



Review article

A review on fractional order (FO) controllers' optimization for load frequency stabilization in power networks



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ABSTRACT

Keeping generation and demand balance is a fundamental requirement in power networks. It maintains frequency of the system within permissible limits. For microgrids, this balance is important to keep tie-line power below a certain threshold. Managing load frequency deviations is indispensable for microgrids and can be managed by coordinating generators, loads as well as other components such as energy storage devices and electric vehicles. Therefore, Load Frequency Stabilization (LFS) research has gained a lot of traction in this field. Building on the importance of this concept, this paper constructs different fractional order (FO) control stratagems which have been applied in different frequency response models. In order to achieve the targeted assignment, the impact of incremental control action of different FO controllers along with the system constraints has been considered for better system dynamics. Moreover, the current research work illustrates the structural control operation with transfer function analysis of different FO controllers considered for multiple single/multi-area power network. To optimally tune the existing FO controller parameters, application of several optimization techniques corresponding to the frequency regulation issues have been undertaken. Furthermore, a visualization of complete utilization of classified FO controllers and their corresponding optimization techniques have been analyzed. In order to make the performance elegant, a review has been performed on application of different existing error functions (J) and some recently developed modified error functions. Finally, the performance of modified J considering different FO controllers have been depicted.

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1. Introduction

Promising strategic policies have been world-widely set for the expansion of renewable energy based generators (REGs) to

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meet growing energy demands (Said and Aly, 2019; Münz et al., 2017) High penetration levels of REGs have been achieved through wide installations of wind, solar photovoltaic (PV) and biomass energy (Aleem et al., 2020). Majority of these REGs are inverter-interfaced and internal power electronics systems are used for improved energy capture, power quality and energy efficiency. However, the high penetration levels of power electronic based REGs and the exaggerated load demands could affect the power system's ability to match generation and demand (Rakhshani et al., 2016; Zhao et al., 2016). The root cause of this problem is the low system inertia caused by high REGs penetration levels. If necessary, control actions are not taken, this leads to successive disturbances and dynamic instability issues that manifest themselves as frequency fluctuations (Δf). Therefore, developing proper coordinated control stratagem and disturbance mitigation techniques is essential for increasing share of REGs in future power networks (Ustun and Aoto, 2019; Zhao et al., 2017). The standard automated load frequency stabilization (LFS) assignment is to keep the Δf within the permitted range (Latif et al., 2020b).

LFC can be considered as a supervisory control system that maintains a power balance between the generation and the demand, hence, keeping the system frequency stable (Dey et al., 2020; Mohd et al., 2021). In line with increasing popularity of hybrid power networks, several works in the literature focused on interconnected LFS for reliable and efficient power supply in such systems (Fathy and Kassem, 2018; Hussain et al., 2020). There are many components in these complex systems and achieving LFS requires robust control stratagem with various algorithmic techniques (Latif et al., 2021).

To accomplish this distinctive stratagem, several works in the literature have leveraged different controllers such as classical, two-degree of freedom, fractional order (FO) and model predictive (Latif et al., 2020c). The common key function is to control the power sharing of different subsystems where area control error (ACE and microgrid ACE (MACE)) is the control input signal of the controllers. Additionally, the advantageous FO controller stands out due to its unique flexible utilization characteristics of lower to higher order frequency response model.

As far as the frequency and tie-line power regulation analysis is concerned, several algorithms are used to help controller improve the frequency profile while keeping tie-line power stabilization. A thorough review of classified fractional order (FO) controllers' optimization for LFS of single–multi-area hybrid power network (hPN) is presented. Based on the above said discussion, the key contributions of the work are summarized below:

- (a) Studies frequency response single/multi-area conventional as well microgrid power network.
- (b) Reviews of established diversified FO load frequency controllers for frequency stabilization of single/multi-area traditional as well as microgrid power network.
- (c) Studies the application of interrelated different algorithmic techniques for optimally adjustment of these classified FO controllers.
- (d) Studies of different objective functions (J) and their comparative assessment for different frequency response models.
- (e) An outlook of future research plan regarding the development of some novel FO controllers and objective functions.

To accomplish this aforementioned systematical review, authors have reviewed the literature in the domain of LFM using important keywords. Table 1 presents the key points of the review methodology.

Table 1
Illustration of the applied review methodology.

Factor	Specification
Domain	Conventional/microgrid Power network (C/MPN)
Sub-domain	Operation & control of C/MPN
Approach	Frequency management
Very specific approach	Load frequency stabilization (LFS)
Key points I	LFS, secondary frequency management
Key points II	Utilization of controller and soft computing tools
Accessibility	Single/multi-area LFS
Database	Accessible Online
	IEEE, Springer, Science direct, Wiley, Taylor & Francis and online data
Type of publication	Article, Conference papers, Books and Book chapters

The rest of the paper is organized as follows: Section 2 provides the structural review of the multi-area multi-source single/interconnected power networks. The review of different classified FO controllers and their applications in frequency response models are given in Section 3. Section 4 provides the survey of different optimization techniques used to improve performance of FO controllers given in Section 3. The performance comparisons of different literatures developed objective functions (J) with existing J methods are provided in Section 5. Finally, general conclusions and future research directions are given in Section 6.

2. A review of frequency control in power systems

The operation in power network is kept stable by adjusting its crucial frequency fluctuation (Δf) with respect to the change in load demand. Considering the identified review title, the aim of the load frequency stabilization (LFS) is to maintain the system frequency (50 Hz or 60 Hz) within a predetermined range ($\sim \pm 0.5$ Hz) by supplying and/or absorbing the adequate amount of power. The electrical power systems are usually sectionalized into several individual power networks. However, the increased demand for bulk energy all over the world has directed the governments to interconnect the neighboring power network via tie line (Shiva and Mukherjee, 2015). This section addresses the relationship between generated power, load demand, inertia coefficient, damping factor, and frequency fluctuation for single and multi-area frequency response (hybrid/non-hybrid) model. The power–frequency relationships of different active power networks for LFS with and without REGs are displayed in subheading

2.1. Frequency response modeling of different power networks

The frequency response modeling of any power network depends on the power–frequency relationship (PFR) mechanism which is used to regulate power sharing for the LFS assignment. The overall mathematical model could be formulated with participation of net generation–load mismatch and the rotor swing equations. The coordinated relationship can be derived with damping factor (D), moment of inertia, Δf , net generated power and load demands. Fig. 1(a) and (b) show this relationship for a conventional power network as well as a microgrid with REGs, respectively.

The corresponding equations can be written for islanded traditional power network as in (1);

$$\sum_{i=1}^{X_G} (\Delta P_{G,i}) - \sum_{i=1}^{X_{LD}} (\Delta P_{LD,i}) = D \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) + 2H_S \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) \quad (1)$$

and for interconnected traditional power network as in (2);

$$\sum_{i=1}^{X_G} (\Delta P_{G,i}) - \sum_{i=1}^{X_{LD}} (\Delta P_{LD,i}) - \sum_{i=1}^{X_{LD}} (\Delta P_{tie,i}) = D \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) + 2H_S \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) \quad (2)$$

where, ΔP_G and ΔP_{LD} are the total change in generated power and demanded load power, respectively. H and D are defined as the system moment of inertia and damping factor of the overall active power network, respectively.

Similarly, for the islanded and interconnected active microgrid power network, the relationship between generator–load model and change in frequency fluctuation (Δf) could be formulated as in (3) and (4);

$$\text{For islanded active microgrid power network;} \\ \sum_{i=1}^{X_G} (\Delta P_{G,i}) - \sum_{i=1}^{X_{LD}} (\Delta P_{LD,i}) = D \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) + M_S \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) \quad (3)$$

$$\text{For interconnected distributed microgrid power network;} \\ \sum_{i=1}^{X_G} (\Delta P_{G,i}) - \sum_{i=1}^{X_{LD}} (\Delta P_{LD,i}) - \sum_{i=1, j \neq i}^{X_{LD}} (\Delta P_{tie,ij}) = D \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) + M_S \cdot \left(\sum_{i=1}^{X_G} (\Delta f) \right) \quad (4)$$

where M, D are the inertia coefficient and damping factor for i th ($i = 1, 2, 3 \dots X_G$) area microgrid power network, respectively. Block diagrams given in Fig. 1 help visualize the relationship between generator–load model and Δf for traditional as well as distributed microgrid power network.

3. Different fractional order (FO) controllers used in frequency response model

When it comes to the problem related to frequency stabilization analysis, the optimal adjustment of the controller improves performance of load frequency controller responding to LFS. This is done by changing the output power of the subsystem associated with that particular controller based on a certain algorithm. To meet higher stability values, robust control method is needed. In fact, the complexity and tuning process of controller parameters have dramatically increased due to higher number of enabled controllers (Kerdphol et al., 2018).

The main objectives of the controllers in the multi-area power systems are regulating the frequency of individual areas and controlling the tie line power to support the system stability. Those controllers can perform LFS functionalities using the input ACE/MACE signals. In addition to the above said control process, the higher control parameters based FO controllers is much more adequate for parametric tuning of their parameters as compares to other controllers. This section gives a review of the variety of existing FO controllers for LFS of active power networks.

3.1. Classical FO controllers

Using only droop method is insufficient for advanced control purposes. Thus, the secondary control loop is needed for better control of frequency fluctuation of the active power network. FO

controller is efficient in many industrial and power system applications. In general, the FO controllers consist of three branches for signal which are the proportional branch (K_P), the integral branch (K_I) with fractional coefficient (λ) and the derivative branch (K_D) with fractional coefficient (μ).

The schematic designs of some classical FO controllers are shown in Fig. 2. In LFS studies, the droop control can prevent fluctuation when fault or load disturbances occur. But, in returning the frequency to the rated values, this method is weak to compensate the steady error. Thus, FO controller is suggested as the extra control loop to compensate the error and returning the values to the reference values.

Considering the above, several works have focused on design and implementation of different classical FO controllers for LFS in active power networks. In that respect, the simulation study for LFS of large scale two-area traditional power network is explored by using FOPI controller (Sharma and Yadav, 2019). Extending the authors views Authors of Alomoush (2010) have established first time non-integer proportional–integral with derivative (PID) controller in LFS model and compared the dynamic responses with integer order based PID controller. The applications of FOPID in one-area (Jain and Hote, 2018; Khosravi et al., 2020; Zaheeruddin and Singh, 2020a) and two-area frequency response model are presented in Kumar and Shekhar (2019) and Saurabh and Kumar (2020).

To study the system dynamics under uncertainties, an interval FO based PID (INFOPID) has been leveraged for two-area frequency response model in Lamba et al. (2019). Authors of Debbarma et al. (2013) leveraged FO based PID controller for LFS of deregulated three-area traditional power network. In addition, the utilization of decentralized FOPID controller for LFS of three-area deregulated traditional power network is discussed in Farook and Raju (2012). To assess the performance of non-integer order PID controller over other integer order integral (IOI), proportional–integral (IOPI) and IOPID controller, a large scale non-reheat based single area frequency response model is considered (Sondhi and Hote, 2014). The impact assessment of FOPI-D controller for frequency containment issue of reduced order active power network is discusses in Guha et al. (2019).

Work in Debbarma et al. (2014) presents a concept of two degree of freedom based FOPID controller and compares the system dynamics with other FOI/FOPI/FOPID controllers. Recently, authors of Taher et al. (2014) have illustrated the benefits of FO based PID controller and shown its application for LFS of large scale three-area active power network. The work in Pan and Das (2015) have applied FOPID controller and extended the work in Debbarma et al. (2014). The suggested FO based PID controller is utilized to contain system frequency in large single area power network (Sondhi and Hote, 2016) and two-area electrical power network (Zamani et al., 2016). A research on FOPID is established to dump out the system dynamics fluctuation as discussed in Morsali et al. (2017). The comparative analysis of FOPID performance is depicted in Morsali et al. (2018). The power compensation of multiple renewable sources system under adaptive fractional order model reference technique is discussed in Djebri et al. (2020). Kazemi et al. developed a novel adaptive FO controller for frequency regulation of wind integrated single-area power system (Verij Kazemi et al., 2020). The application of FO model reference adaptive technique for active and reactive power management is illustrated in Djebri et al. (2019).

Moving on to the newly developed classical FO based controller, authors of Raju et al. (2019) have enabled proportional–integral with fractional order derivative (PIFOD) controller and FO based proportional–derivative with proportional–integral (FOPDPI) (Sahoo et al., 2020) to stabilize system frequency and

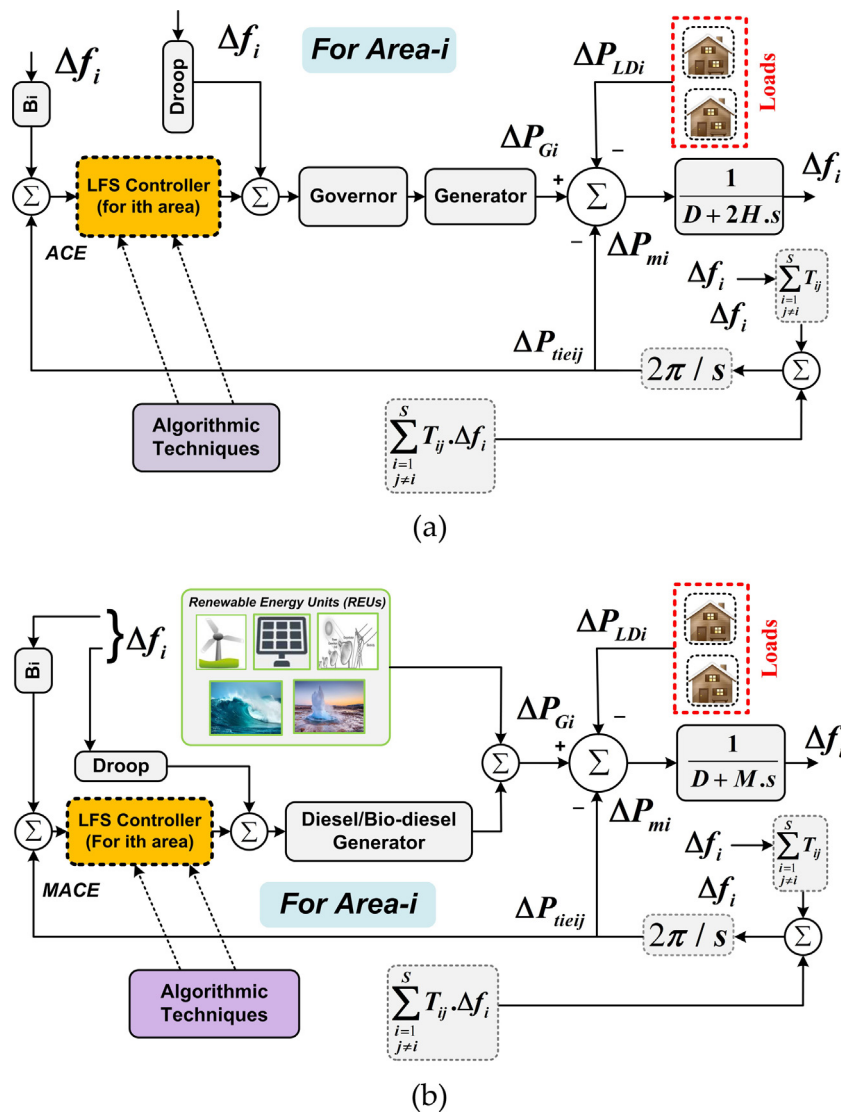


Fig. 1. Schematic view of (a) single and interlinked conventional power network, (b) single and interlinked microgrid power network.

tie power for an interconnected active power network. The combination of proportional–derivative with fractional order integral (PDFOI) is leveraged for LFS of three-area active power system.

Work in Saxena (2019) has developed reduced order frequency response model and tested the system dynamics using FOPID controller. The optimum synthesis of FOPID controller for LFS of a microgrid is established in Mohamed et al. (2020). Authors of Dahiya et al. (2015) have performed fine tuning of the FO based PID controller to deal with LFS assignment of multi-area conventional power network. The dynamic responses of FOPID controller corresponding to IOPID controller are established in Regad et al. (2020).

Building on these results, authors of Debbarma and Dutta (2017) have leveraged a novel FO based integral–derivative with filter controller for LFS of multi-area multisource conventional active power network. In addition, a newly designed higher FO based feedback control stratagem (HFOFC) (Sahin, 2020) has been leveraged for LFS of non-reheat two-area power network. Effective utilization of FO based PID controller to stabilize system frequency is analyzed in Nithilasaravanan et al. (2019). Work in Wang et al. (2017) implemented the FO based PID controller for frequency control of renewable based distributed microgrid power network. The utilization of classical FO controller for LFS

is established in Pan and Das (2016). However, the practical validation of FOPID based LFS is illustrated in Khooban et al. (2018).

The selection of two degree of freedom (2DOF) based non-integer PID controller for LFS study under interlinked conventional power network has shown in Tripathy et al. (2020) and Mohapatra et al. (2020). Recently, developed a new three degree of freedom (3DOF) based non-integer PID controller is developed and compared its responses with 2DOF-FOPID and 1DOF-FOPID controllers (Nayak et al., 2020). On the other hand, Latif et al. (2019b,a) established the impact assessment of FO based PID controllers with other controllers in interconnected frequency response microgrid models. The formulation of some classical FO controllers with their transfer function modeling could be presented as follows;

For FOPID;

$$G_{PI^\lambda}(s) = K_p(s) + K_I/s^\lambda(s); 0 \leq \lambda \leq 1 \tag{5}$$

For FOPID;

$$G_{PI^\lambda D^\mu}(s) = K_p(s) + K_I/s^\lambda(s) + K_D.s^\mu(s); 0 \leq \lambda, \mu \leq 1 \tag{6}$$

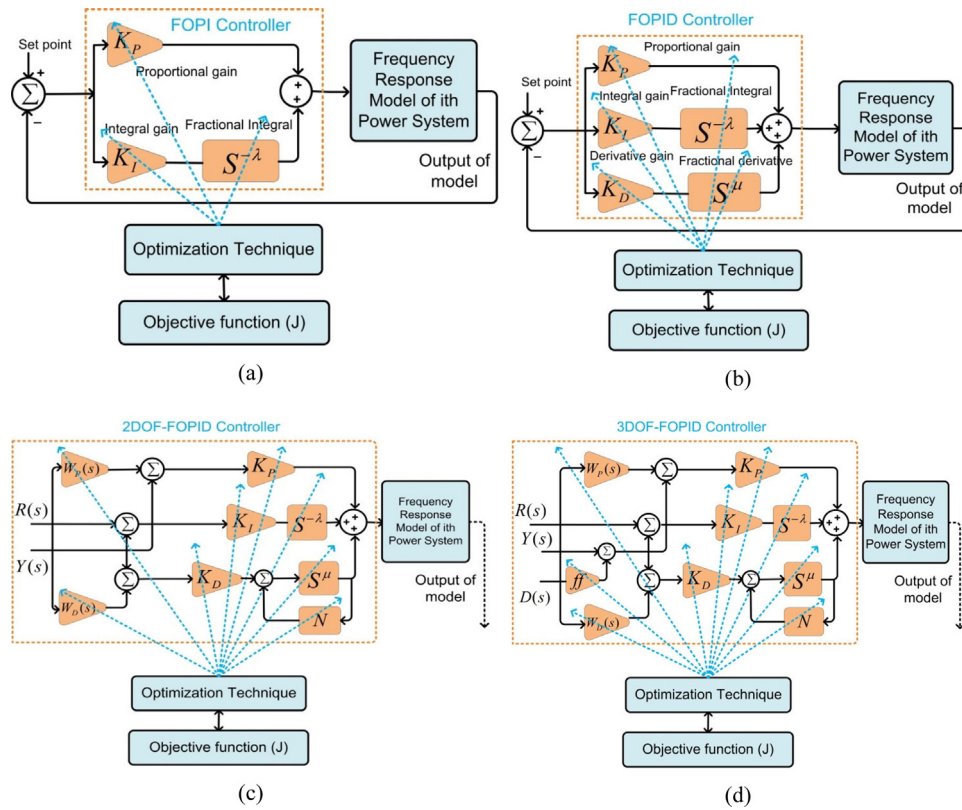


Fig. 2. Structural representation of different classical FO controllers (a) FOPI, (b) FOPID, (c) 2DOF-FOPID, and (d) 3DOF-FOPID controller.

For 2DOF-FOPID;

$$G_{2DOF-PID}^{\lambda, \mu}(s) = K_p \cdot \{R(s) \times W_p(s) - Y(s)\} + \frac{K_i \cdot \{R(s) - Y(s)\}}{s^\lambda(s)} + K_D \cdot s^\mu \left(\frac{N}{N + s^\mu} \right) \{R(s) \times W_D(s) - Y(s)\} \quad (7)$$

where; $0 \leq \lambda, \mu \leq 1$; and $0 \leq W_p, W_D \leq 5$

The K_p, K_i, K_D are the proportional, integral and derivative gain. Integral and derivative coefficients are represented by (λ, μ) . $R(s), Y(s)$ are the control error signal and reference signal. W_p and W_D are the proportional and derivative weight factors.

From Fig. 2(d) the transfer function of 3DOF-FOPID can be formulated as;

$$G_{3DOF-PID}^{\lambda, \mu}(s) = K_p \cdot \{R(s) \times W_p(s) - (Y(s) + D(s) \times ff)\} + \frac{K_i \cdot \{R(s) - (Y(s) + D(s) \times ff)\}}{s^\lambda(s)} + K_D \cdot s^\mu \left(\frac{N}{N + s^\mu} \right) \cdot \{R(s) \times W_D(s) - (Y(s) + D(s) \times ff)\} \quad (8)$$

where

$$0 \leq \lambda, \mu \leq 1; \text{ and } 0 \leq W_p, W_D \leq 5 \quad (9)$$

Considering the same 2DOF-FOPID gains action and weight factors, the term $N(s)$ is used for filter co-factor as shown in Eq. (8). The $ff(s)$ and $D(s)$ are the feed forward controller and input disturbance signal of the 3DOF-FOPID controller, respectively.

3.2. Cascaded and double-stage FO controllers

To meet the challenges of LFS in a reliable and flexible manner, several articles have demonstrated cascaded and double-stage

FO controllers. The general stratagem of cascaded controller is depicted in Fig. 3. Considering the two consecutive controllers such as primary controller $C_1(s)$ and secondary/slave controller $C_2(s)$, the cascaded controller comprises of dual process control loops (inner and outer control loop). The outer control loop is pointed out by $P_1(s)$ which is exposed to disturbances $D_1(s)$ and generates output of the controller $Y(s)$. With this extension, the outer loop input $U_1(s)$ and $Y(s)$ could be formulated as follows;

$$U_1(s) = P_2(s) \cdot U_2(s) \quad (10)$$

$$Y(s) = P_1(s) \cdot U_1(s) + D_1(s) \quad (11)$$

where $P_2(s)$ is the inner process of the controller. To attain referenc input signal $R(s)$, outer process loop needs to be controlled.

To alleviate the specified issue authors of Tasnin et al. (2018a) have developed a cascaded non-integer order PI with PID controller (FOPI-FOPID). A recently established PID with filter cascaded non-integer order proportional-derivative (PIDN-FOPD) controller has been leveraged to regulate the system frequency (Saha and Saikia, 2017). Extending this work, cascaded PIDN with fractional order ID (PIDN-FOID) controller has been utilized to get the optimal result of the frequency response two-area model. The robustness of the controller corresponding to other classical integer order controllers have been analyzed in Saha and Saikia (2018a). Design and development of novel integral with derivative-filter based cascaded FOPD (IDN-FOPD) controller for its load frequency response assessment of three-area power network is discussed in Saha and Saikia (2019). The idea for proposing a novel FOPI cascaded fractional order proportional-derivative (FOPI-FOPD) controller for LFS of large scale two/three area deregulated power network is presented in Tasnin and Saikia (2018) and Çelik (2020). Dynamic response assessment of novel FOPI cascaded FO order IDN (FOPI-FOIDN) controller for LFS of wind power generation integrated large three-area active power

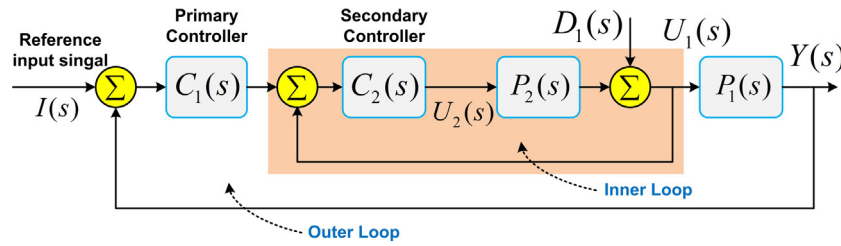


Fig. 3. The general control stratagem of cascaded controller.

network has been given in Babu et al. (2019). Where the structure of the controller is displayed in Fig. 4(a). A two stage FOPID with double derivative (FOPID-DD) controller for LFS of active single-area power is established in Khokhar et al. (2020).

Additionally, the double stage combination of two-degree of freedom PI with non-integer order proportional–derivative-filter (2DOF-PI-FOPDN) is leveraged for LFS of two-area traditional power network. This controller shows better results than IO classical controller (Prakash et al., 2019). Recently, work in Jena and Sahu (2020) proposed a novel double stage 3DOF based FO proportional–integral–derivative-filter with proportional-derivative-filter (3DOF-FOPIDN-FOPDN) controller for frequency regulation of renewable integrated two-area traditional power network. The control signal flow of the above mentioned controller is shown in Fig. 4(b) and formulated by (12) and (13).

Work in Guha and Banerjee (2020) has established a novel 3DOF-FOPID with tilt–integral–derivative controller (TID) (3DOF-FOPID-TID) controller to analyzed the efficacy with respect to other cascaded controllers. Reference Saha and Saikia (2018b) has displayed an extension of 2DOF based double stage {(2DOF-PIDN)-FOI} controller for the abovesaid LFS assignment of renewable energy enabled three-area conventional power network. Examination of a newly developed double stage PIDF with one plus FO derivative (PIDF-(1+FOD)) controller for LFS of interconnected two-area hydro-thermal power network is presented in Prakash et al. (2020). An optimal frequency stabilization of two-area demand response supported renewable microgrid power network by using a double stage proportional–integral FO integral one plus proportional–integral (PIFOD-(1+PI)) controller and compare with other FO controllers (Latif et al., 2020a).

$$W(s) = \left\{ r.K_p + \frac{K_I}{s^\lambda} + l.K_D.s^\mu \left(\frac{N}{N + s^\mu} \right) \right\} .I(s) + \left\{ -K_p - \frac{K_I}{s^\lambda} - K_D.s^\mu \left(\frac{N}{N + s^\mu} \right) \right\} .C(s) \quad (12)$$

$$U(s) = \left\{ -ff.K_p - ff.\frac{K_I}{s^\lambda} - ff.K_D.s^\mu \left(\frac{N}{N + s^\mu} \right) \right\} .D(s) + \left\{ r'.K_p + l'.K_D.s^\mu \left(\frac{N}{N + s^\mu} \right) \right\} .W(s) + \left\{ -K_p - K_D.s^\mu \left(\frac{N}{N + s^\mu} \right) \right\} .C(s) + \left\{ -ff.K_p - ff.K_D.s^\mu \left(\frac{N}{N + s^\mu} \right) \right\} .D(s) \quad (13)$$

where I(s), C(s) are the control error signal and reference signal. r and l are the weight factors. The ff (s) and D(s) are the feed forward controller and input disturbance signal of the (3DOF-FOPIDN)-FOPDN controller, respectively. U (s) is the control output signal of the controller. The design of other cascaded and double stage controllers leveraged for the LFS objective is displayed in Fig. 4(c–d).

3.3. Fuzzy logic integrated FO controllers

The structure of the controller changes as the operating condition varies with higher system complexity. To attain the extra sturdiness of the controller the extension FO controllers with integration of fuzzy logic stratagem is a maiden attempt. The hybridization of FO controller with fuzzy logic approach have been demonstrated in the recent frequency regulation application. Authors (Arya, 2018) have evaluated the performance of fuzzy logic integrated PIDN fractional order integral (FL-PIDN-FOI) controller for frequency regulation of interconnected traditional power network. Arya (2019a, 2020a) has suggested two different fuzzy logic based FO integral–derivative (FL-FOID) and FL-FOID with filter (FL-FOIDF) controllers for LFS of inter-tied traditional power model. The development of FL integrated FO proportional–integral with proportional–derivative (FL-FOPID-FOPD) controller for solving the suggested LFS issue for large traditional frequency response model (Arya, 2019b). By leveraging the concept in Arya (2018) authors in Patel et al. (2019), Mohammadikia and Aliasghary (2019), Arya (2017), Annamraju and Anil (2019) and Zaheeruddin and Singh (2020b) have examine the performance of FO integrated FLPID (FOFLPID) controller for automated frequency response model. Moreover, the comparative decision parameters have indicates its robustness. Application of fuzzy logic based (FOPD+I) controller for LFS of hybrid shipboard system has been illustrated in Khooban et al. (2017). Authors in Gheisarnejad et al. (2019) have implemented a novel interval type-2 FO fuzzy PD with fuzzy PI (T2FO-FLPD-FLPI) controller for investigating the future 5G communication based frequency control model. Incorporation of newly developed FL based PIDN with FOPIDN (FL-PIDN-FOPIDN) controller has proved its sturdiness for LFS study as compare to other FO controller (Arya et al., 2020). To improve the control stratagem a novel FL based FOPID-FOPID (FL-FOPID-FOPID) controller is established for the enhancement of LFS of three-area thermal power model (Arya, 2020b). Putting all the concept of control signals form Eqs. (14)–(19), the control stratagem of FL-PIDN-FOPIDN controller and FL-FOPID-FOPID controller are displayed in Fig. 5 (a–b).

$$G_{FL-PIDN}(s) = c.K_p(s) + c.K_I/s(s) + c.\{K_Ds, N(s)/ (s + N)\} \quad (14)$$

$$G_{FOPIDN}(s) = K_{P1}(s) + K_{I1}/s^\lambda(s) + \{K_{D1}s^\mu.N_1(s)/ (s + N_1)\} \quad (15)$$

$$\Delta P_{c(FL-PIDN-FOPIDN)} = \{(G_{FL-PIDN}(s) - \Delta f) \times G_{FOPIDN}(s)\} \quad (16)$$

$$G_{FL-FOPID}(s) = c.K_p(s) + c.K_I/s^\lambda(s) \quad (17)$$

$$G_{FOPID}(s) = K_{P1}(s) + K_{I1}/s^\lambda(s) + \{K_Ds^\mu(s)\} \quad (18)$$

$$\Delta P_{c(FL-FOPID-FOPID)} = \{(G_{FL-FOPID}(s) - \Delta f) \times G_{FOPID}(s)\} \quad (19)$$

where c is the input control signal of PIDN and FOPID controllers. The stated ΔP_c in (16) and (19) is the output signal of the corresponding controllers. The merit and demerits of different FO controllers for LFS model is depicted in Table 2.

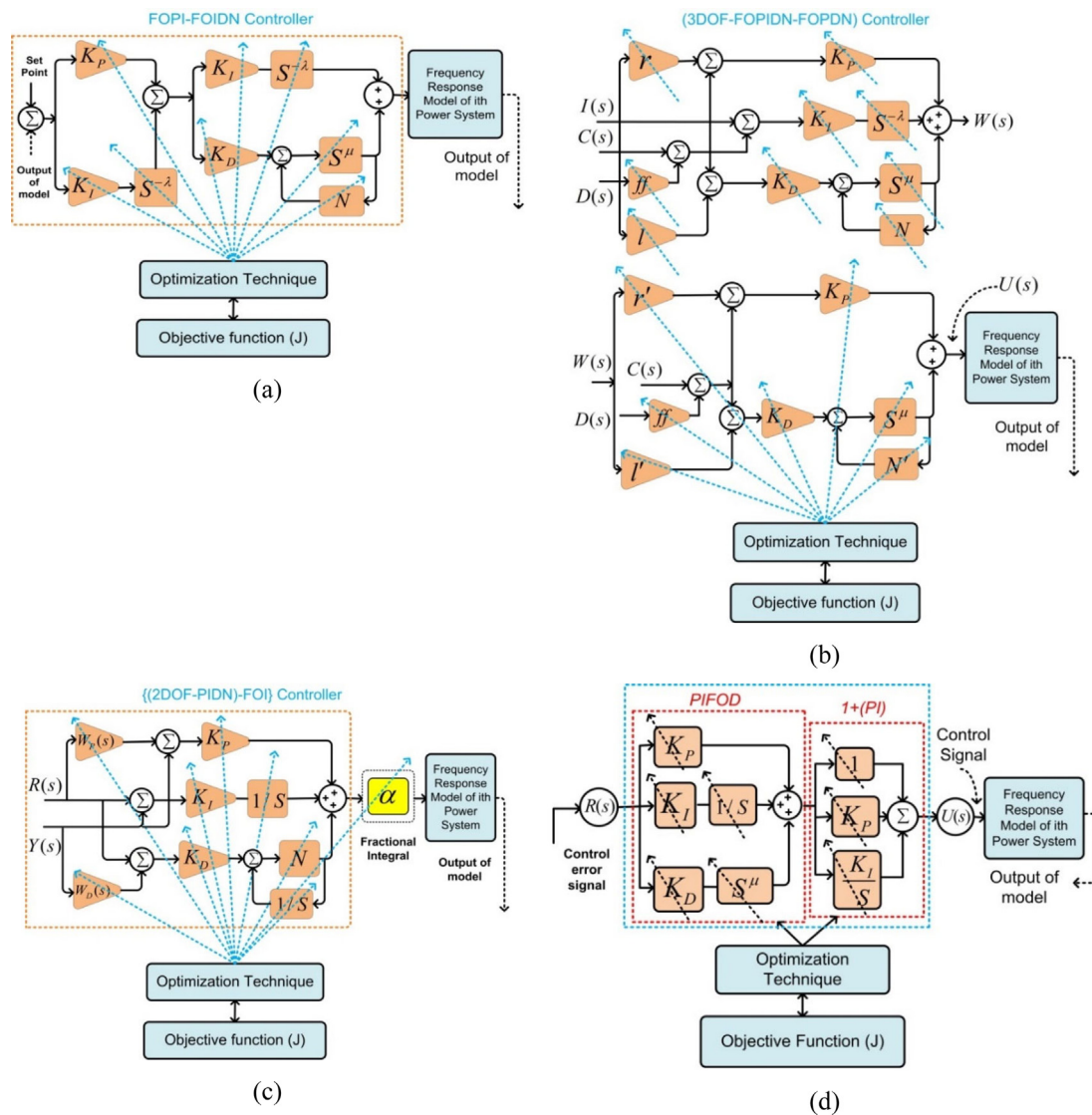


Fig. 4. Control design of different cascaded and double stage FO controllers (a) FOPI-FOIDN, (b) (3DOF-FOPIDN)-FOPDN, (c) (2DOF-PIDN)-FOI, and (d) PIFOD-(1+PI) controllers.

Table 2
Merits and demerits of different FO based controllers.

Type	Controller type	Merits	Demerits
Classical	FOI, FOPI, FOPID, INFOPID, PIFOD, FOPDPI and so on	<ul style="list-style-type: none"> Well explored. Design process is easy. 	<ul style="list-style-type: none"> Elapsed time is more. Unsuitable for all operating conditions.
Cascaded and double stage	FOPI-FOPID, PIDN-FOID, IDN-FOPD, FOPI-FOIDN, FOPI-FOPD PIDF-(1+FOD) and so on	<ul style="list-style-type: none"> Easily model higher order to lower order system. Robust against parametric variation and uncertainties. 	<ul style="list-style-type: none"> Higher-order controller design. Time taken to complete the iterations is more. Not suitable for non-linear system dynamics. Assortment of inner/outer loop is a main factor to get effective dynamic responses.
Fuzzy logic (FL) base	FL-PIDN-FOI, FL-FOIDF, (FL-FOPI-FOPD), FOFLPID, (T2FO-FLPD-FLPI), (FL-PIDN-FOPIDN) and so on.	<ul style="list-style-type: none"> Easily applicable for linear as well as non-linear model. Capable to handle internal as well as external disturbance. Provide better dynamic responses as compare to classical and cascaded FO controllers. 	<ul style="list-style-type: none"> Extensive pre-knowledge requirement for selecting the parameters. Higher tuning nubs lead to more time consuming. Complexity is more as compare to classical FO as well as cascaded FO controllers. Dynamic performance is dependent on the selection of membership function. Needs more computational aspects in the analysis.

4. Application of different optimization techniques in fo based frequency response model

The above-formulated items of optimal controller parameters for single/multi-area interconnected active power networks are the dynamic linear or nonlinear optimization problems. In order to solve such a problem, a fast convergence and efficient search method are needed. In that respect, different evolutionary techniques have been utilized to taken care of frequency stabilization issue to manage the functions associated with LFS design.

In [Sharma and Yadav \(2019\)](#) authors have employed a lion algorithmic technique (LAT) to tune the FO based controller. To get good performance, optimal big bang big crunch (BBBC) technique based FO controller has been proposed for LFS ([Jain and Hote, 2018](#)). Despite those techniques, a predominant bacterial foraging technique (BFT) has been analyzed to deal with restructured LFS structure ([Debbarma et al., 2013](#)). Work in [Farook and Raju \(2012\)](#) presented a hybridized genetic-firefly (hGA-FA) technique to achieve an optimal dynamic response for three-area LFS problem. The comparative analysis of LFS of an active three-area environment by considering FA technique is done ([Debbarma et al., 2014](#)).

An imperialist competitive technique (ICA) is employed for robust stability and enhanced three-area frequency regulation assignment ([Taher et al., 2014](#)). By applying the chaotic NSGA-II technique the control parameters under constraints has been guaranteed for LFS issue ([Pan and Das, 2015](#)). The employment of gases brownian motion technique (GBMT) has proven superior performance for mitigating fast frequency transient of two-area power network ([Zamani et al., 2016](#)). Among various techniques, authors of [Morsali et al. \(2017\)](#) have leveraged improved PSO (IPSO) technique for optimally tuning the controller parameter in LFS issue. The regulation of frequency in active two-area power network is reported with the same IPSO technique ([Morsali et al., 2018](#)). The effective tuning of FO controller for LFS analysis in active multi-area conventional power network is achieved by applying hybrid ant lion-pattern search technique (hAL-PS) ([Raju et al., 2019](#)).

Work in [Mohamed et al. \(2020\)](#) has leveraged Krill Herd technique (KHT) for optimal tuning the FO controller. With this momentum a hybrid disruption based gravitational search technique (hDGST) is analyzed to visualize its impact on conventional LFS model ([Dahiya et al., 2015](#)). Work in [Debbarma and Dutta \(2017\)](#) has applied flower pollination technique (FPT) for the same targeted objective. In addition, to achieve the targeted objective authors ([Wang et al., 2017](#)) have leveraged a multi-objective external technique (MOET). However, the application of chaotic PSO technique for frequency regulation of renewable integrated power network is reported in [Pan and Das \(2016\)](#). The hybrid salp swarm with simulating annealing technique (hSSA-ST) is established for optimal adjustment of FO controller for the targeted issue ([Nayak et al., 2020](#)). Besides different techniques, Authors of [Latif et al. \(2019b,a\)](#) have utilized a nature as well as biological inspired techniques to meet the objective of the work. Results of obtained by water cycle and butterfly technique was compared with PSO and FA algorithms.

The effect of perturbation in the system dynamics on sine-cosine technique (SCA) based FO controller was examined in [Tasnin et al. \(2018b\)](#). Authors in [Saha and Saikia \(2018a\)](#) and [Saha and Saikia \(2017\)](#) have evaluated the comparative change in frequency deviation under whale optimization technique (WOT) tuned FO controller. A new and robust ICA-cascaded FO controller is proposed to absorb frequency fluctuation under generation-demand imbalance ([Arya, 2018](#)). The effect of communication time-response delay in the interconnected system dynamics under WOT tuned cascaded-FO controller is analyzed ([Saha and](#)

[Saikia, 2019](#)). A new cascaded-FO controller is optimally tuned under SCA technique for the targeted objective ([Tasnin and Saikia, 2018](#)).

Introduction of a recently developed crow search technique (CST) has leveraged for selecting the cascaded-FO controller for the targeted assignment ([Babu et al., 2019](#)). Analyzing the system responses with the recently established volleyball premier league technique (VPLT) considering cascaded FO stratagem for extracting LFS issue is discussed in [Prakash et al. \(2019\)](#). The movement of wild gate technique (WGT) to acquire the frequency stabilization with its base value is examined in [Jena and Sahu \(2020\)](#). The distributed generation (DG) integrated large scale frequency response model for LFS by leveraging WOT with novel cascaded-FO controller is depicted in [Saha and Saikia \(2018b\)](#).

By following the LFS study, authors ([Arya, 2018](#)) have leveraged ICA technique for the tuning of fuzzy integrated cascaded FO controller. The movement of leveraging the same algorithmic technique for the tuning of fuzzy-integrated FO controller in interconnected LFS problem is discussed in [Arya \(2019a\)](#) and [Arya \(2019b\)](#). The optimal adjustment of the same fuzzy-integrated FO controllers have performed under ant lion ([Patel et al., 2019](#)), biography inspired technique ([Mohammadikia and Aliasghary, 2019](#)) and ICA technique ([Arya, 2017](#)) for the targeted assignment. The comparison of different technique tuned fuzzy-FO controller with ICA fuzzy-FO controller is discussed and proven in [Arya et al. \(2020\)](#). In recent time a new control stratagem with ICA technique for LFS for large scale power network is discussed in [Arya \(2020b\)](#).

5. Diverse objective functions approach in LFS study

In order to achieve favorable frequency control for an isolated or interconnected power network, objective function of optimization study should be determined carefully. In some studies, the objective function consisting of frequency deviation (Δf) or tie-line deviation (ΔP_{tie}) was used to increase the efficiency of the system. However, in order to increase the efficiency and performance of the system dynamics considerably, it would be more appropriate to designate the objective function (J) multi-objective.

In this study, different existing and recently developed objective functions have been reviewed which leveraged for LFS issue. There are several error-based objective functions for multi-objective control systems, such as the integral squared error (ISE), the integral absolute error (IAE), the integral time squared error (ITSE), and the integral time absolute error (ITAE). Objective functions of these approaches are given in (20)–(23).

In recent times, some new objective functions (J) are estimated by the net deviation in frequency and tie line power as (24)–(25) considering corresponding weights for Δf and/or ΔP_{tie} as W_i and W_{ij} . These could be implemented as the objective functions (J_{MISE}), (J_{IWSE}) named the modified integral squared error (MISE) and the integral weighted square error (IWSE) which needs to be minimized for simultaneous reduction in system frequency-tie line power ([Latif et al., 2019a, 2020a](#)).

The application of fractional order PFOID, PIFOD-(1+PI) controllers for frequency regulation of three/two area microgrid power system under the abovementioned novel MISE/IWSE objective function indexes are depicted in [Fig. 6\(a–b\)](#).

The above said objective functions can be expressed as follows:

$$J_{ISE}(x) = \int_{T_{min}=0}^{T_{max}} \left\{ (\Delta f_i)^2 .dt + (\Delta P_{tie,ij})^2 .dt \right\} \quad (20)$$

$$J_{IAE}(x) = \int_{T_{min}=0}^{T_{max}} \left\{ (|\Delta f_i|)^2 .dt + (|\Delta P_{tie,ij}|)^2 .dt \right\} \quad (21)$$

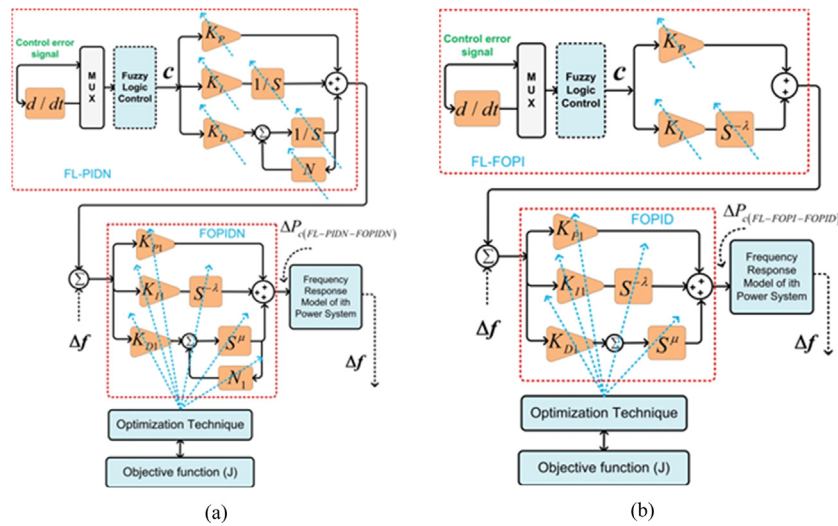


Fig. 5. Control design of different fuzzy logic integrated FO controllers (a) FL-PDNI-FOPIDN, (b) FL-FOPID-FOPID.

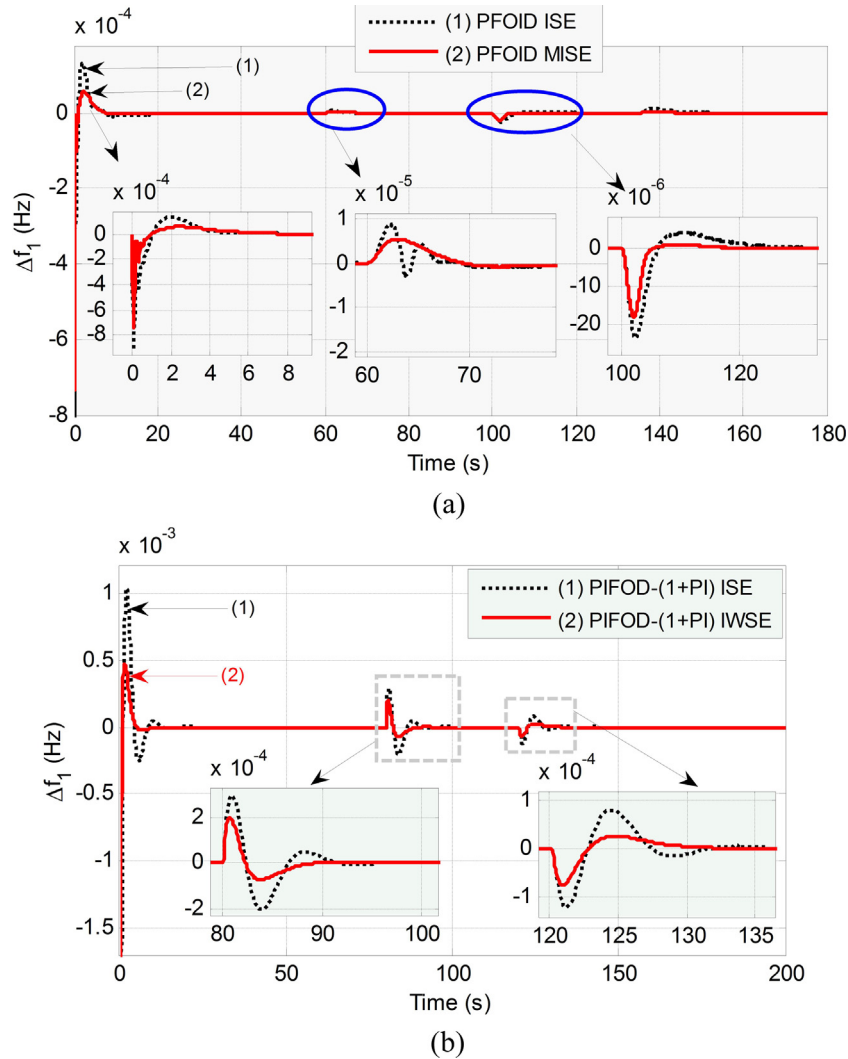
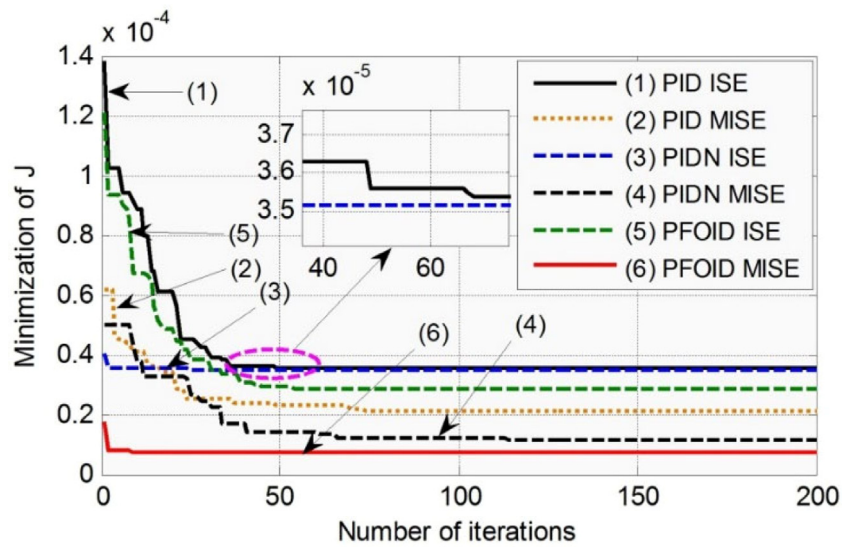


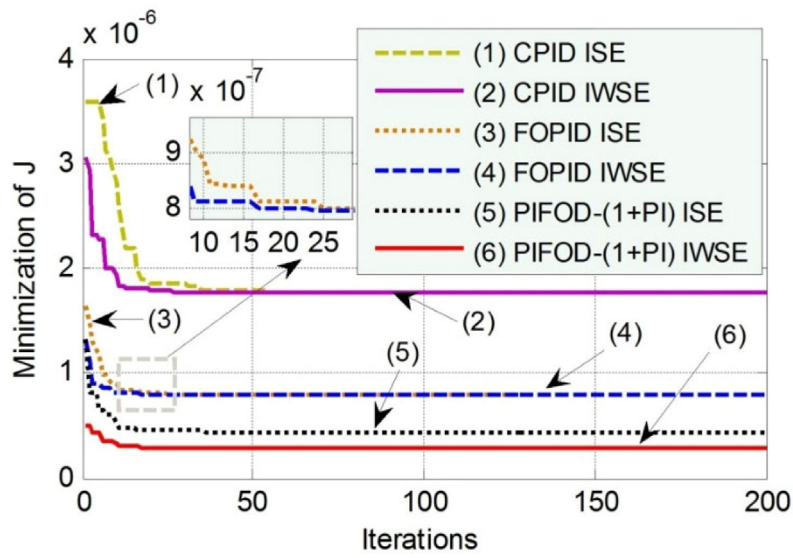
Fig. 6. Performance evaluation of PFOID and PIFOD-(1+PI) controllers under different J index (a) Δf_1 using ISE/MISE employed PFOID controller, (b) Δf_1 using ISE/IWSE employed PIFOD-(1+PI) controller.

$$J_{ITAE}(x) = \int_{T_{\min}=0}^{T_{\max}} t \cdot \{(|\Delta f_i|)^2 \cdot dt + (|\Delta P_{tie,ij}|)^2 \cdot dt\} \quad (22)$$

$$J_{ITSE}(x) = \int_{T_{\min}=0}^{T_{\max}} t \cdot \{(\Delta f_i)^2 \cdot dt + (\Delta P_{tie,ij})^2 \cdot dt\} \quad (23)$$



(a)



(b)

Fig. 7. (a) Comparative assessment of J with ISE and MISE, (b) Comparative assessment of J with ISE and IWSE.

$$J_{MISE}(x) = \left\{ W_i \cdot \int_{T_{min}=0}^{T_{max}} (\Delta f_i)^2 \cdot dt + W_{ij} \cdot \int_{T_{min}=0}^{T_{max}} (\Delta P_{tie,ij})^2 \cdot dt \right\} \quad (24)$$

$$J_{IWSE}(x) = \left\{ \int_{T_{min}=0}^{T_{max}} W_i \cdot (\Delta f_i)^2 \cdot dt + \int_{T_{min}=0}^{T_{max}} W_{ij} \cdot (\Delta P_{tie,ij})^2 \cdot dt \right\} \quad (25)$$

Subject to: $Ub \leq K_{ci} \leq Lb$

where K_c signifies the FO controller gains for i th active power network, considering limits of Lb and Ub (lower and upper bounds). Minimizing of both “ ΔF ” and “ ΔP_{tie} ” with waiting factors together has some advantages such as limiting the required capacity of storage units and diesel/biodiesel fuel consumption constructing the active power system more profitable (Latif et al., 2019a, 2020a). To visualize the performance, a comparative performance assessment of J with different controllers under classical ISE and other recently established objective functions are shown in Fig. 7

(a-b). To find out the applications of different J a comparative review has been established as framed in Table 3.

6. Conclusions

This paper gives a thorough review of FO controller based LFS for active power networks. These controllers can be used for different networks such as active single/multi-area traditional and renewable microgrid power network. In order to achieve the targeted LFS assignment, a mathematical modeling of change in frequency deviation and tie line power error has been presented.

Furthermore, the classifications of several FO controllers have been given. On the basis of control actions, the mathematical transfer function modeling of classified FO controllers has been presented. In order to trace out the controller parameters, different established and newly developed objective functions (J) have been streamlined with the summarization of their corresponding error signals. To this end, comparative studies of different objective functions along with FO controllers have displayed.

Table 3
Comparative review of application of different FO controllers' optimization for different frequency response model.

Reference	Nature of generation	Other subsystems	Control areas	Type of objective function (J)	Type of FO controllers	Optimization technique
Sharma and Yadav (2019)	Thermal-thermal	–	2	ISE	FOPI	LAT
Jain and Hote (2018)	Non-reheat turbine	–	1	ISE, IAE, ITAE	FOPID	BBBC
Debbarma et al. (2013)	Thermal-thermal-thermal	–	3	ISE	FOPID	BFT
Farook and Raju (2012)	Thermal-hydro-gas	–	3	ITAE	FOPID	hGA-FA
Debbarma et al. (2014)	Reheat thermal-reheat thermal-reheat thermal	–	3	ISE, ITAE	2DOF-FOPID	FA
Taher et al. (2014)	Non-reheat-reheat-hydraulic	–	3	ITAE	FOPID	ICA
Pan and Das (2015)	Reheat-reheat	–	2	ITSE	FOPID	chaotic NSGA-II
Zamani et al. (2016)	Thermal-thermal	–	2	ITAE	FOPID	GBMT
Morsali et al. (2017)	Thermal-hydraulic-gas	–	2	ITSE	FOPID	IPSO
Morsali et al. (2018)	Thermal-hydraulic-gas	–	2	ITSE	FO-PID	IPSO
Raju et al. (2019)	Thermal-thermal-hydro	WTG, DEG, FC, BESS	3	ISE	PIFOD	hAL-PS
Mohamed et al. (2020)	Conventional Diesel	WTG, PV, FC, FESS, BESS	1	ISE	FOPID	KHT
Dahiya et al. (2015)	Reheat thermal-hydro-gas	–	3	ITAE	FOPID	hDGST
Debbarma and Dutta (2017)	Thermal-hydro-gas	EVs	3	ITAE	FOPIDN	FPT
Wang et al. (2017)	Conventional Diesel	WTG, PV, FC, FESS, BESS	1	ISE	FOPID	MOET
Pan and Das (2016)	Conventional Diesel	STPG, WTG, FC, FESS, UC	1	ISE	Hybrid fuzzy FOPID	chaotic PSO
Nayak et al. (2020)	Thermal-hydro-diesel	–	2	ITAE	3DOF-FOPID	hSSA-ST
Latif et al. (2019b)	Conventional diesel	WPG-DSPG-PHEV, HP-FRZ	2	ISE	FOPID	WCA
Latif et al. (2019a)	Biodiesel Generator	ST-AWEC-GEC	3	MISE	PFOID	BOA
Arya et al. (2020)	Thermal-Thermal	GTPP, DSTS	2	ISE	FOPI-FOPID	SCA
Saha and Saikia (2018a, 2017)	Thermal-Gas-thermal	With Distributed Generations (DGs)	2 and 2	ISE	PIDN-FOID, PIDN-FOPD	WOT
Saha and Saikia (2019)	Thermal-thermal-thermal	STPP, SHPP, EV	3	ISE	IDN-FOPD	WOT
Tasnin and Saikia (2018)	Thermal-gas-thermal-gas	GTPP	3	ISE	FOPI-FOPD	SCA
Babu et al. (2019)	Thermal-thermal-thermal	STPP, WTG	3	ISE	FOPI-FOIDN	CST
Latif et al. (2020a)	Biodiesel Generator	WTG, MTG, TPG,	2	IWSE	PIFOD-(1+PI)	YSGA
Prakash et al. (2019)	Thermal-hydro-gas	SPV, WTS, DEG, AE, FC	3	ISE	2DOF-PI-FOPDN	VPLT
Jena and Sahu (2020)	Thermal-hydro	WTG, SPV, DEG	2	ITAE	3DOF-FOPIDN-FOPDN	WGT
Saha and Saikia (2018b)	Thermal-gas-thermal-gas	WTG, AE, FC, EV, DEG	3	ISE	(2DOF-PIDN)-FOI	WOT
Shankar et al. (2017)	Reheat/non-reheat thermal and hydrothermal	PV	2	ISE	(FL-PIDN-FOI)	ICA
Guha et al. (2018)	Thermal-hydro	UC	2	ISE	FL-FOID	ICA
Bhatt et al. (2011)	Thermal-hydro	WTG, DEG	2	ITAE	FOFLPID	ALT
Arya et al. (2020)	Thermal-hydro-gas	–	2	ISE	FL-PIDN-FOPIDN	ICA

The performance of the proposed objective function (i.e., MISE, IWES) with classical objective functions has been evaluated. The evaluation criterion is minimizing the error signals by reducing the undesired deviations in power flows between control areas.

As novel contribution, some recently developed dual-stage, cascaded, fuzzy integrated FO controllers have been presented and their corresponding algorithmic techniques. Finally, considering the novel features in literature, a comparative investigation of recently established LFS assignment for active single/multi-area power network under different FO controller optimization traced by different objective problem formulation has been undertaken.

This tutorial is valuable considering that renewable energy penetration is constantly on the rise. As the number of inverter-interfaced generators increase in power networks, frequency deviations become more significant. Different controller designs are investigated to mitigate this phenomenon. Moreover, various parameter optimization algorithms are utilized to improve performance of these controllers. FO controller is a very promising technique and proper understanding and use of these controllers help alleviate negative impacts of renewable energy use in power systems. Comparative review of these controllers and related optimization algorithms is very beneficial to researchers in this field.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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