gain constant (K_5) [17] and solar plant DC voltage due to random and uncertain nature of sunlight. In addition, loads are random and unknown in nature and as results, it may create frequency and voltage deviation with oscillations. Due to above causes, an involuntary stress is faced by distributed generations. These uncertainties and load disturbances deteriorate microgrid overall performance in terms of frequency and voltage fluctuations or even microgrid becomes unstable. Thus, above plant uncertainties may be reduced via a centralized controller based proper coordination and switching of inverter. Thus, more precisely the work done in this paper is as follows:

- A centralized nonlinear sliding mode control (SMC) based microgrid central controller is proposed to mitigate frequency and voltage fluctuations problem in an islanded microgrid.

- The proposed control scheme is capable to regulate both plant in proper coordinated way till frequency and voltage fluctuations approaches to zero.
- Closed-loop system responses improves both transient responses as well as steady state responses simultaneously against solar DC voltage uncertainty and diesel generator parametric uncertainties.
- The proposed controller confirms speedy damp out of rotor oscillation, microgrid frequency and voltage fluctuations, and reduces the limitation of chattering notably without any loss in control accuracy.

This paper is organized as follows: dynamic modeling of diesel generator and a DC voltage solar PV based DC to AC inverter model are reviewed in Section 2 followed by complete state space analysis of islanded microgrid. The application of nonlinear sliding mode controller and the Lyapunov's stability analysis are discussed in Section 3. The simulation results and demonstrations of proposed controller on an islanded microgrid are illustrated in Section 4 followed by concluding remarks in Section 5.

2 Islanded Microgrid System Model

Electrical loads are random and unknown in nature and as results, it may create frequency and voltage deviation with oscillations. Due to above causes, an involuntary stress is faced by distributed generations. As results, harmonic, frequency and voltage oscillations are produced [18]. Hence, a centralized controller is needed to reduce frequency and voltage oscillations against load disturbances and parametric uncertainties. Thus, a linearized model of diesel generator with excitation system and DC to AC converter model is taken and it sufficient to analyze the islanded microgrid dynamics for a small signal approach. Both generation system dynamics are described in the following subsections:

2.1 Dynamic Model of Diesel Generator

A simplified dynamics model of diesel generator with excitation system model is represented in Figure 2 and first order transfer function for small signal analysis has been considered. The diesel generator is a union of diesel engine with electric alternator. It converts mechanical energy received from a combustion engine into electrical energy and is also preferable due to economical usage of fuel in comparison to steam generators [19, 20]. The dynamic model of diesel generator mainly has three components:

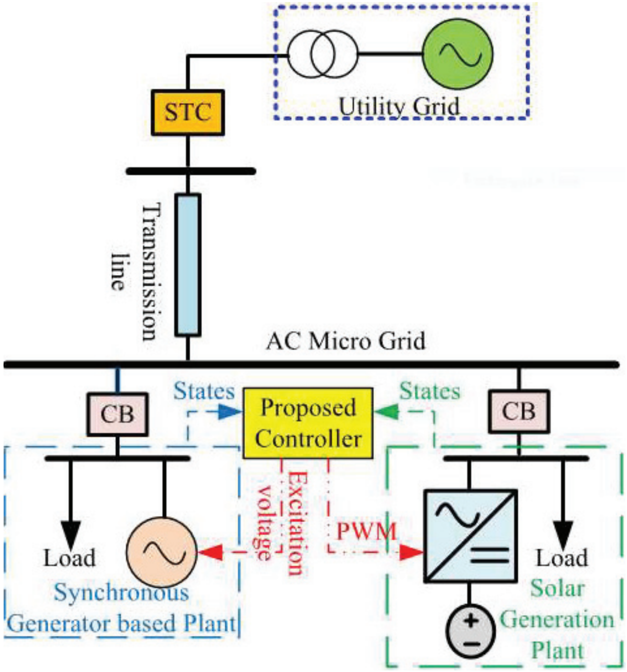


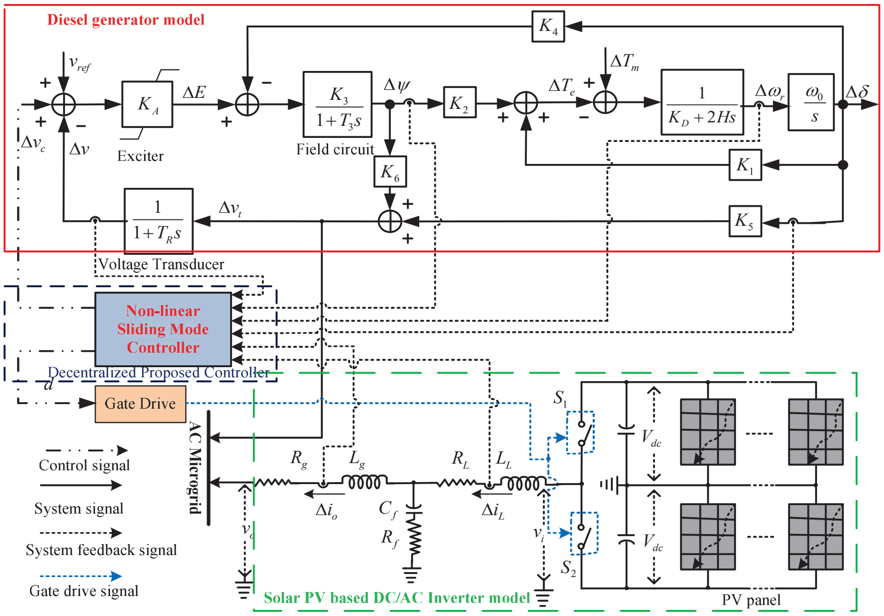
Figure 1 Schematic diagram of the microgrid.

(a) prime mover with speed-governor valve, (b) synchronous generator, and (c) automatic excitation system.

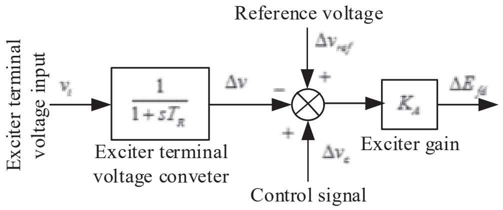
The excitation system stabilizes the generated voltage against variation on mechanical torque uncertainties and the speed-governor valve regulates the prime mover speed linearly to minimize the power mismatch and oscillations [1, 20]. The schematic diagram of microgrid and utility grid has been shown in Figures 1 and 2(b). In this study, classical dynamic model of diesel generator is designed a synchronous generator, an AVR and a speed governor and taken from [17]. The classical diesel generator model acceleration dynamics is described as:

$$\Delta\dot{\omega}_r = \frac{1}{2H}(\Delta \mathrm{T}_m - \Delta \mathrm{T}_e - K_D \Delta\omega_r) \tag{1}$$

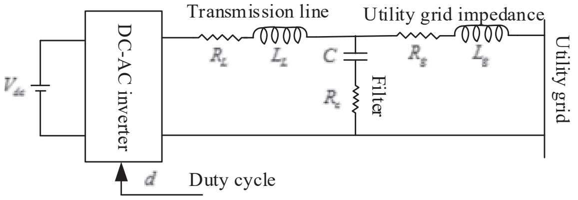
where, terms H, $\Delta\mathrm{T}_m$, $\Delta\mathrm{T}_e$, K_D and f_0 are the inertia constant (per MVA), change in mechanical torque (N-m), change in electrical torque (N-m), damping constant (N per m) and nominal frequency (Hz) respectively. Electrical torque linearized dynamic $\Delta\mathrm{T}_e = K_1\Delta\delta - K_2\Delta\psi$ is considered [17] and



a) Islanded microgrid structure with proposed controller



b) Representation of diesel generator excitation system



c) Simplified DC voltage solar PV based DC to AC inverter model

Figure 2 Microgrid structure with centralized proposed controller [17, 20].

substitutes in Equation (1) as:

$$\Delta\dot{\omega}_r = \frac{1}{2H}(\Delta \mathrm{T}_m - K_1\Delta\delta - K_2\Delta\psi - K_D\Delta\omega_r) \tag{2}$$

where, K_1,K_2 and $\Delta\psi$ are synchronizing coefficients and change in generator magnetic flux.

The dynamics relation between states $\Delta\omega_r$ generator angular speed (rad/s) and $\Delta\delta$ rotor angle (rad) is defined as.

$$\Delta\dot{\delta} = 2\pi f_0\Delta\omega_r \tag{3}$$

Generator field flux dynamics are written as:

$$\begin{aligned}\Delta\dot{\psi} = &-\frac{2\pi f_0 m_1 R_{fd} L'_{ads}}{L_{fd}}\Delta\delta - \frac{2\pi f_0 R_{fd}}{L_{fd}}\left[1 - \frac{L'_{ads}}{L_{fd}} + m_2 L'_{ads}\right]\Delta\psi \\ &- \frac{2\pi f_0 R_{fd} K_A}{L_{adu}}\Delta v + \frac{2\pi f_0 R_{fd} K_A}{L_{adu}}\Delta v_c \end{aligned}\tag{4}$$

where, terms R_{fd}, L'_{ads}, L_{fd}, L_{adu}, m_1 and m_2 are generator field system parameters. The term K_A is derived from exciter transfer function and known as exciter gain. The state variable Δv is field excitation voltage (volt) of the diesel generator respectively. The generator AVR is considered [17] as shown in Figure 2 and is written as:

$$\Delta\dot{v} = \frac{K_5}{T_R}\Delta\delta + \frac{K_6}{T_R}\Delta\psi - \frac{1}{T_R}\Delta v \tag{5}$$

Terminal voltage error can be obtained using following equation:

$$\Delta v_t = K_5\Delta\delta + K_6\Delta\psi \tag{6}$$

where, terms K_5 and K_6 are excitation system parameters. Value of term K_5 is always positive while term K_6 can be either positive or negative due to dependency on the external circuit impedance [17].

2.2 Model of DC to AC Inverter Dynamics

In this study, DC voltage solar PV based DC to AC inverter including battery energy storage system is considered [21] as shown in Figures 2(a) and 2(c). For small perturbation, filter dynamics are neglected and filter terminal voltage is not considered as feedback in controller design. The inverter is simple taken as bi-directional ideal switches [22] and its output voltage v_i is varied from V_{dc} to $-V_{dc}$ as per duty cycle d using centralized controller. Thus, duty cycle is defined based on t_{on} and t_{off} time and written as:

$$d = \frac{t_{on} - t_{off}}{T} \tag{7}$$

where, term $T = t_{on} + t_{off}$ is known as switching time interval. Inverter output voltage can be written using time-average approach as:

$$v_i = \frac{t_{on}V_{dc} + t_{off}(-V_{dc})}{T} = dV_{dc} \tag{8}$$

Now, inverter transmission line current Δi_L and utility grid output current Δi_o are taken as equal due to negligible filter. The equivalent dynamics of transmission line and inductive nature of utility grid [21] as shown in Figure 2 can be written as:

$$v_i - v_g = (R_L + R_g)i_0 + (L_L + L_g)\frac{\partial i_0}{\partial t} \tag{9}$$

After, deviation in grid output current with negligible change in grid voltage is given as:

$$\Delta\dot{i}_0 = \frac{1}{(L_L + L_g)}v_i - \frac{(R_L + R_g)}{(L_L + L_g)}\Delta i_0 \tag{10}$$

After substitution of v_i from Equation (8) into Equation (10), it gives as:

$$\Delta\dot{i}_0 = -\frac{(R_L + R_g)}{(L_L + L_g)}\Delta i_0 + \frac{V_{dc}}{(L_L + L_g)}\Delta d \tag{11}$$

2.3 Islanding Microgrid Model

However, state space model as represented in Figure 2(a) and Equations (1) to (11) are written as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + D\Delta T_m(t) \\ y(t) &= Cx(t) \end{aligned} \tag{12a}$$

where, $x(t)$, $u(t)$, $y(t)$ and $\Delta T_m(t)$ are microgrid state variables, input, output and mechanical torque disturbances respectively. The system matrices

$A \in \Re^{n}$, $B \in \Re^{n\times k}$, $D \in \Re^{n\times r}$ and $C \in \Re^{m\times n}$ are matrices are given as:

$$A = \begin{bmatrix} -\frac{K_D}{2H} & -\frac{K_1}{2H} & 0 & -\frac{K_2}{2H} & 0 \\ 2\pi f_0 & 0 & 0 & 0 & 0 \\ 0 & \frac{K_5}{T_R} & -\frac{1}{T_R} & \frac{K_6}{T_R} & 0 \\ 0 & -\frac{2\pi f_0 m_1 R_{fd} L'_{ads}}{L_{fd}} & -\frac{2\pi f_0 R_{fd} K_A}{L_{adu}} & -\frac{2\pi f_0 R_{fd}}{L_{fd}}\left[1 - \frac{L'_{ads}}{L_{fd}} + m_2 L'_{ads}\right] & 0 \\ 0 & 0 & 0 & 0 & -\frac{R_L + R_g}{L_L + L_g} \end{bmatrix},$$

$$x(t) = \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta v \\ \Delta\psi \\ \Delta i_0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{V_{dc}}{L_L + L_g} \\ 0 & 0 & 0 & \frac{2\pi f_0 R_{fd} K_A}{L_{adu}} & 0 \end{bmatrix}^T,$$

$$C = \begin{bmatrix} 0 & K_5 & 0 & K_6 & 0 \\ 0 & 0 & 0 & 0 & -R_g \end{bmatrix},\ D = \begin{bmatrix} \frac{1}{2H} & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

$$u(t) = \begin{bmatrix} \Delta v_c & \Delta d \end{bmatrix}^T$$

Now, above Equation (12) is transferred into regular form using $z(t) = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = T_{tranf}x(t)$, $T_{tranf}T_{tranf}^T = I$. After simplification, Equation (12) is rewritten as:

$$\begin{bmatrix} \dot{z}_1(t) \\ \dot{z}_2(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ B_2 \end{bmatrix} u(t) + \begin{bmatrix} D_1 \\ D_2 \end{bmatrix} \Delta T_m(t) \tag{12b}$$

where, $z_1(t) = \begin{bmatrix} \Delta\omega_r & \Delta\delta & \Delta v \end{bmatrix}^T$ and $z_2(t) = \begin{bmatrix} \Delta\psi & \Delta i_0 \end{bmatrix}^T$.

2.4 Objective of the Proposed Study

Basic objective of this study is to minimize frequency and voltage fluctuations in microgrid against plant uncertainties. A centralized nonlinear sliding mode control (SMC) controller is proposed to mitigate frequency and voltage fluctuations in an islanded microgrid. The proposed control scheme is capable to regulate both plants in proper coordinated way till frequency and voltage fluctuations approaches to zero. Hence, closed-loop system responses improves both transient responses as well as steady state responses simultaneously against solar DC voltage uncertainty and diesel generator parametric uncertainties.

3 Proposed Control Methodology

The sliding mode control technique is a resilient control scheme against uncertainties, outage of power or load and load disturbances in distributed generations because of its insensitivity nature towards the change in system dynamics and disturbances [23–29]. The utmost benefit of using sliding mode control (SMC) approach is its sliding action along a bounded switching surface or line. The design of sliding mode controller is divided into two dynamic phases i.e., the reaching phase and sliding phase [28, 29]. The trajectories of the closed-loop system are reached and then remains slide on it within pr-defined limit. The load disturbance and system uncertainties in dynamics of reaching phase is highly preferable for selection of nonlinear sliding surface. The nonlinear function is selected any nonlinear function having following two characteristics:

- *Whenever a frequency deviation $\tau(t) = \Delta f$ occurred, nonlinear function $\varphi(\tau)$ changes from zero to a negative of final value.*
- *The nonlinear function should be differential.*

Hence, selected nonlinear function in this study is considered [28] as $\varphi(\tau) = \frac{-\gamma}{1-e^{-1}}(e^{-(1-(\frac{\tau-x_0}{r-x_o})^2)} - e^{-1})$ for islanded microgrid. After selection of nonlinear function, switching surface is designed using nonlinear function $\varphi(\tau)$, initial feedback gain K and positive definite matrix P. The matrix term P is derived from closed loop system stability criterion using linear matrix inequality (LMI) [28]. Thus, the switching surface are given using Equation (12b) as:

$$s = \begin{bmatrix} K - \varphi(\tau)A_{12}^T P & 1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{13}$$

Now apply reaching and sliding conditions [28] on above Equation (13), after simplification, it give:

$$\dot{z}_1 = (A_{11} - A_{12}s_1)z_1 + D\Delta T_m \tag{14}$$

The stable trajectory of Equation (14) depends on nonlinear function $\phi(\tau)$ and nonlinear function also depends on the $\tau(t) = \Delta f$. The variable term $s_1(t) = K - \varphi(\tau(t))A_{12}^T P$ consists of linear and nonlinear terms, and vary according to frequency deviation [28]. First, whenever microgrid frequency deviation is zero means term $\tau(t)$ is zero. Then nonlinear function $\phi(\tau)$ is also zero due to zero frequency deviation and this condition is applied in Equation (14) and it gives:

$$\dot{z}_1 = (A_{11} - A_{12}K)z_1 + D\Delta T_m \tag{15}$$

Above Equation (15) stability is obtained using following LMI:

$$P > 0$$

$$[(A_{11} - A_{12}K)^T P + P(A_{11} - A_{12}K)] < 0 \tag{16}$$

Second, islanded microgrid have non-zero frequency deviation then nonlinear function $\phi(\tau)$ may reach its maximum final value γ [28]. This condition is used to apply in Equation (14) and after simplification, it gives:

$$\dot{z}_1 = (A_{11} - A_{12}\gamma)z_1 + D\Delta T_m \tag{17}$$

Now equivalent damping ratio of Equation (17) is considered as equivalent final state feedback gain K_f. The term K_f is written as:

$$K_f = K + \gamma A_{12}^T P \tag{18}$$

Equation (18) is written in inequality constraints as:

$$A_{12}^T P - \frac{K_f - K}{\gamma} = W,\ \|W\| \leq \varepsilon \tag{19}$$

Now, Equation (19) is converted into LMI using Schur complement [28] as:

$$\begin{bmatrix} \varepsilon \mathrm{I} & \mathrm{W} \\ \mathrm{W}^T & \varepsilon \mathrm{I} \end{bmatrix} > 0 \tag{20}$$

Hence, to achieve desired responses both LMI Equations (16) and (19) should feasible simultaneously. So, linear matrix inequalities (LMIs) optimization technique is used to obtain P:

$$\begin{gathered} P > 0 \\ [(A_{11} - A_{12}K)^T P + P(A_{11} - A_{12}K)] < 0 \\ \begin{bmatrix} \varepsilon \mathrm{I} & \mathrm{W} \\ \mathrm{W}^T & \varepsilon \mathrm{I} \end{bmatrix} > 0 \end{gathered} \tag{21}$$

Theorem 1: To achieve a variable switching surface with variable damping factor of the closed loop system simultaneously, the SMC control law is design as:

$$u = \begin{bmatrix} \Delta v_c \\ \Delta d \end{bmatrix} = -B_2^{-1}\left(s^T A\ z - \frac{d\phi(\tau)}{dt} A_{12}^T P\ s_1 + \bar{\kappa} s + \rho\ sign(s)\right) \tag{22}$$

The control terms Δv_c and Δd are control effort of diesel generator model and inverter model. The variable switching surface is bounded using positive constant ($0 < \bar{\kappa} < 1$) and boundary limit constant $\rho \geq \|\Delta T_m\|$ respectively.

Proof: The asymptotic convergence criteria is proved using the Lyapunov's function as:

$$\vartheta = \frac{1}{2} s^T \mathrm{s} \tag{23}$$

Equation (23) is differentiated and after substitution from Equations (14) and (12b) and simplification, it is written as:

$$\dot{\vartheta} = s^T \left[s^T A z - \frac{d\phi(\tau)}{dt} A_{12}^T P s_1 + (s_1 D_1 + D_2)\tau + B_2 u \right] \tag{24}$$

Equation (22) is substituted in Equation (24) and after simplification, it gives:

$$\dot{\vartheta} \leq -s^T \rho \operatorname{sign}(\mathrm{s}) - \varsigma_{\min}(\lambda)\|s\|^2 + \|s\|(\|s_1\|\|D_1\| + \|D_2\|)\rho \tag{25}$$

The closed loop dynamics of microgrid with SMC law converges asymptotically as $\dot{\vartheta} < -\chi|s|$ for some $\chi > 0$ within a sphere radius as:

$$\|s\| > \frac{1}{\varsigma_{\min}(\lambda)}[(\|s_1\|\|D_1\| + \|D_2\|)\rho] \tag{26}$$

This completes proof.

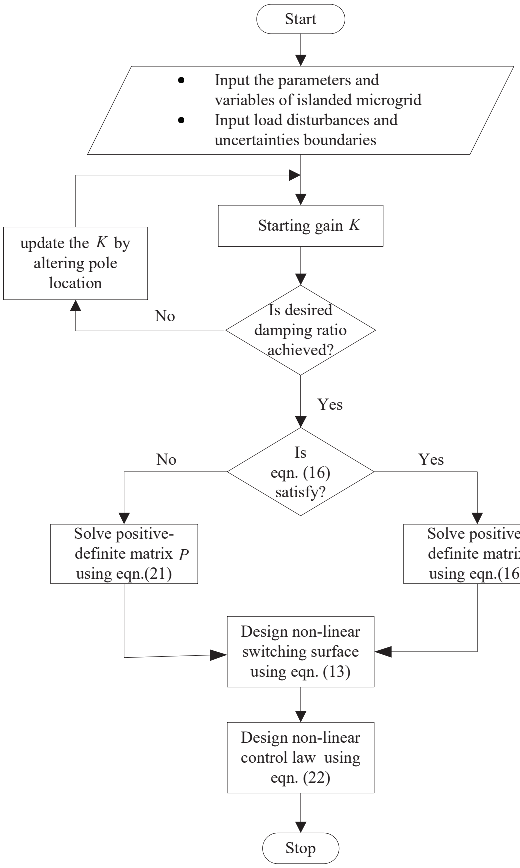
The proposed controller design steps flow chart and state diagram are given in Figures 3(a) and 3(b) respectively.

4 Simulated Responses and Deliberations

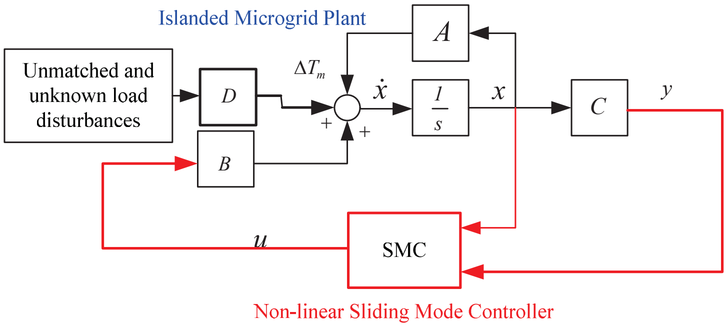
To evaluate the performance of proposed control strategy, state-space dynamics of islanded microgrid is simulated using MATLAB© 2014a software as shown in Figure 2(a). The microgrid system parameters are given in Table 1. In this study, microgrid contains diesel generation [17] and solar PV based battery source [20] with rating 20kW, 3-phase, 4-wire, 60 Hz, 380/220-volt, 1800 rpm and 6 kW, 400 volts respectively. The generator voltage exciter is considered as brushless and represented as first order transfer function with gain 187.0 and time constant 0.05 sec. All simulations are performed at zero initial conditions.

The open-loop system poles, dominant poles damping ratio and natural damping frequency of linearized microgrid system. The eigenvalues of microgrid for both cases i.e., with controller and without controller are given in Table 2. It is seen that open loop system have one poles lie on right hand side and damping ratio as well as natural frequency oscillations are too low and high respectively. As result, open loop system is unstable. The desired closed loop time characteristics are given in Table II and enhanced overall system performance against different disturbances.

The performance of the sliding mode controller is demonstrated in presence of zero initial condition, DC voltage uncertainty and rotor angle feedback gain uncertainty as follows:



a) Flow chart of proposed controller



b) State diagram of complete system

Figure 3 Flow chart of proposed controller.

Table 1 Parameters and its values

System Parameter	Values (In Unit)	System Parameter	Values (In Unit)
$\mathrm{K_D}$	0	$\mathrm{K_a}$	200
H	3	$\mathrm{R_{fd}}$	0.0006
$\mathrm{K_1}$	1.591	$\mathrm{m_1}$	1.0473
$\mathrm{K_2}$	1.5	$\mathrm{L_{fd}}$	0.153
$\mathrm{K_3}$	0.333	$\mathrm{L_{ads}}$	1.64899
$\mathrm{R_L}$	0.01	$\mathrm{L_{adu}}$	1.65
Rg	0.01	$\mathrm{m_2}$	0.8802
$\mathrm{L_L}$	0.005	$\mathrm{L_{as}}$	1
$\mathrm{K_5}$	0.12	$\mathrm{K_a}$	187
$\mathrm{K_6}$	0.3	Lg	0.001
ω_0	376.8	$\mathrm{V_{dc}}$	400
$\mathrm{T_R}$	0.05	$\mathrm{K_r}$	1

Table 2 Microgrid system poles location, damping ratio and natural frequency

Open-loop System Poles Locations	Open-loop System Damping Ratio and Natural Frequency (rad/sec)	Closed-loop System Poles Locations	Closed-loop System Damping Ratio and Natural Frequency (rad/sec)
Dominant poles: −0.9132+29.6993i; −0.9132−29.6993i; Other poles: −18.4711, 12.6009, −3.3333	$\omega_n = 29.7133$ and $\partial = 0.0307$ Remark: open-loop system is unstable.	Dominant poles: −3.000. Other poles: −6.000, −12.500+0.9825i, −12.500−0.9825i	$\omega_n = 12.5386$ and $\partial = 0.9969$ Remark: closed-loop is stable.

4.1 Islanded Microgrid Response in Presence of Rotor Angle Feedback Gain K_5 Uncertainty

The proposed controller is implemented on the islanded microgrid system and simulated with all states zero initial conditions in presence of rotor angle feedback gain uncertainty. The rotor angle feedback gain uncertainty is varied via decrease in step mechanical shaft torque input $\Delta T_m = -4.0$ (N-m). The deviations in frequency, angular frequency, rotor torque angle and flux density in diesel generator dynamics are shown in Figure 4. It is seen that frequency is decreased in short time interval due to decrease in mechanical shaft torque input and frequency is attained nominal value by the action of nonlinear sliding mode controller.

Thus, frequency deviation is minimized via a coordinated control between excitation system of diesel generator and inverter current injections.

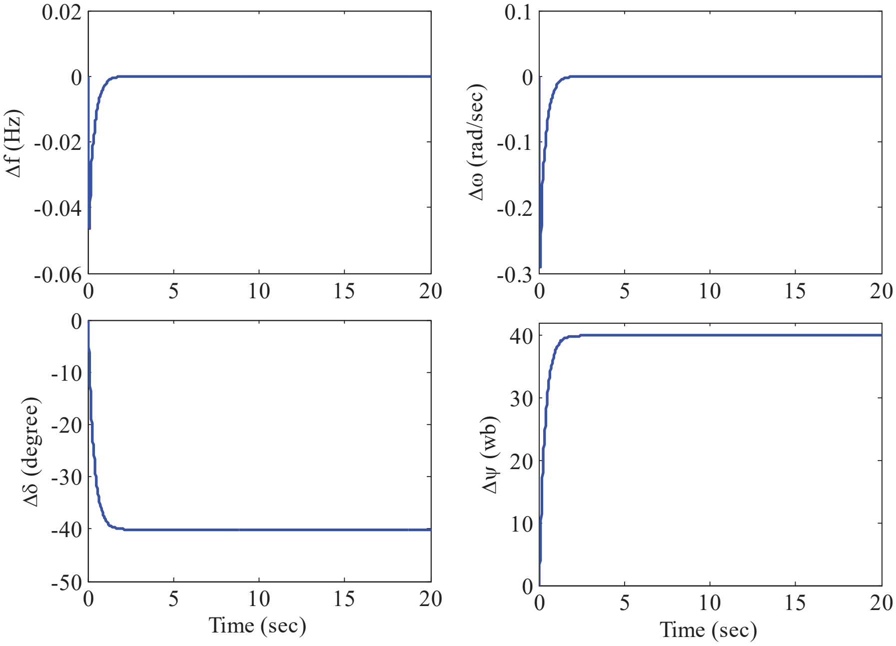


Figure 4 Deviations in frequency, angular frequency, rotor angle and flux density in presence of rotor angle feedback gain uncertainty.

Corresponding nonlinear function and switching trajectory of the diesel generator system only and required control effort of both diesel generator model and inverter are shown in Figure 5. From said figure, it is evident that the proposed controller exhibits zero chattering phenomena in control signals. The proposed design reduces the limitation of chattering notably without any loss in control accuracy. However, it reduces the possibility of failure of the automatic voltage regulators and inverter switches. The deviation in inverter output current and voltage, and deviation in diesel generator voltages are also shown in Figure 6. It is evident that the inverter provides extra power to minimize the frequency deviation in islanded microgrid system using proposed controller against step change in mechanical shaft torque input. The proposed control structure is capable to regulate inverter output power to minimize the frequency within a short time interval. Hence, it confirms speedy recovery of frequency without any rotor oscillation and voltage fluctuations, and reduces the limitation of chattering notably without any loss in control accuracy under step disturbance.

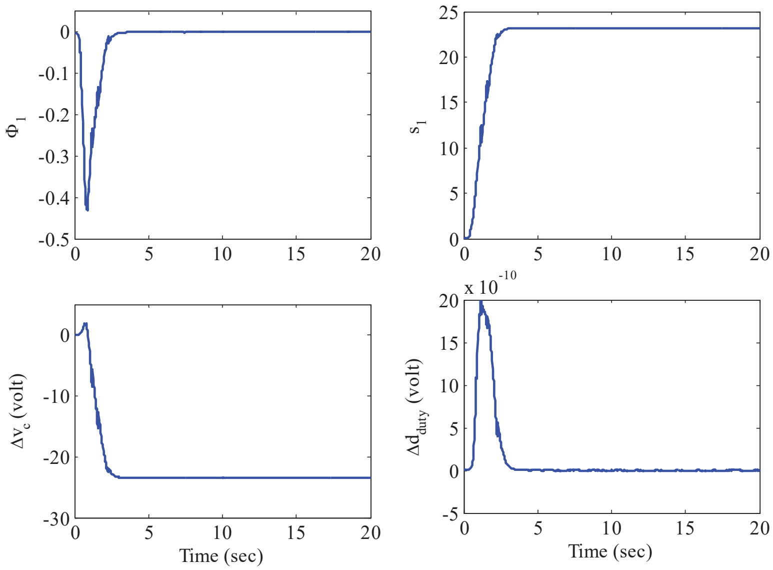


Figure 5 Diesel generator model non-linear function and switching surface, and control efforts in presence of rotor angle feedback gain uncertainty.

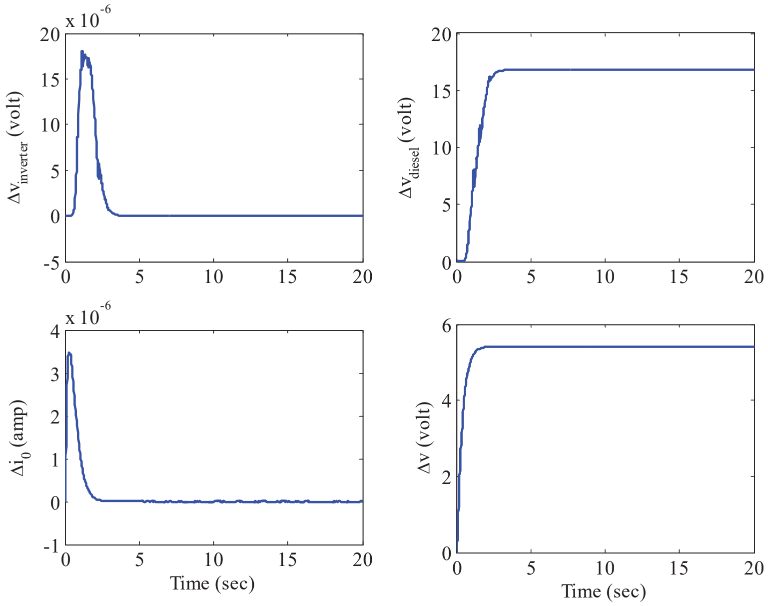


Figure 6 Deviations in voltage and current of diesel generator model and inverter model against step change in rotor angle feedback gain uncertainty.

4.2 Islanded Microgrid Response Under Random Step Change Uncertainty Inputs Pattern in Gain K_5

In this subsection, rotor angle feedback gain and rotor angle deviation uncertainty are varied via a typical random step change pattern mechanical shaft torque input of diesel generator model. Thus, the random (positive and negative) mechanical shaft torque is considered to analyze the effectiveness of the proposed controller scheme for islanded microgrid as shown in Figure 7. The deviations in frequency, angular frequency, rotor torque angle and flux density in diesel generator dynamics are shown in Figure 8 in presence of random change in mechanical shaft torque input patterns. It is observed that the frequency deviation is minimized within 2.0 second time interval using coordinated control approach between diesel generator model and DC voltage inverter model. The nonlinear function and switching trajectory of the diesel generator model and required control efforts for both islanded microgrid are shown in Figure 9. It is evident that the nonlinear function is varied according to frequency deviations in the microgrid. As result, the switching surface is also changed in order to minimize the chattering phenomena in control signals. Above variations are achieved by LMI optimization and reduced the limitation of chattering notably without any loss in control accuracy. Thus, proposed controller is improved both transient responses as well as steady state responses simultaneously. The deviation in inverter output current and voltage, and diesel generator voltages deviations are also shown in Figure 10. It is evident that the inverter system with proposed control scheme is capable to generate additional required power in such way that it can minimize the frequency deviations in islanded microgrid system against any change in mechanical shaft torque input. The proposed control structure

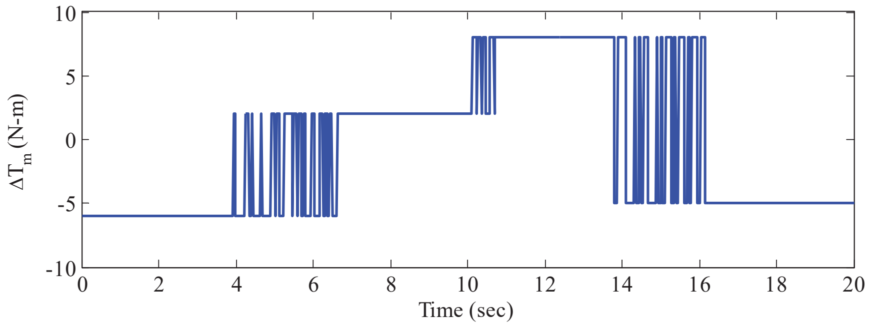


Figure 7 The typical random deviations pattern in mechanical shaft torque input in diesel generator model.

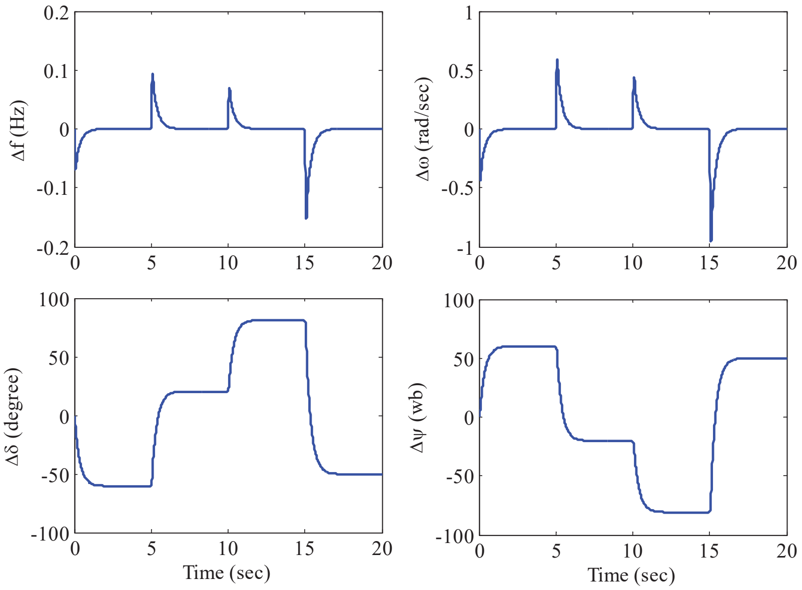


Figure 8 Deviations in frequency, angular frequency, rotor angle and flux density in presence of random step change in gain uncertainty.

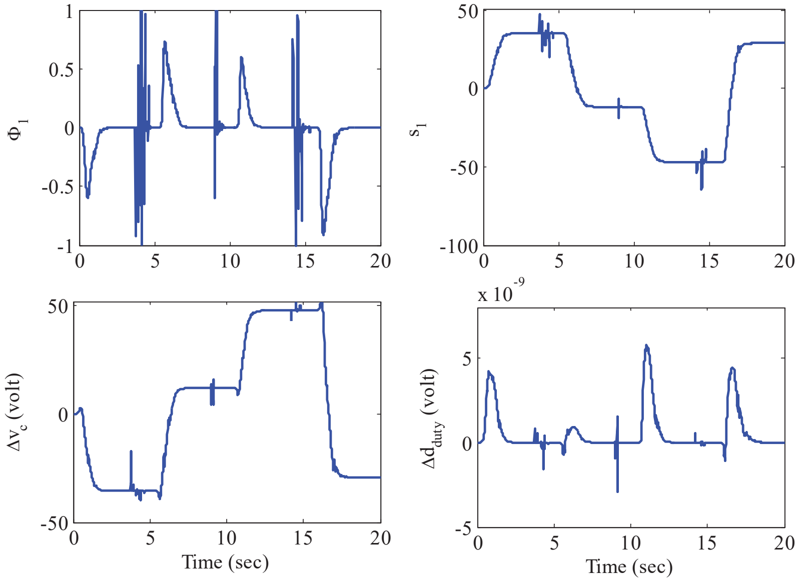


Figure 9 Diesel generator model non-linear function and switching surface, and control efforts in presence of random step change in gain uncertainty.

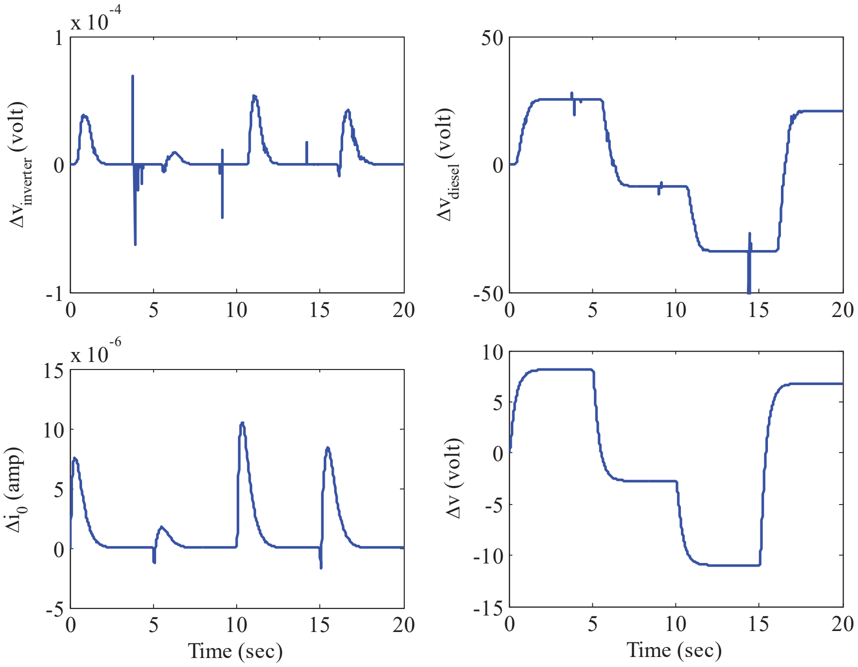


Figure 10 Deviations in voltage and current of diesel generator model and inverter model against random step change in gain uncertainty.

sustains the closed-loop system stability effectively with proper regulation between diesel generator and DC voltage-based inverter output power within 2.0 second time interval.

Hence, proposed controller confirms speedy recovery of frequency without any oscillations as well as it improves both transient responses as well as steady state responses simultaneously with reduction in the chattering against any rotor angle feedback gain channel uncertainty via mechanical shaft torque input variation.

4.3 Performance of Proposed Control Scheme Through a Comparative Simulation Study

Now, the performance of the proposed control scheme is compared with existing state proportional-integral-derivative (PID) controller [30] in presence of random rotor angle feedback gain uncertainty as shown in Figure 6. The deviations in microgrid frequency and diesel generator angular frequency, rotor angle and flux density are depicted in Figure 11. From said

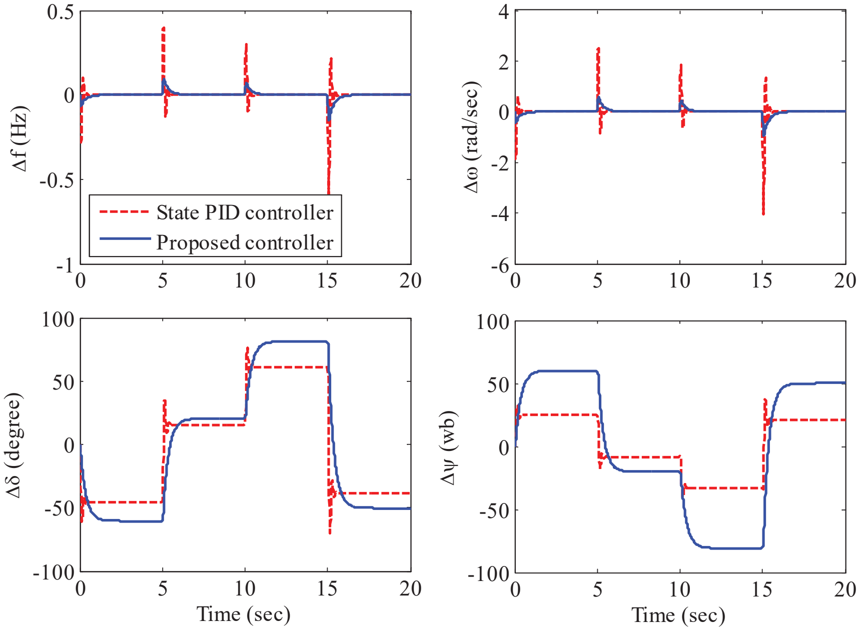


Figure 11 Comparative responses of the proposed control scheme and state PID controller [30].

figure, state PID controller [30] have larger over/undershoots compared to proposed control scheme. At time instance 15.0 second, the proposed control scheme gives smaller undershoot and zero overshoots compared to state PID controller [20]. The settling time of the proposed control scheme is also smaller compared with state PID controller. The deviations in diesel generator rotor angle and flux density are also found satisfactorily compared to state PID controller without any oscillations. It is evident that the proposed control scheme enhanced closed loop stability of the islanded microgrid.

4.4 Robustness of Proposed Controller Using a Comparative Simulation Analysis Against DC Voltage Uncertainty and Diesel Plant Parametric Uncertainty

In addition, the robust characteristics of the proposed control scheme is demonstrated and compared with state PID controller in presence of solar plant DC voltage uncertainty and diesel generator parametric uncertainties. Thus, the ±20 percent DC voltage input variation is considered randomly as shown in first figure in Figure 12. The diesel generator d-q frame has

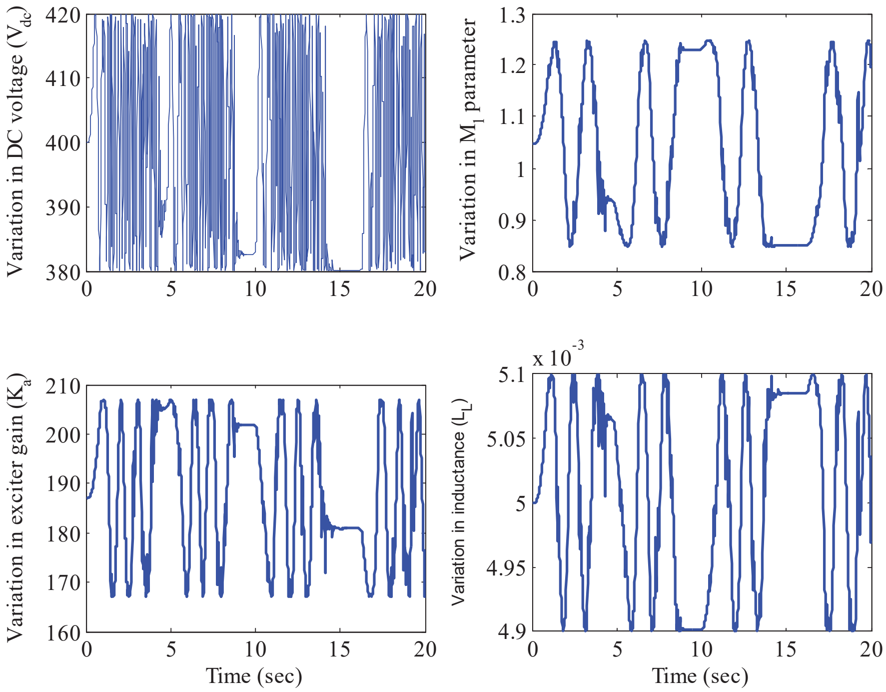


Figure 12 Microgrid parametric uncertainties patterns.

uncertainty due to unequal flux distributions and considered here as similar to second figure depicted in Figure 12. The automatic voltage regulator (AVR) has also several uncertainties and one uncertainty in exciter gain K_a is assumed as equivalent pattern as shown in third figure of Figure 12. Similarly, the inverter output side, an uncertainty is considered in the transmission line inductance parameter L_L and represented in fourth figure of Figure 12 respectively.

However, the proposed control scheme and state PID controller [30] is simulated in presence of the above uncertainties in islanded microgrid system. The deviations in microgrid frequency and diesel generator angular frequency, rotor angle and flux density are depicted in Figure 13 in the presence of uncertainties in DC voltage, generator d-q frame parameter, exciter gain and line inductance. Due to presence of parameter uncertainties, state PID controller performance deteriorates in terms of larger time characteristics while proposed control scheme is completely insensitive against above parameters uncertainties.

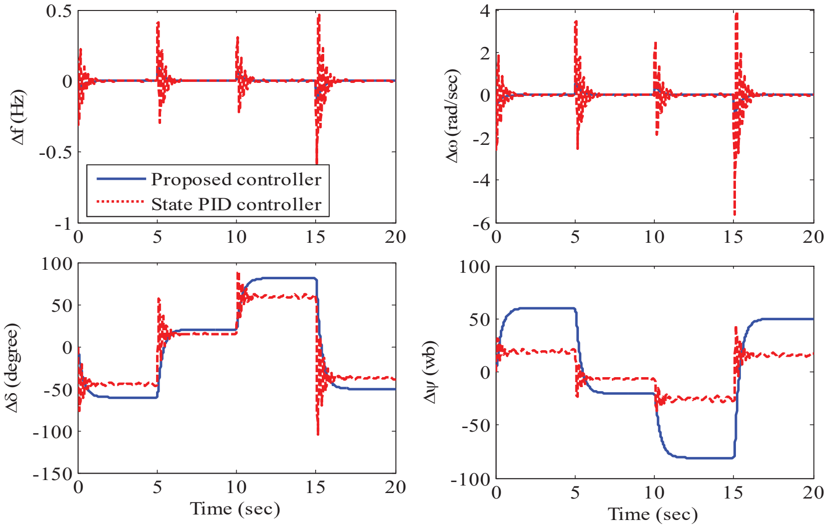


Figure 13 Comparative performance of the proposed control scheme in presence of parameter uncertainties.

The proposed control scheme has negligible oscillations in diesel generator rotor angle and flux density deviations compared to state PID controller. It is observed that nonlinear sliding mode-based control scheme sustained the islanded microgrid system insensitive even in presence of parameter uncertainties. Thus, proposed control scheme is able to minimize islanded microgrid frequency issue effectively.

4.5 Effectiveness of Proposed Controller Demonstration Using Performance Indices

In this subsection, the performance indices of the proposed control scheme and state PID controller [30] i.e., integral square error (ISE), integral absolute error (IAE) and integral time absolute error (ITAE) are obtained for the scenarios *4.1, 4.2, 4.3* and *4.4* against step change and random step change in mechanical shaft torque input in diesel generator model.

The islanded microgrid frequency deviation is considered in the calculation of the performance indices as given in Table 3. It is evident that the proposed control exhibits robust performance against any change in the mechanical shaft torque input and microgrid parameter uncertainties compared to state PID controller [30]. As results, it enhances the closed-loop system stability, robustness and its applicability.

Table 3 The performance indices against step and random change in torque input

Scenarios		ISE	IAE	ITAE
Step change in mechanical torque (scenario-4.1)		0.0026	0.0061	0.0170
Random change in mechanical torque (scenario-4.2)		0.0511	0.1410	1.3118
State PID controller [30] (scenario-4.3)		0.1030	0.4460	4.1358
In presence of parameter uncertainties (scenario-4.4)	Proposed controller	0.0511	0.1410	1.3118
	PID controller [30]	0.1120	0.4889	4.5719

5 Conclusions

In this paper, a linearized model of both diesel generator with excitation system model and DC voltage solar PV based DC to AC inverter model is considered for small signal analysis and farmed as an islanded microgrid. A nonlinear sliding mode controller proposed to mitigate the frequency and voltage fluctuations, and also minimize the rotor oscillation problems in an islanded microgrid. Based on LMI optimization toolbox and Lyapunov stability theorem, enough states derived to assure the asymptotic stability of the nonlinear sliding surface and system dynamic error. The control law obtained to ensure the existence of sliding mode around nonlinear surface in limited time. The proposed controller design effectively interpreted the challenges arises due to uncertainties in the plants. Hence, the proposed controller effectively generated additional required control efforts in proper coordinated way till rotor oscillation and voltage fluctuations approaches to zero. In addition, the closed-loop system responses improved both transient responses and steady state responses simultaneously against solar DC voltage uncertainty and diesel generator parametric uncertainties. The performance and robustness of the proposed controller is compared with state PID controller. As results, proposed controller confirmed speedy recovery of frequency without any oscillations and reduced the limitation of chattering notably without any loss in control accuracy. In future, the integration of the microgrid will be analyzed using a centralized controller in presence of communication delays.

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