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RESEARCH ARTICLE

# Decentralized Optimized Integral Sliding Mode-Based Load Frequency Control for Interconnected Multi-Area Power Systems

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**ABSTRACT** In this paper, a decentralized load frequency control (LFC) is proposed for the frequency regulation of multi-area power systems applying optimized integral sliding mode control (OISMC) scheme. A modified particle swarm optimization (MPSO) algorithm is utilised to optimize the control variables of the proposed controller for improving the performance of frequency response. A comprehensive model of a multi-area power system is developed where each area is considered to power from conventional sources, renewable energy resources (RERs), and electrical vehicle (EV) aggregators. Different types of interconnectors have been considered to tie different power regions. This system is subjected to random generation and loading conditions, as well as model uncertainties, which cause its frequency and area control error (ACE) to deviate from their nominal values. A decentralised OISMC is implemented for the proposed model to keep the frequency variation within the nominal range. Further, a validation study investigates the performance of the proposed control technique in MATLAB simulation environment to mimic the real power system operation. This study includes different test scenarios considering the dynamic events such as variations in load demand, amount of generated power, participation factor of EV reserve, system parameters, disturbances, and time delay. The simulated results support better frequency regulation with the suggested OISMC compared to other alternative control approaches.

**INDEX TERMS** Area control error, load frequency control, integral sliding mode control, secondary control, optimized control variables.

## I. INTRODUCTION

### A. PROBLEM STATEMENT

Load frequency control (LFC) as a secondary control, is in charge of active power balancing in the event of changes in generation or demand caused by fluctuations in the generation or the load itself. This unbalance deviates the frequency from its nominal value and this, in turn, can jeopardise the stability and security of the power system [1]. The NERC report has suggested that allocating time for frequency deviation settlement to a pre-specified range should be within 30 seconds. For interconnected power systems, the frequency shift in any of the areas further causes a variation in the tie-line power flow to the other areas. Therefore, frequency regulation is an important task for safe and stable power system operation. Furthermore, in a modern power system, fast frequency regulation is a challenge due to the increasing integration of intermittent renewable energy sources, involve-

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ment of new bidirectional loads such as electric vehicles (EVs), prosumers, and intermittent and distributed production [2], [3]. This is due to an increase in unpredictability and intermittent events, which leads to highly stochastic system characteristics [4]. As a result, the conventional power system model needs to be redesigned to include stochastic as well as fixed disturbances in the system dynamics, necessitating the use of an advanced controller to combat these disturbances [5]. A suitable control scheme, which is flexible, robust, and capable to overcome the new challenges of wide power systems encompassing various new developments is highly recommended. In the following subsection, previous work is reported that will be helpful to propose a control strategy considering the aforementioned problem statement.

### B. LITERATURE SURVEY

In a power system, frequency is a critical characteristic that must be constantly monitored and controlled. Conventional control schemes are best suited for LFC under specific operating points. Although, solving the problems of large integrated power systems with non-linearity and uncertainties becomes a challenge for such schemes. Besides conventional control schemes, other control schemes such as evolutionary computing control, intelligent control, state feedback control, etc. have been reported for LFC. Compared to the centralised control scheme [6], decentralized control has been found to be more effective [7] for interconnected power systems. A comprehensive report of LFC control schemes has been presented with their related advantages and shortcomings [6], [8]. In addition, several optimization techniques have been detailed for an optimal LFC framework [9]. Alternatively, sliding mode control (SMC) is a robust method, insensitive to system parameters and inaccurately modeled plants to enhance the transient performance with a fast response [10], [11], [12]. These features have encouraged researchers to seek its application in the realm of LFC. SMC is widely used in the frequency control issues for integrated power systems in the presence of uncertainties and model inaccuracy [7], [14], [15], [16], [18], [19], [20], [22], [23]. The selection of sliding surface (such as proportional (P), integral (I) etc.) as well as the control law, are two vital factors in the design of SMC. Also, the control law induces sliding modes during the control process. The SMC control input has two components: (i) equivalent control input (derived from reaching condition) and (ii) discrete control input (using switching functions). Authors have solved the LFC problems using different combinations of these components [13], [14], [20], [21]. In the SMC design for a centralized 2-area power system, [21] has included disturbance, $w(t)$ in the system dynamics and formulated the I-based sliding surface. After satisfying the reaching condition, the equivalent control input includes disturbance, $w(t)$. Likewise, the control law has incorporated disturbance, $\hat{d}_i(t)$ (after estimation with the help of an observer), and the sliding surface parameters have been tuned using $H_{\inf}$ satisfying the linear matrix inequalities (LMIs) [24]. The work of [13] and [14] have considered disturbance, $d_i(t)$ including matched and unmatched components in the formulation of control law. The former has designed the sliding surface considering both components of disturbance where as latter has considered sliding surface invariant to the matched uncertainty. Based on this, the $H_{\inf}$ approach has been used to design the P-based sliding surface without optimally determining the sliding manifold. An adaptive SMC with an improved sliding surface that takes into account a discrete control law where $d_i(t)$ has assumed only matched uncertainty has been developed [25]. Thus, the selection of control law is critical for obtaining the system's trajectory on the sliding surface for stable operation under a wide range of operating conditions, as well as regulating the frequency to maintain the area control error (ACE) of each area to a minimum [12]. Likewise, the effectiveness of the control law is influenced by the type of switching function and its switching frequency. Based on this philosophy, a variety of SMC forms have been put forward for the LFC of multi-area interconnected power systems in the aforementioned work as summarised in Table 1.

The issue of frequency deviation has been addressed by incorporating a P-based sliding surface for SMC [14], followed by an I-based SMC approach [19], [20] for regulating the area frequency error with improved steady-state response. In addition, signum and saturation functions are used for the control law design. In the aforementioned LFC problem, the mostly signum function has been used for framing the control law. However, the signum function introduces chattering in the output response of the system [26]. This issue of chattering has been resolved using higher order SMC applying adaptive control law [27] and adaptive fuzzy-based super twisting SMC [17] for frequency control in the presence of model uncertainty and disturbance. Also, improved SMC design has been proposed adaptive learning strategy using dynamic programming to provide a supplementary control signal for frequency regulation [25]. Further, the saturation function is a modified form of the signum function with the feature of replacing its discontinuity using the boundary layer approach and causing the trajectory to stay within it rather than follow the sliding surface. This is at the cost of losing invariance. The switching function is the function of sliding surface which in turn is determined by the system error [10].

In the proposed control scheme, this concept is exploited in saturation function by modifying it as a product of sliding surface and states deviations to improve the frequency regulation and ACE reduction. Also, [6], [19] have applied PI-based SMC using signum function to a three-area system to improve the frequency response. Furthermore, in a two-area system with wind power and EV power, observer-based SMC with PI sliding surface using signum as a switching function has been proposed for LFC for system stability [20]. A performance study of SMC with the implementation of variable structure observer has been investigated considering only step disturbance [1]. Further, it is a tedious process to tune the control variables to get a satisfactory performance, especially with a large number of control variables.

**TABLE 1.** Comparison of reported and proposed work of SMLFC for multi-area power systems.

| Author | Multi-area Considered | Type of SS | Function used in Control Law | Optimization Algorithm | Tie-line, RESs & EV Model Considered | SD (p.u.) | $\approx ACE/\Delta f(p.u)$ |
|---|---|---|---|---|---|---|---|
| [14] | 3 | P | Signum | $H_\infty$ | No | 0.001 | $-7e^{-3}(ACE_1)$ $7.85e^{-4}(ACE_2)$ |
| [7] | 3 | PI | Signum | — | No | 0.01 0.015 0.02 | $-0.025(f_n)$ |
| [15] | 2 | P | Not mentioned | — | No | 0.01 0.05 | $-0.025(ACE_1)$ $-0.005(ACE_2)$ |
| [18] | 2 | PI | Signum | — | RER consider without EV | 0.01, 0.02 | $-0.02(\Delta f_n)$ |
| [19] | 3 | Nonlinear | Nonlinear | — | No | 0.01 0.015 0.02 | < 0.3 |
| [20] | 2 | PI | Signum | Lyapunov Stability Principle | Yes | 0.01 0.02 | + 0.0235 |
| [22] | 2 | PD | Signum | Modified Twisting Control | No | 0-0.02 0-0.02 | < 0.002 |
| [23] | 2 | PID | Signum | PSO, GW | No | 0.01 0.1 | $-0.0005$ |
| Proposed Work | 4 | PI | Saturation | MPSO | Yes | 0.01 0.03 0.05 | Refer Table 6 |

P:Proportional, I:Integral, D-Derivative, SS: Sliding surface, SD: Step disturbance, $f_n$: Frequency nadir, GW-Grey Wolf

Optimization techniques such as PSO have been used to get the optimized control parameters of SMC [16], [23], although modified PSO has shown better results with time-varying inertia weight strategy [26]. In this technique, the fixed inertia weight, and time-invariant acceleration constant of the conventional PSO have been replaced by non-linear inertia weight and time-varying acceleration constants respectively. Further, with the use of the tangent function, the inertia weight is made large for robust initial global search of swarm, and lesser weight to make local search strong. Also, acceleration constants influence the movement of swarm particles towards global best. Employing time-varying acceleration constants, the swarm particles in the initial stage roam through wide search space and then in the final stage of the search, converge towards the global optimum. This control strategy is significant due to the substantial number of uncertainties encountered by the excessive penetration of renewable energy resources. It is, particularly for the LFC problem that the majority of authors have implemented SMC with signum function while considering interconnected control areas with traditional power system models that do not include EVs, RERs, and sensor noise. Following the aforementioned literature review, a gap in the previous research is found, necessitating the development of a control algorithm to deal with stochastic disturbances in the system caused by generation or load uncertainty. Furthermore, the controller must deal with uncertainties such as time delay, modelling inaccuracy, and parameter fluctuations for a secure and stable system operation.

### C. PROPOSED WORK

In this paper, a novel decentralized LFC strategy is proposed for a multi-area system. It is the integral sliding mode with saturation function-based control law with an integral controller in each area. This multi-area system is sectioned into different control areas which are interconnected by tie lines under pool operation to provide the following benefits under steady-state conditions: (i) maintaining scheduled tie-line power interchanges: The interconnected areas share their reserve power for handling anticipated load peaks and unanticipated generator outages, (ii) absorbing each area's own load change: Interconnected power system areas can withstand larger load changes with smaller frequency deviations than isolated power system areas. For the interconnected multi-area power system shown in Fig. 1, the SMC strategy is proposed for regulating the frequency of each area to its reference value and also keep the area control error (ACE) to minimum for stable operation of the system. This is the first time when SMC is implemented to multi-area interconnected power system with a variety of tie-lines with their respective dynamics. Also, the work has demonstrated the significant contribution of variation of RES generation and EV storage power on the frequency response model. Here, additional factors that are regarded as matched and mismatched disturbances to the system include load change, intermittent variation in RES, time delay, and parameter uncertainty. The proposed control strategy is decentralized and control variables of SMC of individual area are optimized using MPSO keeping integral of square of frequency deviation (ACE) and tie-line power exchange as objective function. Now, in each area control loop, the control variables are optimized using modified particle swarm optimization (MPSO) technique. The robustness and performance of the proposed controller is investigated under various non-linearity such as time delay, governor dead-band (GDB), and time-delay (TD). As a result, optimized integral sliding mode load frequency control (OISMFLC) acts as a stochastic disturbance accommodating controller, amending the necessary corrections to the nominal control input and thus minimising the adverse effects of system uncertainties and external disturbances on

**TABLE 2. Terms used in system dynamics.**

| Symbol | Variable (p.u.) |
|---|---|
| $\Delta f$ | Frequency deviation |
| $\Delta P_g$ | Output electrical power deviation |
| $\Delta P_r$ | Reheater output mechanical power deviation |
| $\Delta X_g$ | Valve position deviation |
| $\Delta P_e$ | Output power of EVs deviation |
| $\Delta P_{di}$ | Difference of RERs generation and demand deviation |
| $\Delta P_{tie}$ | tie-line power deviation |
| $T_g, T_r$, $T_t$,& $T_e$ | Time constants of governor, reheater, thermal turbine, and storage system |
| $K_g$, $K_r$, $K_t$, & $K_e$ | Gains of governor, reheater, thermal turbine, & EV system |
| H, D, & R | Inertia constant, damping coefficient, & speed droop of the alternator |
| $\Delta ACE$ & $b$ | Area control error (ACE) & frequency bias |
| $i$ indices of the $i^{th}$ area | |

the controlled system. The MPSO optimization parameters are selected in order to achieve an optimum SMC control variables to stabilise the frequency of the current system.

The main highlights of paper are listed as:

- Development of an interconnected multi-region power grid model in which each control area is integrated with RESs and EV reserve power, as well as stochastic nonlinearities, to better reflect the real power system with unfavourable effects resulting from uncertainties and noise;
- Considering aforementioned comprehensive model, development of a decentralised and optimal sliding mode-based control strategy to provide robust solution of LFC problem with saturation switching function without chartering, better tuning of controller with MPSO technique, and reduced steady state error using integral control component and PI-based Sliding surface;
- Performance validation of proposed OISMLFC control strategy with simulated case studies under various scenarios, and detailed comparative analysis made with the existing approaches.

The rest of the paper is organized as follows: After a brief introduction, literature survey, and proposed work in section I, a dynamical model of the system is presented in section II. The design of a rudimentary OISMC is presented in section III. The control methodology of LFC power system using a modified OISMFLC is discussed in section IV. The theoretical presentation of the proposed control scheme for the power system model is justified with the help of a simulation study and is tested to verify it's robustness in section V. Based on the result analysis, finally, conclusions are drawn in section VI.

## II. SYSTEM MODEL AND DYNAMICS

In this section, each control area of the system has share of generation from conventional sources and RERs. A frequency response (SFR) based benchmark model is considered [28] that consists of an equivalent reheated thermal power plant associated with an aggregated EV charging units with storage

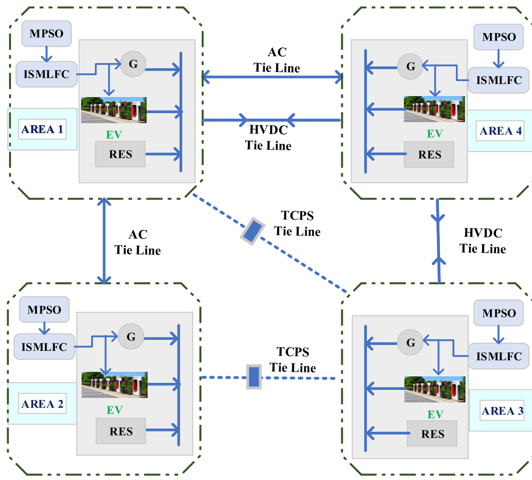


**FIGURE 1. Schematic diagram of interconnected four-area power system with different tie-lines.**

as flexible demand, an uncontrolled power input model to represent variation in electric demand and integrated RES generation. Also, the dynamical model incorporates process noise with demand and supply having fixed as well as random components. In this model time delay is included that may be due to communication delay, and delay caused by governor setting. The areas of the power system are interconnected by variants of transmission lines like AC transmission lines, HVDC transmission lines, and AC tie-lines with thyristor-controlled phase shifter (TCPS). The schematic diagram of a benchmark four-area interconnected power system LFC model is presented in Fig. 1 and its $i^{th}$ area frequency model is shown in Fig. 2. The control of interconnected power system is decentralized, therefore, each area has its own load frequency controller.

The dynamics of power system is non-linear and time-varying but its linearized model is acceptable in the LFC problem as only insignificant deviations is anticipated during its normal operation [29]. Based on the system model shown in Fig. 2, the linear dynamic equations of the $i^{th}$ area are derived as:

$$\begin{aligned}
\Delta\dot{f}_i &= \frac{1}{2H_i}\Delta P_{ri} + \frac{1}{2H_i}\Delta P_{ei} - \frac{1}{2H_i}\Delta P_{di} \\
&\quad - \frac{D_i}{2H_i}\Delta f_i - \frac{1}{2H_i}\Delta P_{tie} - \Delta P_{tie} \\
\Delta\dot{P}_{gi} &= \frac{K_{ti}K_{ri}}{T_{ti}T_{ri}}\Delta X_{gi} + \frac{T_{ti}-K_{ri}}{T_{ti}T_{ri}}\Delta P_{ri} - \frac{1}{T_{ri}}\Delta P_{gi} \\
\Delta\dot{P}_{ri} &= \frac{K_{ti}}{T_{ti}}\Delta X_{gi} - \frac{1}{T_{ti}}\Delta P_{ri} \\
\Delta\dot{X}_{gi} &= -\frac{K_{gi}}{R_iT_{gi}}\Delta f_i - \frac{1}{T_{gi}}\Delta X_{gi} + \frac{K_{gi}\alpha_{gi}}{T_{gi}}\Delta P_{ci} \\
\Delta\dot{P}_{ei} &= -\frac{1}{T_{ei}}\Delta P_{ei} + \frac{}{T_{gi}}\Delta X_{gi} + \frac{K_{gi}\alpha_{gi}}{T_{gi}}\Delta P_{ci} \\
\Delta ACE_i &= b_i\Delta f_i + \Delta P_{tiei}
\end{aligned} \tag{1}$$

The terms used in Eq.(1) are described in Table 2.

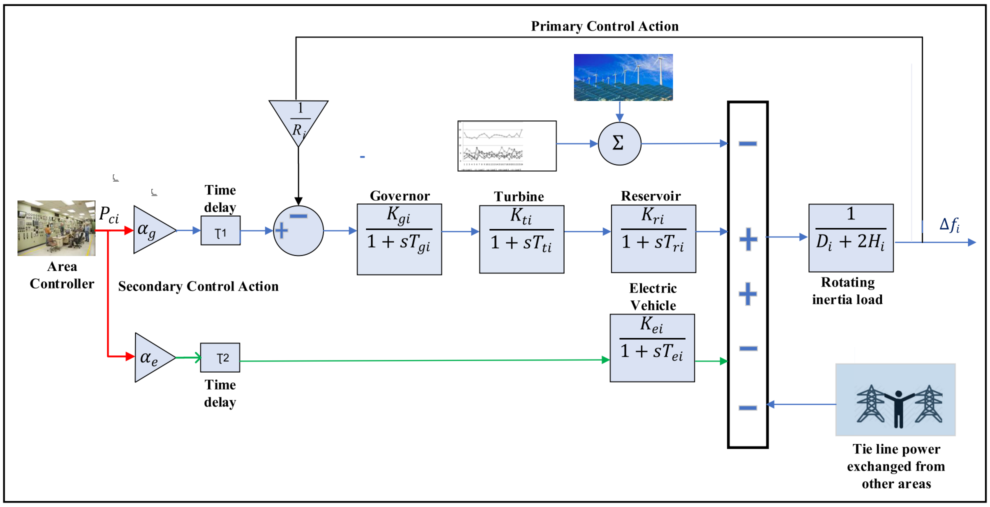


**FIGURE 2.** **Frequency response model of $i^{th}$ area of interconnected power system configuration under study.**

It is to be noted that this dynamical model has $\Delta f$, $\Delta P_g$, $\Delta P_r$, $\Delta P_e$, and $\Delta X_g$ as non-random components and $\Delta P_d$, $\Delta P_{tie}$ including other system uncertainties as the random components. The state space model of the power system for frequency studies has been formulated and expressed in general matrix vector form as given:

$$\dot{X}(t) = AX(t) + Bu(t) + Ed(t)$$
$$Y(t) = C.X(t) \tag{2}$$

where, $X(t) \in \mathbb{R}^{n\times 1}-$ state variable vector, $u(t) \in \mathbb{R}^{r\times 1}-$ control input vector, $y(t) \in \mathbb{R}^{m\times 1}-$ output vector, and $d(t) \in \mathbb{R}^{q\times 1}-$ the disturbance vector. Also, $A \in \mathbb{R}^{n\times n}-$ system matrix, $B \in \mathbb{R}^{n\times r}-$input matrix, $C-$output matrix, and $E \in \mathbb{R}^{n\times q}-$ disturbance matrix.

In (1), state vector, input vector, and disturbance vector for $i^{th}$ area is expressed as:

$$X_i = [\Delta f_i \;\; \Delta X_{gi} \;\; \Delta P_{ri} \;\; \Delta P_{gi} \;\; \Delta P_{ei} \;\; d_i]^T$$
$$u_i = [\Delta P_{ci}]; \;\; d_i = [\Delta P_{di} \; \Delta P_{tie,i} \;\; \xi_{ti}] \tag{3}$$

It is considered in (3) that the lumped and bounded disturbance $d_i(t)$ in the system has both modeled ($\Delta P_{di}$, $\Delta P_{tiei}$) and unmodelled parts ($\xi_{ti}$) due to many factors like time-delay, modelling errors, parameter uncertainty, etc. Under the condition that the system is handling the random disturbance caused by the mismatch of intermittent RES generation and unpredictable load pattern, the following assumption has to be fulfilled i.e. $||d_i(t)|| \leq \tilde{d}_i$, and $||\dot{d}_i(t)|| \leq \tilde{\dot{d}}_i$. In this work, it is assumed that $d_i(t)$ is accurately predictable with the convergence of disturbance estimation error to sufficiently close to zero with time by any of methods as described in [24], [28], and [37].

Since the operating point undergoes continuous adjustment due to continuous variations in the difference of power supply and load demand. Further, the system faces parameter uncertainties at various operating point, besides time delay. Therefore, to keep the system parameters within the nominal range, a control action is required for ensuring stability. The next section describes the robust sliding mode control strategy proposed for a generalised LFC system.

## III. SLIDING MODE CONTROLLER DESIGN

Sliding mode control (SMC) is a non-linear, variable structured, and stochastic featured scheme which is based on state feedback control law [7], [36]. In this method, a discontinuous control is utilized to force the system state trajectories to a predefined sliding surface on which the system has requisite properties like stability, disturbance rejection capability, and tracking ability [30]. This significant feature of sliding mode control [31], [32], [33], [34], [35] is exploited to ensure its effective control strategy for non-linear and inaccurate modeled systems. For such higher-order model, SMC has the capability to observes its system dynamics and stability through $1^{st}$ order sliding surface around the switching line. Thereby, in SMC, the system closed-loop behavior is determined by a sub-manifold in the state space [36].

In this decentralized approach, the proposed controller guarantees the asymptotic stability of the power system meeting these significant norms: (i) selection and design of the sliding surface for the desired performance; (ii) existence of the sliding mode and its reaching condition; (iii) determination of the control law to derive the system trajectory to the surface and maintain motion on it [21], [30]. These norms are discussed below.

### A. SLIDING SURFACE SELECTION

For design of SMC, the selection of a suitable sliding surface (SS) is a crucial step to describe the required system dynamics. For the proposed controller, a SS with PI switching surface $i^{th}$ area is selected as:

$$S_i(t) = Q_iX(t) - \int_0^t Q_i(A_i - B_i \times K_i)X(\tau)d(\tau) \tag{4}$$

where $t$ is the time to reach the sliding mode, $Q_i \in \mathbb{R}^{1\times n}$, $K_i \in \mathbb{R}^{1\times n}$, and $A_i \in \mathbb{R}^{n\times n}$ are constant matrices, in which $Q_iB_i$ is non singular. The matrix $K_i$ is designed using pole assignment so that the eigen values of matrix $(A_i - B_iK_i)$ are negative. The following criterion for the switching function must be met when the dynamic trajectory (system states) enters sliding mode and continues to slide on it.

$$\begin{aligned} S_i(t) &= 0, \\ \dot{S}_i(t) &= 0; \quad \forall t \geq 0 \end{aligned} \tag{5}$$

### B. EXISTENCE OF THE REACHING CONDITION

As the system states reach the sliding surface and continue to slide on it, at that very precise instant, an equivalent control is introduced as continuous approximation of the switching component of the control signal. The switching function, as the switching law, ensures the Lyapunov stability condition for the system to be in the sliding mode. and is given as:

$$S_i(t)\dot{S}_i(t) < 0 \tag{6}$$

This condition guarantees the trajectory of the system to be in the regime. In the next subsection, a specified control law is designed for the decentralised LFC of the system followed by fulfillment reachability condition.

### C. DETERMINATION OF THE CONTROL LAW

In the proposed SMC design, PI based SS is selected (4) and to meet the condition expressed in (6), the value of $\dot{X}(t)$ from (2) is substituted in the derivative of $S_i(t)$ of (4) and the resulted expression is given as:

$$\begin{aligned} \dot{S}_i(t) &= Q_i\dot{X}_i(t) - Q_i(A_i - B_i \times K_i)X(t) \\ &= Q_i[A_iX(t) + B_iu_i(t) + E_id_i(t)] \\ &\quad - Q_i(A_i - B_iK_i)X_i(t) \end{aligned} \tag{7}$$

Equating Eqn. (5) = 0, the equivalent control is derived as:

$$u_{eq,i}(t) = -K_iX_i(t) - (Q_iB_i)^{-1}Q_iE_id_i(t) \tag{8}$$

Substituting $u_i(t) = u_{eq,i}(t)$ from (8) in the state space Eqn. (2), the system dynamics in sliding mode is modified as:

$$\dot{X}_i(t) = (A_i - B_iK_i)X_i(t) + (I - B_i(Q_iB_i)^{-1}Q_i)E_id_i(t) \tag{9}$$

where, $I \in \mathbb{R}^{n\times n}$ is the identity matrix. Also, substituting the value of $u_{eq,i}(t)$, the derivative of the sliding surface (7) is further modified as:

$$\begin{aligned} \dot{S}_i(t) &= Q_i\dot{X}_i(t) - Q_i(A_i - B_iK_i)X_i(t) \\ &= Q_iA_iX(t) + Q_iB_iu_{eq,i}(t) + Q_iE_id_i(t) \\ &\quad - Q_i(A_i - B_iK_i)X_i(t) \\ &= Q_iB_iK_iX_i(t) + Q_iB_iu_{eq,i}(t) + Q_iE_id_i(t) \end{aligned} \tag{10}$$

In the aforementioned expression, the selection of matrix $Q_i$ is in such a way to ensure that matrix $Q_iB_i$ is non-singular i.e. $Q_iB_i \neq 0$.

Then, the control law is given by:

$$u_i(t) = u_{eq,i} + \Delta u_i \tag{11}$$

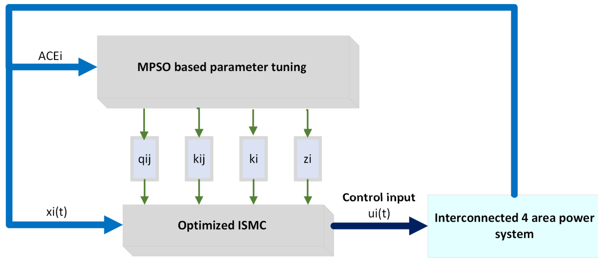


**FIGURE 3. Optimized integral sliding mode control scheme.**

where $u_{eq,i}$ is the equivalent control (8) for ideal sliding mode, and $\Delta u_i$ is the discontinuous term as switching function of high frequency [11] which takes the form as:

$$\Delta u_i(n) = -k_i sat(S_i(n)) \tag{12}$$

Here, $u_i(n)$, and $S_i(n)$ respectively are the switching function, and sliding surface at the $n^{th}$ sampling instant of the $i^{th}$ area; and $k_i$ is the switching gain matrix designed through pole placement.

Verification of existence condition gives the switching function $\psi_i(n)$ based on saturation function $sat(S_i(n))$ for the control input $u_i(n)$. In the present study, we have considered saturation function based ISMC where the switching function is modified as the product of sliding surface, and state error. The $\psi_i(n)$] is defined as:

$$\psi_i(n) = sat(S_i(n)) = \begin{cases} +1, & \text{if } S_i(n)X_i(n) > L; \\ \dfrac{S_i(n)}{L}, & \text{if } S_i(n)X_i(n) \leq L; \\ -1, & \text{if } S_i(n)X_i(n) < -L. \end{cases} \tag{13}$$

where, $L$ defines the threshold for entering the boundary layer. In this proposed work, $L = 0.5$. Using control law (11), the $\Delta P_{ci1}$ is discretized to take the form as:

$$\begin{aligned} \Delta P_{ci1} = u_i(n) &= -K_iX_i(n) - (Q_iB_i)^{-1}Q_iE_id_i(n) \\ &\quad - (Q_iB_i)^{-1} - k_i sat(S_i(n)X_i(n)) \end{aligned} \tag{14}$$

Thus, the control law (14) drives the system (2) to the sliding surface (5) and maintain a sliding motion thereafter.

The reaching condition of a sliding mode using the compact state space model (2) (formulated from the power system dynamical model (1)) can be derived which can guarantee the asymptotic stability of the system in finite time. For this, the Lyapunov function, V(t) is used to test the reachability condition for each area as below:

$$V(t) = \frac{1}{2}S^T(t)S(t)$$

The derivative of V(t) is derived as:

$$\begin{aligned} \dot{V}(t) &= \frac{1}{2}\dot{S}^T(t)S(t) + \frac{1}{2}S^T(t)\dot{S}(t) \\ \dot{V}(t) &= S^T(t)\dot{S}(t) \end{aligned} \tag{15}$$

Substituting the control input (11) (7) and results:

$$\dot{V}(t) = \sum_{i=1}^{n} S_i[Q_iB_iK_iX(t) + Q_iB_iu(t) + Q_iE_id_i(t)]$$

$$= \sum_{i=1}^{n} S_i[Q_iB_iK_iX_i(t) + Q_iB_i(-K_iX_i(t)$$

$$- [Q_iB_i]^{-1}Q_iE_id_i(t)) - k_isat(S_i(n)) + Q_iE_id_i(t)]$$

$$= \sum_{i=1}^{n} S_i[Q_iB_iK_iX_i(t) - Q_iB_iK_iX_i(t) - Q_iB_i$$

$$\times (Q_iB_i)^{-1}Q_iE_id_i(t) - Q_iB_ik_isat(S_i(n)) + Q_iE_id_i(t)]$$

$$= \sum_{i=1}^{n} S_i[Q_iB_ik_isat(S_i(n)] \quad (16)$$

$$\dot{V}(t) = \sum_{i=1}^{n} -||S_i||||Q_iB_ik_i||) < 0 \quad (17)$$

The expression (17) satisfies the reaching condition (6) ensuring the system's state trajectory to the predefined sliding surface on which the system achieves asymptotic stability, disturbance rejection, and tracking ability of the proposed decentralised OISMLFC for the interconnected power system. In addition, with saturation function (13), the trajectory once within its boundary layer do not follow the sliding surface rather stay within the boundary layer, eliminating high frequency chattering. Considering this function (13) in the switching law (11) improves the stability and performance of the system.

## IV. OPTIMIZED INTEGRAL SLIDING MODE LOAD FREQUENCY CONTROL (OISMLFC)

The dynamic performance of the proposed four-area power system is studied for LFC by employing tie-line bias control and ISMC in the control loop. To circumvent the undesirable issues of (i) persistent static frequency error, and (ii) persistent static tie-line power flow error, Integral control as tie-line bias control is incorporated to the multi-area system. This objective is achieved by considering the area control error as a linear combination of area frequency error and tie-line power flow error as:

$$ACE_i = b_i\Delta f_i + \Delta P_{tie,i} \quad (18)$$

and giving command to the speed changer as:

$$\Delta P_{ci2} = -z_i \int (b_i\Delta f_i + \Delta P_{tie,i})dt \quad (19)$$

where $z_i$ is integrator gain, and $b_i$ is the frequency bias parameter. The minus sign shows that for each area, there is increase in its generation whenever its frequency deviation or tie-line power deviation goes negative.

The operation of ISMC in the control loop is based on modified switching function $\psi_i(n)$ which participates in regulating the system frequency $f_i$ to bring the deviation in system frequency ($\Delta f_i$) to the minimum. In the proposed control scheme, an integral controller is implemented to minimize

**TABLE 3. Simulation experiment environment.**

| S.No. | Simulation Study Environment | Details |
|---|---|---|
| 1 | System Model | Ref. Eq. 1 and Fig. 2 |
| 2 | Disturbance Fixed + Random | In steps of: 0.01-0.05 + WGN of covariance: $10^{-8} - 10^{-6}$ |
| 3 | Interconnected Areas | 4 |
| 4 | Simulation Time, $T_{sim}$ | 30s |
| 5 | Simulation Time for Which Results are Considered | 0-30s |
| 6 | Optimization Technique | Modified Particle Swarm Optimization (MPSO) |
| 7 | Performance Index for Optimization Technique | Integral Square Error(ISE) |

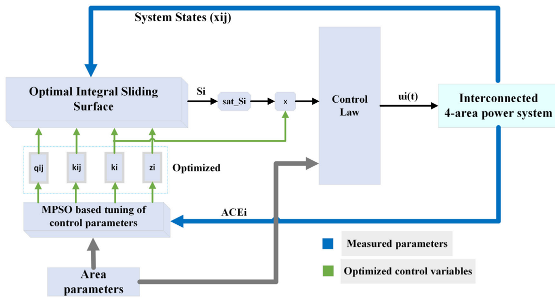


**FIGURE 4. Schematic diagram of optimized ISMC for LFC of multi-area power system.**

the steady state error in the output response. Referring (14) and (19), the control input $\Delta P_{ci}$ in is computed as:

$$P_{ci} = P_{ci1} + P_{ci2}$$

$$P_{ci}(n) = -z_i[\sum b_i\Delta f_i(n) + \Delta P_{tie,i}(n)] + u_i(n) \quad (20)$$

where, n is the sampling instant.

The performance of the interconnected power system is dependent upon the selection of the control variables such as adjustable parameters. For six states proportional gain of sliding surface: $q_{i1}$ $q_{i2}$, $q_{i3}$, $q_{i4}$, $q_{i5}$, $q_{i6}$, & integral gain of sliding surface: $k_{i1}$, $k_{i2}$, $k_{i3}$, $k_{i4}$, $k_{i5}$, $k_{i6}$, and switching function gain $k_i$ of the control loop of the $i^{th}$ area as well as integral gain of the controller ($z_i$) of $i^{th}$ area. But for an isolated system the control variables are: $q_{11}$ $q_{12}$, $q_{13}$, $q_{14}$, $q_{15}$, $k_{11}$, $k_{12}$, $k_{13}$, $k_{14}$, $k_{15}$, and gain $k_1$ of the control loop of the area as well as integral gain of the controller ($z_1$).

As the state, $X_6$ i.e. ACE is not considered for isolated area LFC model, the number of control variables for sliding surface gain are reduced.

To optimise the control variables of ISMLFC scheme, the following modifications are made in the algorithm of PSO for better performance of frequency response. Thus, the alterations in the algorithm of MPSO includes: (i) the inertia weight is changed from fixed to nonlinear and is varied using a tangent function in decreasing order. This improves the global search for the fast convergence; (ii) time-invariant acceleration constant is replaced with time-varying to influence the movement of the swarm particles towards the

**TABLE 4. Selection of MPSO parameters.**

| S.No. | Parameter | Value |
|---|---|---|
| 1 | No. of Control Variables (n) | 56 for Four-Area<br>12 for isolated system |
| 2 | Dimension of Swarm Size (m) | 200 |
| 3 | Range of Control Variables | 0.5 |
| 4 | Maximum no. of Iterations | 150 |
| 5 | Initial Largest Value of Inertia Weight ($w_{max}$) | 0.9 |
| 6 | Final Smallest Value of Inertia Weight ($w_{min}$) | 0.4 |
| 7 | Acceleration Constant ($c_1$) with Particle's Best Position ($c_{1i}, c_{1f}$) | (2.5, 0.2 ) |
| 8 | Acceleration Constant ($c_1$) with Particle's Best Position ($c_{2i}, c_{12f}$) | (2.5, 0.2) |
| 9 | Range of Random Numbers ( $r_1, r_2$) | 0-1 |

**TABLE 5. Simulation case study for performance analysis.**

| S.No. | Case | Details |
|---|---|---|
| 1 | Variation in Step Disturbance | (i) 0.01-0.05 in Single area<br>(ii) Different Combination of 0.01 and 0.02 in different Four areas |
| 2 | Variation in Control Law | sgn fn. and sat Fn. |
| 3 | Variation in System parameters with Governor and Turbine Time Constant ($T_g, T_t$) | $\pm 5\%, \pm 10\%$<br>keeping $\alpha_g = 0.75, \alpha_e = 0.25$ |
| 4 | Variation in Generation Participation Factor($\alpha_g, \alpha_e$) | (0-100%) |
| 5 | Variation of Noise Level (Covariance) | With $10^{-6} - 10^{-8}$<br>keeping $\alpha_g = 0.9, \alpha_e = 0.1$ |
| 6 | Variation in Time Delay, $\tau_d$ | 0.001, 0.005, 0.01, 0.05 |
| 7 | Variation in EV Time Constant ($T_e$) | $\pm 5\%, \pm 10\%$) |

global-best and personal-best position. With this, the swarm particles traverse a wide search space in the early stages of the search and finally, converge on the global optimum.

For the present LFC problem, integral square error (ISE) as objective function (J) is selected to optimize the control variables. This is expressed as:

$$J = \int_0^{T_{sim}} \sum_{i=1}^{4} \Delta ACE_i^2 \tag{21}$$

## V. SIMULATION STUDY AND RESULT ANALYSIS

In this section, an extensive simulation study is conducted for the performance validation of the proposed OISMLFC control scheme, using a benchmark power system model (refer Fig. 1). This dynamical model takes into account parameter variation, modelling error, lumped disturbance due to load and generation perturbation, time delay, nonlinearities (GDB & GRC), conventional generation, and EV aggregate reserve power participation. Although this scheme (shown in Fig. 4) is suggested for a generalized power system model but in this work, isolated as well as four-area systems (connected by distinct tie-lines such as HVDC, AC, and TCPS) are considered for performance analysis. A large power system model that incorporated different tie-line dynamics is created using MATLAB software version 2020a to replicate a real system for the purpose of testing the developed controller. A decentralized control algorithm is implemented on the test system (Fig. 2). The Simulink model, and the script file of the area-parameters are developed using dynamics given in (1) and values of different parameters used are referred from [37]. For investigation, the simulation experiment environment is created and presented in Table 3. Using iterative simulation during MPSO algorithm, the optimized control parameters are obtained based on the performance index given in (21). During optimization, the present control scheme has adjustable parameters for states with control gain in each area control-loop and different MPSO parameters during optimization are listed in Table 4. The optimization of these control variables is done considering without any time delay ($\tau_1$ & $\tau_2$ ), step disturbance of 0.02 and random disturbance as white Gaussian noise (WGN) with covariance $10^{-7}$.

To mimic the real power system, the investigation of the performance of present work is conducted under various test scenarios presented in Table 5 considering different cases of disturbance, and operating conditions. For interconnected system, Table 6 shows the variations in the loading condition among four areas and their corresponding effects on frequency deviation ($\Delta f$) and ACE are reflected with the help of simulations results. The simulation study is conducted to investigate the dynamic performance of both isolated and interconnected power systems. The simulation results are displayed and analysed as follows.

### 1) PERFORMANCE ANALYSIS OF AN ISOLATED SYSTEM

Considering isolated control area, the tie-line power deviation has no influence on its ACE, so $ACE_i = \Delta f_i$ as $\Delta P_{tiei} = 0$ and $b_i = 1$ (refer Eq. 1). For simulation, Area 1 is considered as an isolated area and the performance of OISMLFC is evaluated under the influence of different scenarios such as (i) impact on different system states; (ii) impact of signum and saturation functions at different step loading; (iii) impact of random disturbance level (iv) impact of switching function types under different step loads; (v) impact of variation in system parameters by changing governor and turbine time constants ($T_g$ and $T_t$); (vi) impact of EV contribution($\alpha_e$).

The related simulation results are displayed in Fig. 5 (i)-(vi). The performance of each case is evaluated by examining the frequency nadir ($\Delta f_n$), steady state error ($e_{ss}$) and settling time ($t_s$).

It is observed from Fig. 5 (i) that deviations in system states ($\Delta f_1$, $\Delta P_{g1}$, $\Delta P_{r1}$, $\Delta X_{g1}$, and $\Delta P_{e1}$) in the presence of random disturbance and non-random disturbance (step loading) settle before 10 seconds and are well within the permissible limits.

Fig. 5 (ii) shows the effect of I-component in the sliding surface of SMC with saturation function. This result implies the effect of using PI-based SS in contrast to only P-based SS. The transient and steady-state behaviour of the PI surface has improved the frequency response. Also, the persistence of *ess* with P- sliding surface grows with the increase of load

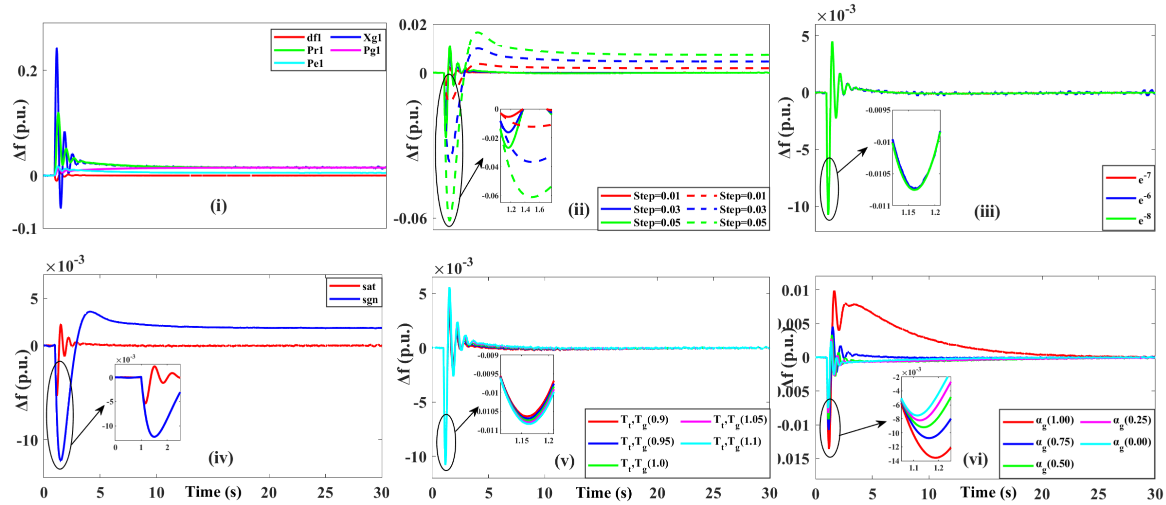

**FIGURE 5.** Performance analysis of ISMC for single area: (i) States (ii) Integral effect (iii) Effect of noise level (iv) Effect of using sgn & sat function in control input (v) Effect of parameter variations (vi) Contribution of EV.

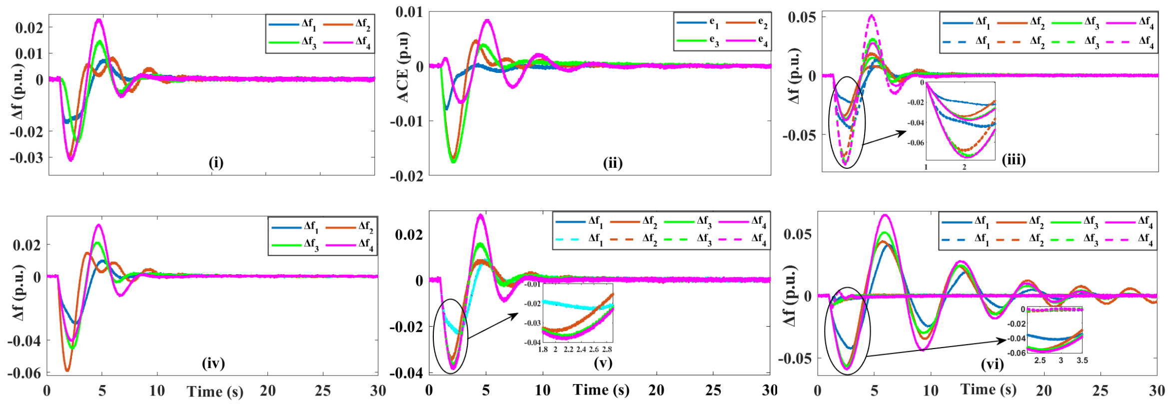

**FIGURE 6.** Performance analysis of multi-area: (i) Scenario 1 (ii) Scenario 2 (iii) ACE in scenario 3 (iv) Scenario 4 (v) Scenario 4 and 5 (vi) Contribution effect of EV reserve power with Scenario 4.

disturbance. Further, with the increase in fixed load disturbance, frequency ($\Delta f_n$) is affected. However, in all cases, the frequency deviation is within limits and converges to its nominal value almost in 6 seconds with $e_{ss}$ in the $10^{-5}$ range, which is acceptable.

Fig. 5 (iii) shows the effect of varying covariance of random disturbance from $10^{-8}$ to $10^{-6}$ keeping fixed load disturbance at 0.02 step. Increase in covariance increases the fluctuation in system frequency but settles its steady state value within limits (in the range of $10^{-5}$). The extreme value of $\Delta f_n$ is observed to be less than 0.011 p.u.

The performance of the proposed control scheme is investigated using both signum and saturation functions in the control law and results are shown in Fig. 5 (iv). It is found that frequency response using OISMLFC with saturation function gets improved. This can be observed by comparing the $\Delta f_n$ and $e_{ss}$ in the responses of both cases.

The performance of the test system under varying system parameters is observed by plotting error in frequency ($\Delta f$) vs time as shown in Fig. 5 (v). The robustness of the proposed controller is tested under the variation in the system parameters. It has been found from simulation result and quantitative analysis (refer Table 7) that with a parameter uncertainty of +10% in $Tg$ & $Tt$, the $\Delta fn$ decreases by 6.5% of the nominal value, whereas the $fn$ increases by 9% with a parameter uncertainty of +10%. The maximum change in frequency i.e. $\Delta f_n$ is found to be in permissible limit and transient settles quickly.

The percentage contribution of EV reserve power ($\alpha_e$) is varied from 0-100 % and the frequency response is shown in Fig. 5 (vi). Corresponding to this response plot and Table 7, it is inferred from the response that 100% contribution of conventional power deteriorates the performance with maximum undershoot ($\Delta f_n$) and overshoot, $t_s$ and ($e_{ss}$). With the increase of $\alpha_e$ contribution, the transient and steady state performance gets improved assuming the system inertia to be maintained at the same value. However, in practice, system inertia decreases with the decrease in $\alpha_g$ contribution. Furthermore, the effect of time delay in system is investigated by keeping its value to 0, 1/1000 s, and 1/100 s. The performance

**TABLE 6.** Case study: effects of loading disturbance on frequency nadir and area control error of interconnected multi-area system.

| | Area 1 | | | Area 2 | | | Area 3 | | | Area 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cases | $L_1$ | $f_{n1}$ | $ACE_1$ | $L_2$ | $f_{n2}$ | $ACE_2$ | $L_3$ | $f_{n3}$ | $ACE_3$ | $L_4$ | $f_{n4}$ | $ACE_4$ |
| 1 | 1% | -1.68 | -7.42 | 1% | -2.94 | -16.73 | - | -2.40 | -8.39 | 1% | -3.07 | -17.66 |
| 2 | 1% | -2.92 | -6.13 | 2% | -5.92 | -33.25 | 1% | -4.50 | -21.10 | 1% | -4.01 | -19.75 |
| 3 | 1% | -1.58 | -7.95 | 1% | -3.31 | -16.97 | 1% | -3.07 | -17.68 | - | -1.90 | -6.73 |
| 4 | 1% | -2.28 | -6.88 | 1% | -3.40 | -16.67 | 1% | -3.69 | -19.29 | 1% | -3.81 | -19.77 |
| 5 | 2% | -4.43 | -13.36 | 2% | -6.79 | -32.93 | 2% | -7.31 | -38.40 | 2% | -7.55 | -38.70 |

L-Loading; $f_n$-Frequency nadir (in range of $10^{-2}$); ACE-Area control error (in range of $10^{-3}$)

**TABLE 7.** Quantitative result analysis of single area.

| Case | Variation | $\delta f_n$ | | $t_s$ | |
|---|---|---|---|---|---|
| | | With I-based SS | Without I based SS | With I-based SS | Without I based SS |
| 1 | 1% Loading | -0.0053 | -0.012 | 3.47 s | 6.01 s |
| | 3% Loading | -0.016 | -0.0367 | 3.58 s | 6.04 s |
| | 5% Loading | -0.027 | -0.06 | 3.61 s | 6.08 s |
| 2 | 2% Loading | With sat Fn. | With sgn Fn. | With sat Fn. | With sgn Fn. |
| | | -0.0053 | -0.012 s | 3.48 s | 7.65 s |
| 3 | 10 % $T_g, T_t$ | $-1.083 \times 10^{-2}$ with $e_{ss} = -3.53 \times 10^{-5}$ | – | 1.16 s | – |
| | Nominal | $-1.074 \times 10^{-2}$ with $e_{ss} = -3.73 \times 10^{-5}$ | – | 1.16 s | – |
| | -10 % $T_g, T_t$ | $-1.063 \times 10^{-2}$ with $e_{ss} = -3.63 \times 10^{-5}$ | – | 1.16 s | – |
| 4 | $\alpha_e = 0\%$ | $-1.353 \times 10^{-2}$ with $e_{ss} = 7.16 \times 10^{-5}$ | – | 10.63 s | |
| | $\alpha_e = 25$ % | $-1.074 \times 10^{-2}$ with $e_{ss} = -3.73 \times 10^{-5}$ | – | 2.46 s | – |
| | $\alpha_e = 50\%$ | $-0.92 \times 10^{-2}$ with $e_{ss} = -8.55 \times 10^{-5}$ | – | 2.41 s | – |
| | $\alpha_e = 75$ % | $-0.82 \times 10^{-2}$ with $e_{ss} = -6.01 \times 10^{-5}$ | – | 2.38 s | – |
| | $\alpha_e = 100$ % | $-0.75 \times 10^{-2}$ with $e_{ss} = -0.816 \times 10^{-5}$ | – | 2.28 s | – |

of proposed control scheme is found to be robust as no significant change is observed in frequency response.

From the simulation study, it is inferred that under all cases, the control system is robust with OISMLFC to withstand the aforementioned operating scenarios.

### 2) PERFORMANCE ANALYSIS OF THE INTERCONNECTED SYSTEMS

Considering the interconnected four area system, the proposed MPSO optimized control scheme is implemented to minimize the frequency deviation, and ACE despite of transients in any of the areas. A simulation study is conducted considering different cases of loading among four areas as listed in Table 6. The time delay in all control areas is set to 0.001 s. The control parameters for each area are optimised, and then the optimised ISMC is applied to individual areas. The performance of overall system is evaluated and the corresponding results of frequency deviation during each case study is shown in Fig. 6 (i)-(vi). Also, for different fixed loading in different areas, the values of their respective $\Delta f_n$ and ACE are shown in the table. It is worthy to note that loading affects frequency nadir, $\Delta f_n$ and deteriorates it. For example in Case 1, there is no step loading in area 3 (L3) giving better $f_{n3}$ as compared when it is loaded in Case 2- Case 5. Similar observation is in Case 3 for area 4. Further, a relative change in $\Delta f_n$ w.r.t. change in the step load as seen Case 4 and case 5, it is observed that the $f_{n1} - f_{n4}$ gets nearly double by making $L_1 - L_4$ twice. Also, for Area 1, least $\Delta f_n$ is observed. This can be justified on the basis of its interconnection with all other areas which are contributing to control not only its own frequency but also of other linked areas. Despite of decentralised control approach, the frequency stabilization is achieved for interconnected system.

Based on the plots of Fig. (5) and (6) corresponding to case study (refer Table. 4), the quantitative analysis of some of this research output is presented in Table 6 and Table 7. The preceding findings lead to the conclusion in the following section.

## VI. CONCLUSION

This paper has successfully solved the LFC as stochastic control problem using an optimised ISMC approach. In the proposed control scheme, the saturation function based control law was developed to minimize the area control error and regulate the system frequency within the desired range. The increase of loading has resulted corresponding rise in $\Delta f_n$ and $t_s$. The incorporation of I-component in the sliding surface has a positive impact for improving the $\Delta f_n$ and the transients settled at almost 3.66 s which is much less than that without I-based sliding surface (> 6.2 s). In addition, using the saturation function in the control law reduced oscillations and steady-state error significantly when compared to the Signum function, while improving *fn* and *ts* by more than two times. The robustness of the proposed controller is validated under the variations in system parameters, time delay, EV reserves. Thus, it is concluded that proposed OISMLFC has the ability of resolving the LFC issue for isolated area and interconnected multi-area effectively. Refer to Table 6 and Fig. 6, the scheme has reflected its capability in tolerating the fluctuations in the parts of the system within the predefined tolerance bounds of the nominal dynamic behavior. These effects are admissible and indicate the efficacy of the proposed controller. Besides this, the quality of control action was excellent as well as robust over a wide range of operations justifying the implication of the proposed controller for the real power system. Further, it is inferred from comparative study with previous work of SMC on interconnected power system (refer Table 1) that OISMLFC has the potential to address the issue of frequency deviation and ACE for complex, stochastic for a dynamical systems. As a future work, higher order SMC can be designed for better transient behaviour of a multi-area power systems integrated with RERs and energy storage system.

## APPENDIX

The state space approach of modelling facilitates the control design to include many inputs. For better insight, the state space model for $i^{th}$ area (2) can be concisely expressed in the canonical form as:

$$\begin{bmatrix} \dot{x_{i1}}(t) \\ \dot{x_{i2}}(t) \\ \dot{x_{i3}}(t) \\ \dot{x_{i4}}(t) \\ \dot{x_{i5}}(t) \\ \dot{x_{i6}}(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\ A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66} \end{bmatrix} \begin{bmatrix} x_{i1}(t) \\ x_{i2}(t) \\ x_{i3}(t) \\ x_{i4}(t) \\ x_{i5}(t) \\ x_{i6}(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} u_i(t) + \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \end{bmatrix} d_i(t) \tag{22}$$

where, each term is defined in Section II.

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