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Distributed Load Frequency Control of Deregulated Nigerian Power System

Y. M. Abdullahi[1]*, S. B. Yusuf[1], A. B. Kunya[2], Y. Jibril[2]

[1]Department of Electrical Electronics Engineering, Umaru Ali Shinkafi Polytechnic, Sokoto State – Nigeria,
[2]Department of Electrical Engineering, Ahmadu Bello University, Zaria, Kaduna State – Nigeria
*yusufabdullahi5050@gmail.com,

Research Article

Abstract

In this study, load frequency control (LFC) of the 330kV, 50Hz Nigerian Power System (NPS) is studied. The aim of the work is to develop a control scheme that maintains near-zero steady state errors for deviation in system frequency and that of net inter-area power flow within an acceptable limit in a deregulated environment. The entire NPS network, comprising of 11 distribution companies (DISCOs) and 8 generation companies (GENCOs) is partitioned into seven control areas (CAs). The control scheme is developed with distributed control architecture. Each of the seven CAs (CA_1, CA_2, … CA_7) is equipped with a proportional integral (PI) controllers. These local PI controllers (slave controllers) compute the optimal control signal for appropriate valve positioning of all the generators in its CAs, which in regulate the frequency and tie-line powers. In addition, each of the slave controllers exchange the information about their control action with the neighboring controllers as well as a central master controller located at the National Control Center (NCC), Osogbo, Osun State. The local PI controllers are optimally tuned using moth flame optimization (MFO) algorithm by minimizing the Integral Square Error (ISE) of the state errors. A model predictive controller (MPC) applied as the master controller is used to establish the optimal set-points of the slave PI controllers. The effectiveness of the developed scheme is verified by implementing it on the seven-CA Nigerian deregulated power system perturbed with a step load demand. From the simulations carried out in MATLAB environment, it is established that the developed scheme is not capable of maintaining near-zero steady state errors for deviation in system frequency and tie-line powers but outperformed the present conventional control scheme in optimality and stability.

Keywords
Load Frequency Control, Model Predictive Controller (MPC), Multi Area Power System, Nigerian Power System, PI Controller

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1. Introduction

In order to maintain steady frequency in power system, active power generation and demand must always match. When the demand changes, the generation must also change in order balance up with the new demand. Mismatch in generation-demand balance deteriorates the system performance severely via incessant variations in the tie-line power, frequency and voltage levels, among others. The severity of the deterioration worsens if the PS has multiple control areas (CA) due to the increased nonlinearities of the system (Sujan, 2017; Daneshfar & Hosseini, 2012). A small perturbation in generation-demand balance in one CA of the MAPS can lead to frequency deviation in that particular CA as well as its neighbors. Active load disturbance is the major cause of generation-demand mismatch as such electrical power generation is carefully monitored (Gupta, 2008; Saxena, 2019). Unless the generation-demand balance is regained, the frequency and tie-line powers keep deviating from the corresponding nominal values (Wadhwa, 2010; Chidambaram & Velusami, 2005). If these undesirable deviations persist, the system generators (mostly synchronous) no longer be coherent, hence the system collapses. The ancillary service applied to maintain the frequency by continuously changing the generation due to the change in the demand is referred to as load frequency control (LFC). It is the most perplexing task in the control of power system (Kunya, *et al*., 2019; Anne Mai Ersdal, 2015). Earlier frequency control scheme used flyballs to activate a hydraulic system for adjusting the throttle valves of the system prime movers. Modern generators use electronic governors to accomplish the same task (Zhang, *et al*., 2017; Stil & Mehmedovic, 2018).

There are numerous research works carried out on LFC, which mainly applied modern optimal control (Saxena & Shankar, 2022; Pradhan & Bhende, 2019), adaptive and sliding model variable structure methods (Liu, e*t al*., 2022; Zhu, et al., 2021), robust approaches (Khajehoddin, 2016; Ejegi, et al., 2016), and intelligent approaches (Sahoo, *et al*., 2018; Rahmani & Sadati, 2013). While in some studies apply classical control such PI in (Guolian et al., 2011; Simhadri & Mohanty, 2019) and PID controllers (Abd-Elazim, 2010; Mehta, *et al*., 2017; Hota & Mohanty, 2016). This family of controllers has been applied widely not only for LFC application but control of other dynamic systems, largely owing to the simplicity of the concept and ease of implementation. However, the robustness of classical controllers worsens greatly with the nonlinearities increases (Machowski., 2008). As such, numerous studies paid considerable attention to improve their robustness and stability. Like in (Abd-Elazim, 2010), a bacterial foraging optimization algorithm (BFOA) was applied to optimize the gains of the PI and revealed its improved performance compared to that optimized using Genetic Algorithm (GA) in a two-area non-reheat system. Application of Grey Wolf Optimization is demonstrated in (Saikia, 2015) for LFC in MAPS based on the minimization of the Integral of Time Multiplied by Absolute Value of Error (ITAE) of the some selected states.

In a similar study, application of fuzzy PI controller for frequency control of a linear and nonlinear MAPS is investigated in (Satapathy, *et al.*, 2018). The gain of the controller in tuned using Jaya optimization algorithm with and without the effect of governor dead band (GDB). In (Pradhan & Bhende, 2019), same algorithm is applied to tune a fuzzy controller online for LFC of WT integrated MAPS.

Moreover, robust control techniques such as sliding mode control (SMC), model predictive control (MPC) (Ejegi, *et al.*, 2016; Kunya & Argin, 2018; Anne Mai Ersdal, 2015), linear quadratic regulator (LQR) (Kumari & Jha, 2014; Rahman, *et al*., 2018), fuzzy controller (Pradhan & Bhende, 2019; Azeer, *et al*., 2017; Sahu, *et al*., 2018) or hybrid of these schemes (Mohamed, *et al*., 2015; Prasada, *et al.*, 2019) were proposed. While in (Liu, et al., 2019), improved LFC based on MPC is applied to a hybrid MAPS comprising of WT and thermal generation system. The scheme is designed in such a way that these hybrid sources are controlled concurrently with the MPC generating their reference orders. Frequency regulation of MAPS with high penetration of DGs is presented in (Yang, et al., 2021). The frequency regulation problem is expressed as a predictive control problem. An algorithm based on distributed projection by means of peer-to-peer communication is then proposed for its solution. LFC in a restructured MAPS using LQR controller is presented (Shahalamia & Farsi, 2018). Most of this studies is not applied on real-life systems, as such their effectiveness and applicability in that regard cannot be ascertained (Ansari, *et al.*, 2022; Lee, *et al.*, 2022).

In this study, a distributed LFC scheme is developed and applied to the deregulated Nigerian Power System (NPS) portioned into seven CAs. The aim is to maintain near-zero steady state errors in the system frequency and that of net inter-area power flow. Each of the seven CAs are equipped with a slave proportional integral (PI) controller as which compute the optimal control signal for appropriate valve positioning of all the generators that respective CAs. Moth flame optimization (MFO) is applied to optimally tune the slave controllers, subject to system dynamic constraints. A model predictive controller (MPC) applied as the master controller is used to establish the optimal set-points of the slave PI controllers. The key contributions of this study are itemized as: -

i- Partitioning Nigerian Transmission Network into 7 CAs.
ii- Developing the partitioned NPS network in MATLAB simulation environment.
iii- Developing a distributed LFC scheme for the developed system.
iv- Demonstrating the applicability of the developed LFC scheme on real system and its superiority over conventional LFC as applied to the present NPS.

The remaining part of the paper is organized with the highlights on the NPS presented in Section 2, formulation of the proposed LFC architecture explained in Section 3. Section 4 discusses the simulation results and the paper concluded in Section 5.

2. Nigerian Power System

Nigerian transmission network operated on 330kV, 50Hz with a total transmission wheeling capacity of 7,500MW and spanning over 20,000km, is faced with frequency instability due to insufficient generation, transmission losses approximated at 7.4%, frequent system collapse (average of 35 annually) and poor market policies, among other hiccups facing the system. Some of these problems can be attributed to the inadequate transmission line capacity, as the network wheeling capacity is far below the total installed generation capacity of 12,500MW.

Presently, there are eight (8) generation companies (GENCOs) operating twenty-five (25) grid-connected generation stations which are either thermal or hydro (Ajimotokan, *et al.,* 2009; Ogbonnaya, *et al.,* 2019). The thermal generation stations located near to the sources of gas in the southern part of the country contributing to about 68.30% of the total installed capacity, while the hydroelectric stations are located further north accounting for the remaining 31.70%. There are various ongoing projects for the construction of new power plants

The frequency control in the NPS is carried out in a centralized, thereby making the frequency control and economic dispatch (ED) inefficient. The Nigerian Grid Code Frequency Standard is 49.75Hz – 50.25Hz while the WAPP Frequency standard is 49.80Hz – 50.20Hz.

For the purpose of this study, the Nigerian transmission network is partitioned into 7 CAs as shown in Fig. 1 and 2.

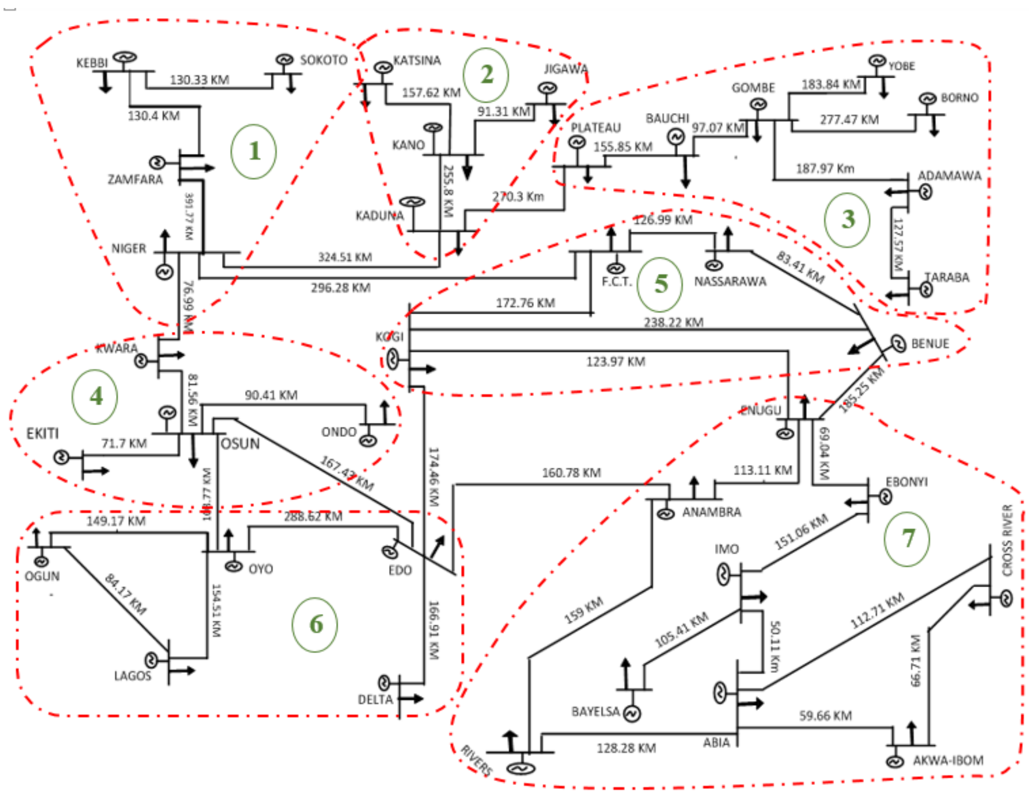

Fig. 1: Nigerian Transmission Network Partitioned into Seven Control Areas

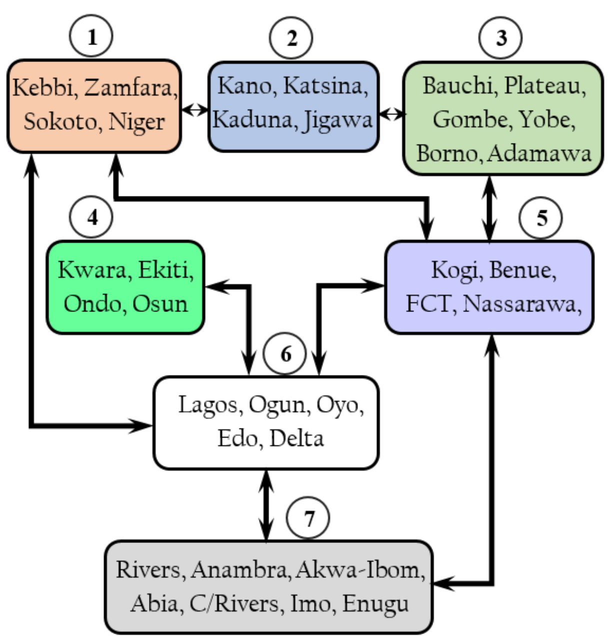

Fig. 2: Schematic Diagram of the Partitioned NPS Network

3. Control Structure

2.1 Multi-Area Power System LFC

The formulation of the model of the NPS is centered at differential equations describing the dynamics of the individual components of the system like tie-line powers, governor and turbine dynamics, among others. Fig. 3 shows the transfer function representation of a CA in a typical MAPS with thermal power plants.

From the block diagram depicting the dynamic model of the CA, the state space model can be derived distinctively.

The frequency deviation, f_i is formulated from a linearized *swing equation* shown in (1) (Ejegi, et al., 2016).

$$\frac{df_i}{dt} = \frac{1}{M_i}\left(P_i^G - D_i f_i - P_i^{tie} - P_i^D\right) \qquad (1)$$

Where P_i^D is the net disturbance formed by taking the resultant effects of the sources of disturbance in the *i*th CA.

M_i represents the *i*th CA net inertia constant. It defines the characteristic value for each synchronous machine in each CA. With the assumption that generators in that area form a coherent group, it is acceptable to define a single frequency for each area.

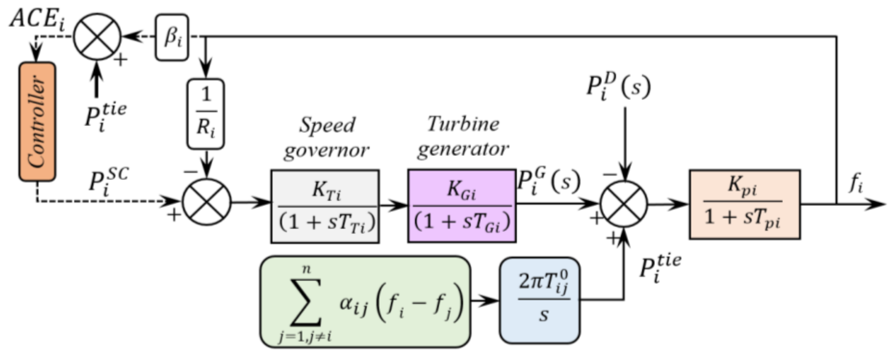

Fig. 3: Transfer function representation of the CA

Not all the generators in the system participate in LFC. Only generators providing spinning reserve at a particular time are engaged in LFC, which for security consideration, are often scheduled hours ahead. As modelled in (2), the generation from this set of generators are added up as CA aggregate generation, P_i^G (Kunya & Argin, 2018).

$$P_i^G = \sum_{j=1}^{G} P_{i,j}^G \, ; \qquad (2)$$

The MAPS in this study has deregulated structure, hence the tie-line power model is obtained considering all the power exchanges with the neighboring areas, as in (3).

$$\frac{dP_i^{tie}}{dt} = \sum \dot{P}_{ij} \, ; \qquad (3)$$

$$\frac{dP_{ij}}{dt} = 2\pi W_{ij}^0 (f_i - f_j); \quad P_{ji} = -\frac{P_{MVA_i}}{P_{MVA_j}} P_{ij} = -\alpha_{ij} P_{ij} \quad (4)$$

Where W_{ij}^0 is the synchronizing coefficient which depends on the static transmission capacity of *ij*th line. In real MAPS, CAs have different MVA rating, hence α_{ij} defines the ratio of the rated capacities of *i*th and *j*th CAs as shown in (4).

The system frequency is adjusted by varying the set point of the turbine. Assuming a slight perturbation in the system, the dynamics of *g*th turbine in the *i*th CA is modelled as (5);

$$\frac{dP_{i,g}^G}{dt} = sat_{\dot{P}_{i,g}^G}^{i} \left\{ \frac{1}{T_{T_{i,g}}} \left(P_{i,g}^{Gov} - P_{i,g}^G \right) \right\} \qquad (5)$$

To adjust the set point of each generator turbine, a supplementary optimal control signal, P_i^{sc} obtained from the LFC controller is used. Since the set points cannot be adjusted instantly, additional state is added to model as speed governor. The adjustment in the governor valve position, as a function of frequency deviation is expressed in (6) (Prasada, *et al*., 2019);

$$\frac{dP_{i,g}^{Gov}}{dt} = \frac{1}{T_{Gov_{i,g}}} \left(P_{i,g}^{sc} - P_{i,g}^{Gov} - \frac{1}{R_{i,g}} f_i \right) \qquad (6)$$

The *i*th Area Control Error (ACE) is formulated by combining the deviations in the frequency and tie-line power as defined in (7) (Ejegi, *et al*., 2016). The ACE forms the feedback input signal to the controller as depicted in Fig. 2.

$$\mathrm{ACE}_i = \beta_i f_i + P_i^{tie} \qquad (7)$$

The LFC controller then compute the $P_{i,g}^{sc}$ based on certain control law at a predefined time interval.

The modelling equations in (1) – (7) defining the state variables are rearranged to a standard state-space of form (8) as shown in (9) and (10);

$$\begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + E_i d_i^{int}(t) + F_i d_i^{ext}(t) \\ y_i(t) = C_{ii} x_i(t) \end{cases} \qquad (8)$$

$$\frac{d}{dt}\begin{bmatrix} f_i \\ P_{i,g}^G \\ P_{i,g}^{Gov} \\ P_i^{tie} \end{bmatrix} = \begin{bmatrix} -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 & -\frac{1}{M_i} \\ 0 & -\frac{1}{T_{T_{i,g}}} & \frac{1}{T_{T_{i,g}}} & 0 \\ -\frac{1}{R_{i,g} T_{Gov_{i,g}}} & 0 & -\frac{1}{T_{Gov_{i,g}}} & 0 \\ \sum_{j \in \mathcal{A}_i^{tie}} 2\pi W_{ij}^0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_i \\ P_{i,g}^G \\ P_{i,g}^{Gov} \\ P_i^{tie} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{Gov_{i,g}}} \\ 0 \end{bmatrix} P_{i,g}^{sc} + \begin{bmatrix} -\frac{1}{M_i} \\ 0 \\ 0 \\ 0 \end{bmatrix} P_i^{net} + \begin{bmatrix} -\frac{1}{M_i} \\ 0 \\ 0 \\ -2\pi \sum_{j \in \mathcal{A}_i^{tie}} W_{ij}^0 \end{bmatrix} f_j \quad (9)$$

$$\mathrm{ACE}_i = (\beta_i \quad 0 \quad 0 \quad 1)\left(f_i \quad P_{i,g}^G \quad P_{i,g}^{Gov} \quad P_i^{tie} \right)^T \qquad (10)$$

The state vector, x_i is defined as $\left[f_i \quad P_{i,g}^G \quad P_{i,g}^{Gov} \quad P_i^{tie} \right]^T \in \mathbb{R}^4$ is the state vector, $u_i = P_{i,}^{sc}$ is the supplementary control signal, $d_i^{int} = P_i^{net}$ is the system disturbance within the CA, while $d_i^{ext} = f_j$ is the disturbance attributed to frequency deviations from neighboring CAs and $\mathrm{ACE}_i: \forall i = 1, 2, \ldots n$ is the system output.

The partitioned network with the PI controller installed on each area is developed in a MATLAB/Simulink as shown in Fig. 4.

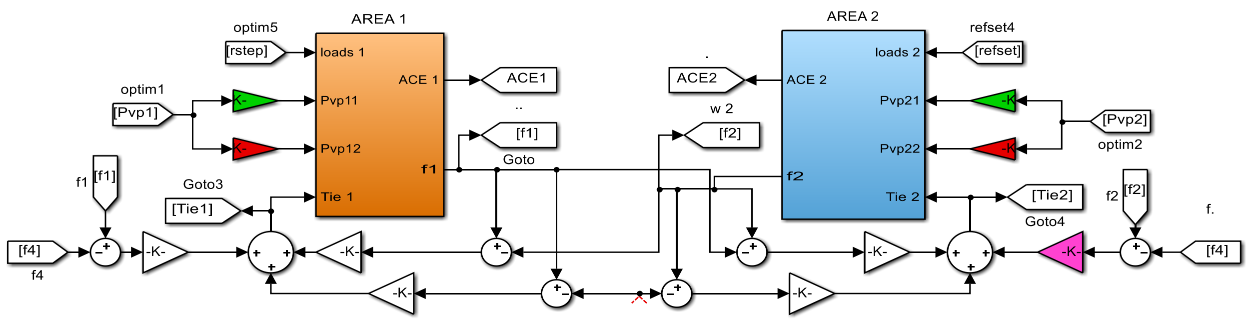

Fig. 4: MATLAB Implementation of the Partitioned System (Only CA1 an CA2 shown for brevity)

The frequency and tie-line powers are controlled with the application of the supplementary control action signal to the generators. The PI controllers at this control level generates the control signal, P_i^{sc} for each area. Moth Flame Optimization (MFO) (discussed in the next sub-section) is applied to tune the controllers, based on the ISE criteria as shown in (11).

$min(J_i)$ Such that,

$$J_i = \int_0^t \left(u_i^{ref} - ACE_i\right)^2; \quad i = 1, 2, 3 \qquad (11)$$

The ISE criterion is chosen for the controller design in order to curtail the effect of large initial errors and minimize the control effort.

For physical consideration, the proportional gains (K_{P1}, K_{P2} and K_{P3}) and integral gains (K_{I1}, K_{I2} and K_{I3}) of the controller are constrained within some upper and lower limits for practical considerations, as shown in (12) and (13);

$$K_{Pi}^{min} \leq K_{Pi} \leq K_{Pi}^{max}; \qquad (12)$$

$$K_{Ii}^{min} \leq K_{Ii} \leq K_{Ii}^{max}; \qquad (13)$$

With the reference set points from the master MPC, the local PIs in the lower level then generate the control signal for each area, using (14).

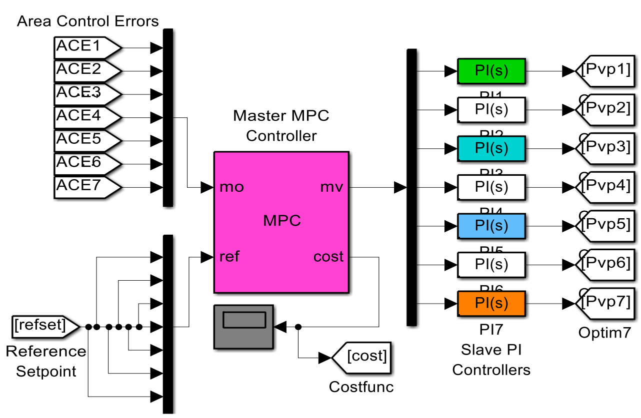

Fig. 5: MATLAB Implementation of the Control Architecture

$$u_i = K_{Pi}\mathrm{ACE}_i(t) + K_{Ii}\int_0^t \mathrm{ACE}_i(t)\,dt; \quad i = 1, 2, 3 \; (14)$$

Similarly, the control architecture developed is also designed in MATLAB/Simulink as shown in Fig. 5.

4. Results and Discussion

To investigate the effectiveness and superiority of the proposed LFC scheme over conventional PI-based LFC scheme implemented in presented Nigerian system, the seven-area interconnected system developed is subjected to single area step disturbance. The system is then simulated in MATLAB (R2016a) environment.

The load demand in CA_1 (consisting of Sokoto, Kebbi, Zamfara and Niger) is set to a step change of 0.1*pu* (10% of the total installed capacity assumed to be 5000MW). While the rest of the control areas are maintained intact. The frequency and tie-line power responses all the CAs obtained with the developed control scheme are analyzed and compared with conventional PI control scheme.

Fig. 6 – 12 show the close-loop responses of the frequency changes in CA_1 to CA_7 obtained with the proposed scheme as well as the conventional control scheme. It can be seen from the dynamic responses that the frequency change in CA_1 has larger undershoot compared to the other two areas. This is an indication that the disturbance occurred in CA_1.

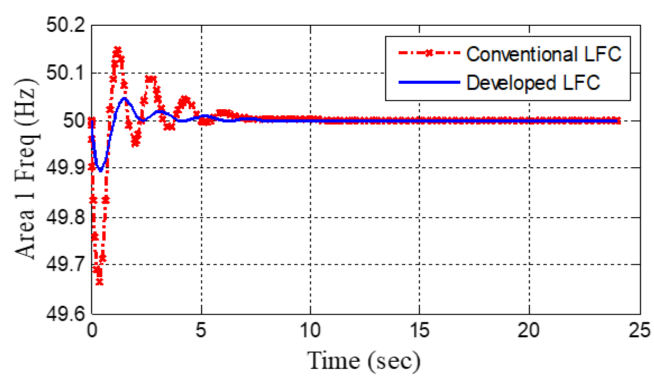

Fig. 6: CA_1 Frequency Response

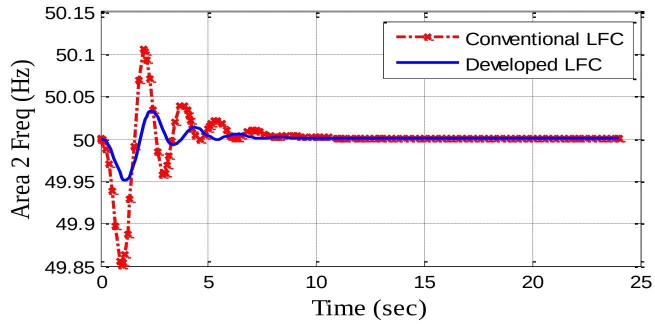

Fig. 7: CA_2 Frequency Response

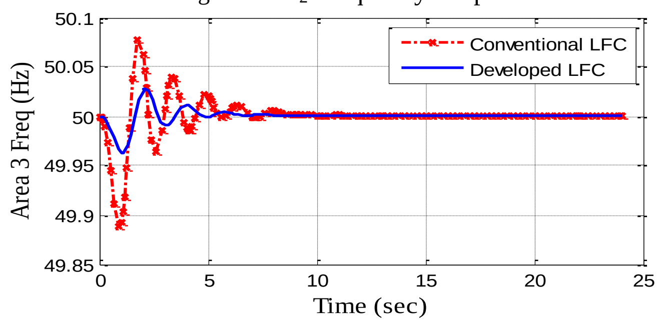

Fig. 8: CA_3 Frequency Response

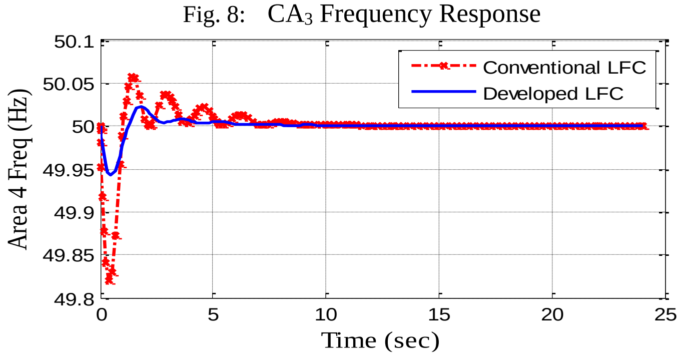

Fig. 9: CA_4 Frequency Response

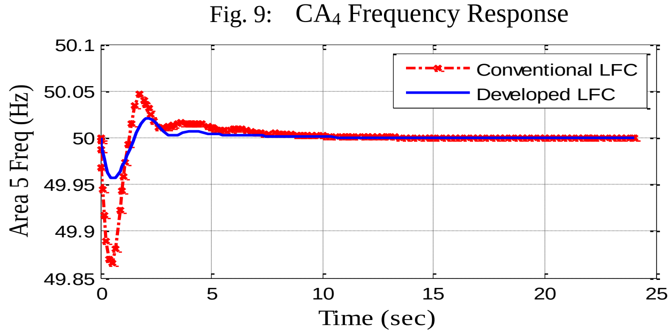

Fig. 10: CA_5 Frequency Response

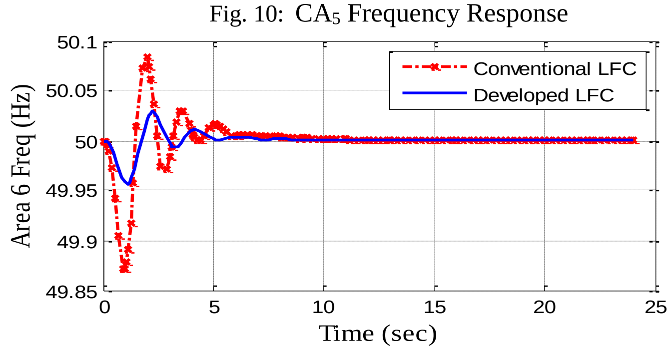

Fig. 11: CA_6 Frequency Response

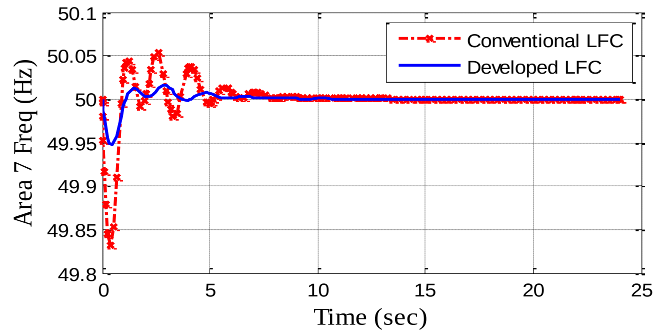

Fig. 12: CA_7 Frequency Response

From the trajectories of the frequency changes in all the areas, it can be observed that the developed control schemes can restore the system frequencies to their allowable range with approximately zero steady state error. However, the proposed scheme achieved better performance with reduced overshoot and faster settling time compared to the conventional scheme. This is due to the coordinated control action and excellent constraints handling of the proposed scheme.

Similar improvements are observed with regards to the tie-line powers considering their responses. Fig. 13 to Fig. 16 shows the tie-line power responses of CA_1, CA_3, CA_5 and CA_7.

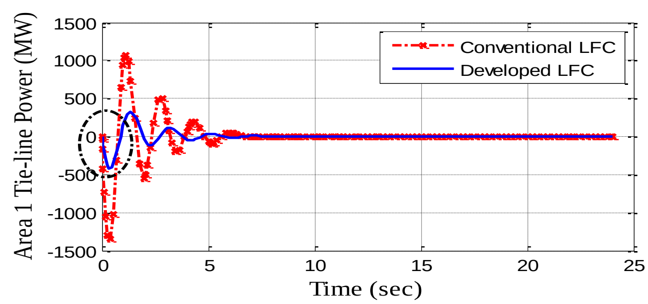

Fig. 13: CA_1 Tie-line Power Response

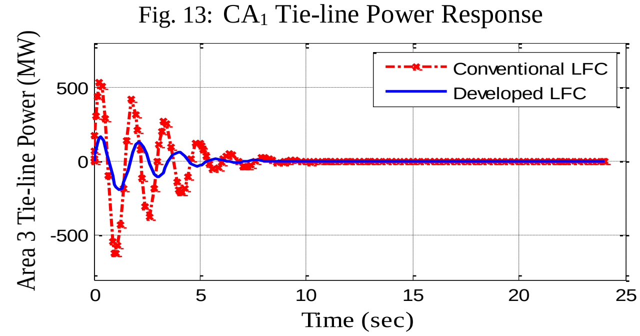

Fig. 14: CA_3 Tie-line Power Response

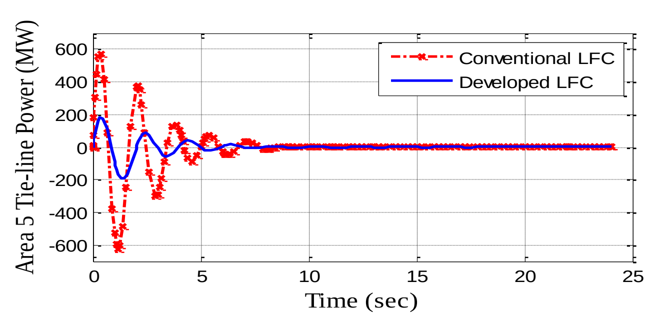

Fig. 15: CA_5 Tie-line Power Response

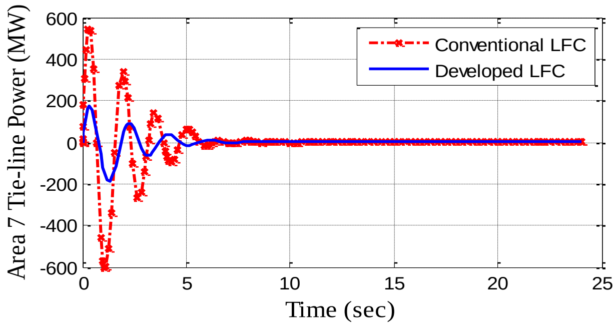

Fig. 16: CA_7 Tie-line Power Response

The negative undershoot in the CA_1 indicates that the load disturbance occurred at that particular control area. The overshoots of the tie-line power deviations are observed to have reduced by 20.27%, 22.5%, 23.46% and 21.76% in the four respective areas, when compared with the conventional method.

The improvements in the dynamic responses is not only noticeable in the over/undershoots of the responses, but also in their settling times.

Following the disturbance, the frequency-responsive spinning reserves respond by adjusting their output powers according to the new P_i^{sc}. At steady state, only the generator(s) in the perturbed area balance up the net disturbance. This is established from the response of the generators shown in Fig. 17 to 19. The generators in CA_1 generates the load change of $0.1pu$ at steady state, while the generators in the other CAs settle at zero.

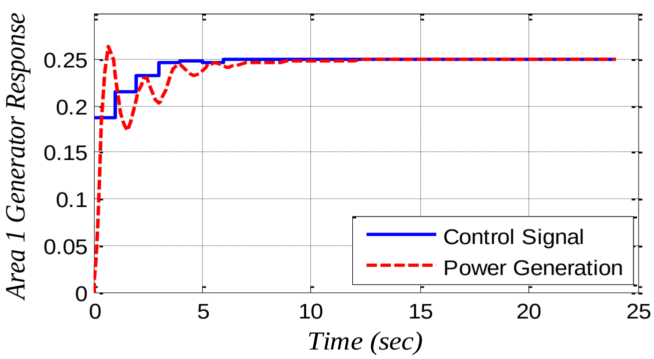

Fig. 17: CA_1 Generators' Responses with the Control Signal

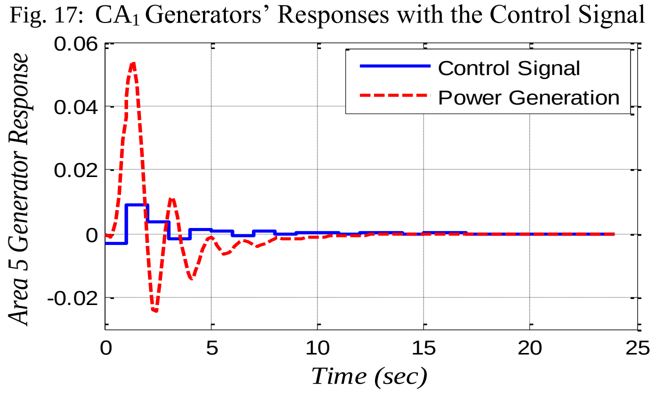

Fig. 18: CA_1 Generators' Responses with the Control Signal

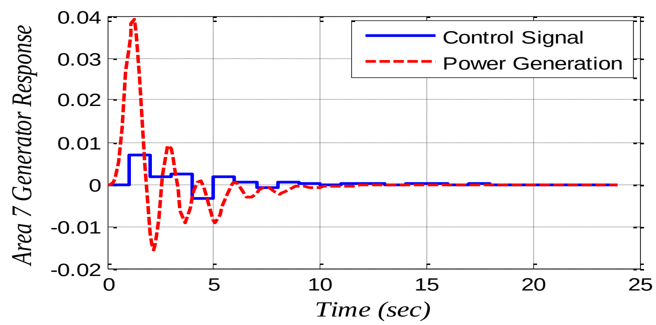

Fig. 19: CA_1 Generators' Responses with the Control Signal

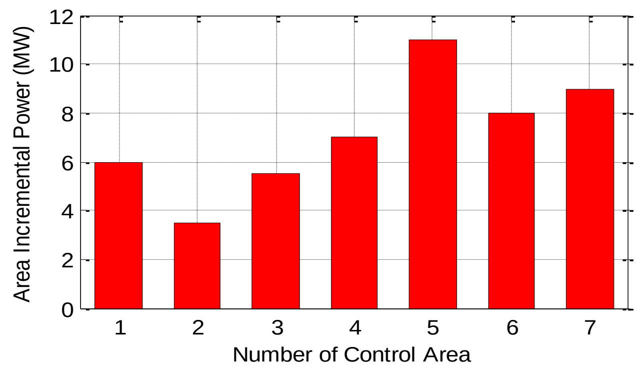

Fig. 20: Generators Participations from all the CAs.

During the transient, the generators in all the CAs responded by supplying power to the disturbed area. Then at steady state, only the disturbed area continues to carter for its load changes. Fig. 20 shows the generators participation from each CA.

5. Conclusion

This study presents the load frequency control (LFC) of the 330kV, 50Hz Nigerian Power System (NPS). A control scheme that maintains near-zero steady state errors for deviation in system frequency and that of net inter-area power flow within an acceptable limit in a deregulated environment is developed. It is developed with distributed control architecture with each of CAs been equipped with a proportional integral (PI) controllers. These local PI controllers (slave controllers) compute the optimal control signal for appropriate valve positioning of all the generators in its CAs, which in regulate the frequency and tie-line powers. In addition, each of the slave controllers exchange the information about their control action with the neighboring controllers as well as a central master MPC controller. The local PI controllers are optimally tuned using moth flame optimization (MFO) algorithm by minimizing the Integral Square Error (ISE) of the state errors. An MPC applied as the master controller is used to establish the optimal set-points of the slave PI controllers. The effectiveness of the developed scheme is verified by implementing it on the seven-CA Nigerian deregulated power system perturbed with a step load demand. From the simulations carried out in MATLAB environment, it is established that the developed scheme was able to maintain near-zero steady state errors for deviation in system frequency and tie-line powers and outperformed the present conventional control scheme.

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