Improved-Fitness Dependent Optimizer Based FOI-PD Controller for Automatic Generation Control of Multi-Source Interconnected Power System in Deregulated Environment

AMIL DARAZ, SUHEEL ABDULLAH MALIK, (Member, IEEE), HAZLIE MOKHLIS, (Senior Member, IEEE), IHSAN UL HAQ, (Member, IEEE), FARHAN ZAFAR, AND NURULAFIQAH NADZIRAH MANSOR, (Member, IEEE)

1Department of Electrical Engineering, Faculty of Engineering and Technology, International Islamic University Islamabad, Islamabad 44000, Pakistan
2Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

Corresponding author: Amil Daraz (amil.phdee108@iuiu.edu.pk)

ABSTRACT This paper presents a Fractional Order Integral-Proportional Derivative (FOI-PD) controller for Automatic Generation Control (AGC) of two-area Interconnected Power System (IPS) with six multiple generations units in a restructured environment. Further, the two-area IPS is composed of multiple non-linearities with Time Delay (TD), Boiler Dynamic (BD), Governor Dead Zone/ Band (GDZ/ GDB) and Generation Rate Constraint (GRC). The gains of the proposed controller are optimized by a most recent powerful meta-heuristic algorithm known as Improved-Fitness Dependent Optimizer (I-FDO). The efficiency of the proposed approach is compared with other techniques such as Firefly Algorithm (FA), Fitness Dependent Optimizer (FDO) and Teaching Learning Based Optimization (TLBO) algorithms. Further, to enhance the performance of the system, Redox Flow Batteries (RFB) is incorporated in each area and Thyristor Controlled Series Compensator (TCSC) in the tie-line of the power system. Results reveal that our proposed approach performs superior in terms of less Overshoot (Os), Settling time (Ts) and Undershoot (Us). Robustness of the proposed controller is verified by changing system parameters within a range of ±25%.

INDEX TERMS Fractional order integral-proportional derivative (FOI-PD) controller, deregulated power system, improved-fitness dependent optimizer, automatic generation control, fractional order proportional integral derivative controller (FOPID), and load frequency control.

I. INTRODUCTION

The modern power system consists of complicated electrical networks with interconnected control areas. A reliable power system should be able to supply continuous power to support consumers demand at all time, considering load variations. Load variations in power system mainly affect the system’s frequency and cause an imbalance between power generations and consumer utilization. On the other hand, the power system typically consists of active and reactive components; active power is accountable for constant frequency and whereas reactive power is responsible to maintain network voltage within tolerable limits. In this regard, AGC plays an important role to ensure stable power system operation and control during load variations. AGC is needed to maintain constant frequency within the acceptable range and tie-line power of interconnected area system [1]–[3].

In the conventional power sector, Distribution Companies (DISCOs), Generation Companies (GENCOs) and Transmission Companies (TRANSCOs) are possessed by a single body known as Vertically Integrated Utility (VIU) which delivered power at the regulated tariff. However, development in power industries has changed the structure of VIU into deregulated power system in which GENCOs, TRANCOs and DISCOs are owned by separate entities and they function independently in the competitive electricity market. Each company has the authority to contract others in the same or different control areas [4], [5].
Regulations that govern all the electricity transactions and auxiliary services such as automatic generation control taken by the GENCOs and DISCOs are usually handled by a body known as Independent System Operator (ISO) [6], [7]. In this regard, several control approaches have been proposed previously by various researchers to control the system frequency and tie-line power of the interconnected system. The basic concept of DISCO Participation Matrix (DPM) in the restructured framework has been proposed in [8] by examining the bilateral conventions of the power system. Permar et al. in [9] have used an optimal feedback controller for the multi-generation unit in a deregulated system. Authors in [10] suggested AGC for three area IPS in the restructured environment and optimized the parameters of the controller by employing the Genetic Algorithm (GA). Debbarna et al. in [11] have suggested FOPID controller where the gains of the controller are tuned using Bacterial Foraging Optimization (BFO) approach for AGC of multi-area thermal reheat unit under restructured power system. Dellip Kamari et al. in [12] have used Tilt Integral Derivative (TID) controller for Load Frequency Control (LFC) of two area reheat, hydro and gas power unit under deregulated environment incorporated with GRC, GDB and Boiler Dynamic (BD). The gains of the proposed controller are tuned using hybridization of TLBO with pattern Search (PS) algorithm.

Authors in [13] have studied AGC of multi-source IPS considering Flexible Alternating Current Transmission System (FACTS) devices with DC/AC link in the restructured environment including GRC and GDB. Shiva et al. in [14] have proposed a PID controller for AGC of three area multi-unit deregulated system. Quasi Oppositional Harmony Search (QOHS) method have been used to optimize the gains of the proposed controller. However, in literature, the consequence of physical limitations such as GDZ, TD, GRC, and BD non-linearity is not observed which needs further inclusive study.

In literature, numerous researchers have focused on FACTS and energy storage devices for improved performance of power system dynamics and for damping out of frequency oscillation, respectively. Authors in [15] proposed Thyristor Controlled Phase Shifter (TCPS) for AGC of the hydrothermal unit under a deregulated environment. Padhan et al. in [16] described the impact of TCSC and Superconducting Magnetic Energy Storage (SMES) for enhancing the load frequency dynamics of IPS. A Capacitive Energy Storage (CES) device incorporated with Static Synchronous Series Compensator (SSSC) for the multi-generation unit under deregulated environment has been reported in [17]. Impact of SMES and Unified Power Flow Controller (UPFC) [18], RFB [19], RFB and UPFC [20], Interline Power Flow Controller (IPFC) and RFB [21], [22], and TCSC [23], [24] have also been considered for stabilizing the power frequency and dynamic performance of several test systems.

In the last few decades, meta-heuristic optimization algorithm has attained incredible attention in the field of engineering particularly for the optimization of power system problems. For example, these methods have been successfully employed for the optimization of controllers gain. In this aspect, authors in [25] have used Particle Swarm Optimization (PSO) for tuning of Fraction High Order Differential Feedback Controller (FHODFC) in LFC of IPS. Hasanian in [26] has used the PID controller tuned with Whale Optimization Algorithm (WOA) considering a new model of renewable energy sources and conventional power system with the inclusion of GRC and GDB non-linearities. Similarly, some other meta-heuristic techniques have also been used to study the AGC of interconnected power system such as Sine Cosine Algorithm (SCA) [27], Imperialist Competitive Algorithm (ICA) [28], Modified Group Search Optimization (MGSO) [29], Fitness Dependent Optimizer (FDO) [30], Improved Ant Colony Optimization (IACO) [31], Salp Swarm Algorithm (SWA) [32], PSO hybridized with Gravitational Search Algorithm (hPSO-GSA) [33], Improved Gray Wolf Optimization (IGWO) [34], and Volleyball Premier League (VPL) [35]. Therefore, it is worth to further study the application of meta-heuristic techniques to solve problems related to AGC. A literature review on a group of papers related to AGC studies is provided in Table 1. The table also comprises of system type i.e. conventional or deregulated, the number of areas, effects of non-linearity, structure of controllers, optimization techniques and generation source types considered in AGC problem.

The literature study recognizes that numerous control structure with various optimization methods has been used to solve the AGC problem of power systems. PID controller is widely used to solve the AGC problem due to its simple structure, easy operation and better performance. However, due to complexity and non-linear behaviour of power systems the fractional-order and fuzzy order controllers have been used to improve the performance of the system. Similarly, some other modified structures of controllers have been used for AGC problem such as Fractional-Order Fuzzy PID (FOFPI), Fractional Order Integral (FOI) cascaded with FOPD controller. Fuzzy Fractional-Order PI-Fractional-Order PD (FFOP- FOPD) and fuzzy PID with filter-based cascade controller i.e. FPIDF-(1 + P). However, the literature divulges that no attempt has been made yet to develop FOI-PD controller which is the modified form of FOPID controller for solving multi-source interconnected power system under the deregulated environment. Therefore, in this study, the modified form of FOPID controller with I-FDO algorithm has been successfully applied for the AGC problem.

The performance of the AGC system can be improved by properly designing the controller and optimizing its parameter. Therefore, in this work, a novel modified FOPID controller called as FOI-PD controller is designed and developed for AGC of two areas, six-generation units under the deregulated environment with consideration of various non-linearities including TD, GDZ, BD and GRC. A more recent, meta-heuristic algorithm called as Improved-Fitness Dependent Optimizer (I-FDO) is employed for the

VOLUME 8, 2020
TABLE 1. Brief literature review of AGC.

| Reference No | System Type       | Generation Sources | Number of Areas | Non-Linearity Effect | Optimization Techniques | Controller Type | Other Device Used |
|--------------|-------------------|--------------------|----------------|----------------------|-------------------------|-----------------|------------------|
| [1]          | Conventional      | Thermal-Hydro      | 3              | GRC, GDB             | hFEA-PS                 | FPD            | -                |
| [2]          | Conventional      | Thermal-Hydro-PV   | 2              | GRC, GDB, TD         | ICA                     | FPDN-FOI       | -                |
| [3]          | Deregulated       | Thermal            | 2              | -                    | QOHS                    | PID            | TSCC             |
| [4]          | Deregulated       | Thermal            | 4              | -                    | ANFIS                   | -               |
| [5]          | Deregulated       | Thermal-Hydro      | 3              | GRC, BD, GDB         | 2DOF-PIDN-FOI           | ISA            | DG, EV           |
| [6]          | Deregulated       | Thermal-Hydro-Gas  | 2              | -                    | Feedback controller     | -               |
| [7]          | Deregulated       | Thermal-Hydro      | 3              | -                    | PID                     | GA             | -                |
| [8]          | Deregulated       | Thermal-Gas-Hydro  | 2              | -                    | FOPID                   | BFOA           | -                |
| [9]          | Deregulated       | Thermal-Gas-Hydro  | 3              | GRC, BD, GDB         | TID                     | TLBO-PS        | TCPS, SMES        |
| [10]         | Deregulated       | Thermal-Gas-Hydro  | 2              | GRC, BD, GDB         | PID                     | FID            | -                |
| [11]         | Deregulated       | Thermal-Hydro      | 2              | I                    | ICA                     | SSSC, CES      | -                |
| [12]         | Deregulated       | Thermal-Hydro      | 2              | -                    | Fuzzy-PID               | FA             | UPFC, SMES        |
| [13]         | Deregulated       | Thermal-Hydro      | 2              | GRC                   | AGC Regulators          | -              | RFB              |
| [14]         | Deregulated       | Thermal-Hydro      | 2              | TID                  | hDE-PS                  | UPFC, RFB      | -                |
| [15]         | Conventional      | Hydro-Thermal      | 2              | GRC                  | I                       | PSO            | TCPS             |
| [16]         | Conventional      | Thermal-Thermal    | 2              | GRC, TD               | PID                     | DE             | TSCS, SMES       |
| [17]         | Conventional      | Thermal-Hydro-Gas  | 2              | GRC                   | I                       | GA             | TSCS             |
| [18]         | Deregulated       | Thermal-Hydro-Gas  | 2              | GRC, TD               | Fuzzy-PID               | TPS            | UPFC, SMES       |
| [19]         | Deregulated       | Thermal-Hydro-Gas  | 2              | GRC                   | AGC Regulators          | -              | RFB              |
| [20]         | Deregulated       | Thermal-Hydro-Wind | 2              | GRC, BD, BD           | MID                    | hDE-PS         | UPFC, RFB        |
| [21]         | Deregulated       | Thermal-Hydro      | 2              | GRC, TD               | I                       | BFOA           | IFPC, RFB        |
| [22]         | Deregulated       | Thermal-Thermal    | 2              | GRC, TD               | PIDF                    | DE             | IFPC, RFB        |
| [23]         | Deregulated       | Thermal-Gas-Hydro  | 2              | GRC                   | I                       | IPSO           | TSCS             |
| [24]         | Deregulated       | Thermal-Thermal    | 2              | GRC                   | I                       | GA             | TSCS             |
| [25]         | Deregulated       | Thermal-Hydro-Gas  | 2              | GRC, BD               | FO-HDFC                 | PSO            | -                |
| [26]         | Conventional      | Thermal-PV         | 2              | -                    | PID                     | WOA            | -                |
| [27]         | Conventional      | Thermal-Geothermal | 2              | -                    | FOPID                   | SCA            | -                |
| [28]         | Conventional      | Thermal-Thermal    | 3              | GDB, TD               | CFFOPI-FOPID            | ICA            | -                |
| [29]         | Deregulated       | Thermal-Gas-Hydro  | 2              | GRC, GDB              | FO                      | IPSO-MGSO      | SSC              |
| [30]         | Conventional      | Thermal-Gas-Hydro  | 2              | GRC, GDB, TD, BD      | 1-PD, PID               | FDO            | -                |
| [31]         | Conventional      | Thermal-Hydro      | 2              | GDB                   | FPID                    | IACO           | -                |
| [32]         | Conventional      | Wind-Thermal-PV    | 2              | GRC, TD, GDB          | PID                     | SSA            | -                |
| [33]         | Conventional      | Thermal-Gas-Hydro  | 2              | GRC, GDB              | PID                     | PSO-GSA        | -                |
| [34]         | Conventional      | Wind, PV, Diesel   | 2              | GDB                   | FO-T2-FPID              | IGIWO          | BES, EV          |
| [35]         | Deregulated       | Thermal- Hydro-Gas | 2              | GRC, BD, GDB          | 2DOF-PL-FOPD            | VPL            | -                |
| [36]         | Deregulated       | Thermal-Hydro-Gas  | 3              | GRC, GDB              | PPFPID                  | GOA            | RFB              |
| [37]         | Proposed          | Model              |                |                       |                         |                |                  |
| [38]         | Deregulated       | Thermal-Hydro-Gas  | 2              | GRC, BD, TD, BD       | FOL-PD                  | FID            | RFB, TSCC        |
| [39]         | Deregulated       | Thermal-Hydro      | 2              | -                    | -                       |                |                  |

optimization of the proposed controller. Further, the dynamic profile of the system is enhanced by incorporating RFB in each area and TCSC in series with the tie-lines. The effectiveness of the proposed approach is compared with other algorithms such as FDO, FA and TLBO. Further, the proposed controller employing I-FDO technique is compared with other controllers such as FOPID, I-PD and PID controllers. Moreover, the robustness of the proposed controller is tested by changing the system parameters of the multi-source deregulated power system.

This paper is structured as follows; Section II describes the modelling of the system, followed by AGC in a deregulated power system and modelling of TCSC and RFB system. Section III discusses the controller’s design and formulation of a fitness function. An overview of optimization algorithms followed by FDO and I-FDO algorithms are presented in section IV. Implementation of the proposed approach and results are described in Section V. Finally, some concluding comments are presented in section VI.

II. SYSTEM MODELLING

A realistic model of two areas six-generation unit with several non-linearities of Boiler Dynamic (BD), Generation Rate Constraint (GRC), Time Delay (TD) and Governor Dead Zone (GDZ), in the restructured environment, is presented in Figure 5. Area-1 comprises of hydro, gas, thermal reheat, TCSC and RFB unit with two DISCOs (DISCO-1 and DISCO-2) and Area-2 consist of hydro, wind, thermal reheat and RFB unit with two DISCOs (DISCO-3 and DISCO-4). Thermal reheat generation unit composed of the turbine, governor and reheat with Transfer Function (TF) \( \frac{1}{ST_{r}T_{r}+1} \) and \( \frac{1}{ST_{r}T_{r}+1} \) respectively. While gas power unit is composed of valve position TF \( \frac{1}{ST_{g}T_{g}+1} \), governor TF \( \frac{1}{ST_{g}T_{g}+1} \), fuel combustion reaction TF \( \frac{1}{ST_{c}T_{c}+1} \) and TF of compressor discharge \( \frac{1}{ST_{c}T_{c}+1} \) respectively. Various non-linearities including GDZ, BD, TD and GRC have been incorporated in two area multi-generation IPS to make the realistic system. Generation rate constraint mainly affects the system performance due to the limitation of a turbine concerning power generation unit. The generation rate for thermal reheat system is around 3-10% p.u. MW/minute, while for
the hydro system is 270%/minute for rising and 330%/minute for falling the generation. Governor dead band is the total quantity of speed changes where there is no change in valve position. The non-linear relationship of GDB is articulated as follows:

\[
G(s) = 0.8 - \frac{0.2}{s} \quad (1)
\]

where \(G(s)\) represents the transfer function of the Boiler Dynamic (BD) model integrated with reheat thermal unit for a steam generation under pressure. The block diagram of BD is depicted in Figure 1. Time delay (TD) may interrupt system stability if it is not addressed appropriately. In this study TD of 2 sec for AGC model has been considered. Each generation unit has its area participation factor (apf) and regulatory parameters that determine contribution in the TD of 2 sec for AGC model has been considered. The sum of all apf in each area is equal to unity. Because of the presence of an enormous thermal unit, the hydro system is about 30%. Whereas, the generation of gas and wind power unit is lower and their participation factor is in the range of 50-60 %, and their participation factor for hydro, thermal, and wind/ gas are assumed to be 0.3, 0.575 and 0.125 respectively.

\[
DPM = \begin{bmatrix}
cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\
cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\
cpf_{31} & cpf_{32} & cpf_{33} & cpf_{34} \\
cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \\
cpf_{51} & cpf_{52} & cpf_{53} & cpf_{54} \\
cpf_{61} & cpf_{62} & cpf_{63} & cpf_{64} \\
\end{bmatrix} \tag{2}
\]

In Eq (2) \(DPM\) represent DISCO Participation Matrix and cpf shows contract participation factor. Cpf signifies the fraction of each GENCOS contribution to the entire load demand of DISCOs. Whereas, diagonal elements denote the local demand and off-diagonal entities show the participation from other areas. The sum of all column elements of Eq (2) is equal to unity which can be expressed as below:

\[
\sum_{i} cpf_{ij} = 1 \quad (3)
\]

The scheduled tie line (\(\Delta P_{\text{tie12}}^{\text{Sch}}\)) power may be expressed as:

\[
\Delta P_{\text{tie12}}^{\text{Sch}} = \sum_{m=1}^{2} \sum_{n=3}^{4} cpf_{mn} \Delta P_{Ln} - \sum_{m=3}^{4} \sum_{n=1}^{2} cpf_{mn} \Delta P_{Ln} \quad (4)
\]

where \(\Delta P_{Ln}\) represents a change in DISCO load of n-th area. Error in tie-line power (\(\Delta P_{\text{Error12}}\)) from area-1 to area-2 is expressed as below:

\[
\Delta P_{\text{Error12}} = \Delta P_{\text{actual12}} - \Delta P_{\text{Sch12}} \quad (5)
\]

whereas

\[
\Delta P_{\text{actual12}} = \frac{2\Pi T_{12}}{s} \lfloor \Delta f_1 - \Delta f_2 \rfloor \quad (6)
\]

where \(T_{12}\) shows synchronization constant of tie-line and \(\Delta f_1, \Delta f_2\) represents a change in the frequency of area-1 and area-2 respectively. Error in tie-line power (\(\Delta P_{\text{Error12}}\)) from area-2 to area-1 is expressed as follows:

\[
\Delta P_{\text{Error21}} = a_{12} \Delta P_{\text{Error12}} a_{12} = -1 \quad (7)
\]

The Area Control Error (ACE) for area-1 and area-2 can be expressed as below:

\[
ACE_1 = \beta_1 \Delta f_1 + \Delta P_{\text{Error12}} \quad (8)
\]

\[
ACE_2 = \beta_2 \Delta f_2 + a_{12} \Delta P_{\text{Error12}} \quad (9)
\]

where \(\beta_1\) and \(\beta_2\) represents the bias factor of area-1 and area-2 respectively.

\[A. AGC IN DEREGULATED POWER SYSTEM\]

In a deregulated system, GENCOS is permitted to trade power to any DISCO while a DISCO has the complete autonomy to deal with GENCOS in their area or any other area [4]. Such transaction is known as “bilateral transactions” which is supervised by ISO. The idea including DISCOs-GENCOS bilateral trading is articulated by DPM in which columns denote DISCOs and rows indicate GENCOS [8, 39]. Whereas, each entity in DPM shows Contract Participation Factor (cpf). Let us consider a two area IPS in a deregulated environment which is described by two DISCOs and three GENCOS in each control area and is expressed by (2) [20].

\[\text{FIGURE 1. Transfer function model of boiler.}\]

\[\text{A. TCSC MODELLING IN AGC}\]

The flow of current for an interconnected area can be expressed as below:

\[
I_{12} = \frac{|V_1| \angle \delta_1 - |V_2| \angle \delta_2}{J(X_{12} - X_{\text{csc}})} \quad (10)
\]

where \(V_1, V_2, \delta_1\) and \(\delta_2\) represents terminal voltages and respective phase angles. Complex tie-line power can be articulated as:

\[
P_{\text{tie}} - JQ_{\text{tie12}} = V_1^* I_{12} = |V_1| L (\angle \delta_1) \left( \frac{|V_1| \angle \delta_1 - |V_2| \angle \delta_2}{J(X_{12} - X_{\text{csc}})} \right) \quad (11)
\]
where $P$ and $Q$ represent real and reactive power respectively. $X_{Tcsc}$ shows reactance of TCSC and $X_{12}$ represent reactance of tie-line. The real part of Eq (11) can be written as below:

$$P_{tie12} = \frac{|V_1| \cdot |V_2|}{(X_{12} - X_{Tcsc})} [\sin(\delta_1 - \delta_2)]$$ (12)

The above equation in respect of percentage compensation ($K_c$) can be expressed as:

$$P_{tie12} = \frac{|V_1| \cdot |V_2|}{X_{12}(1 - K_c)} [\sin(\delta_1 - \delta_2)]$$ (13)

where $K_c$ denote degree of compensation and can be written as:

$$K_c = \frac{X_{Tcsc}}{X_{12}}$$ (14)

Equation (13) can be written as:

$$P_{tie12} = \frac{|V_1| \cdot |V_2|}{(X_{12} - X_{Tcsc})} [\sin(\delta_1 - \delta_2)]$$

The first term in Eq (15) represents tie-line power without TCSC while the second term denotes tie-line power with TCSC. The incremental tie-line power can be attained as:

$$\Delta P_{tie12} = \frac{|V_1| \cdot |V_2|}{(X_{12})} \left[ \cos(\delta^0_1 - \delta^0_2) \right] [\sin(\Delta \delta_1 - \Delta \delta_2)]$$

$$\Delta P_{tie12} = \frac{|V_1| \cdot |V_2|}{(X_{12})} \left[ \cos(\delta^0_1 - \delta^0_2) \right] [\sin(\delta^0_1 - \delta^0_2)]$$ (16)

Since the deviation of the bus voltage angle is practically small for minor variation in the actual power load, therefore,

$$\sin(\Delta \delta_1 - \Delta \delta_2) \approx \Delta \delta_1 - \Delta \delta_2$$ (17)

$$\Delta P_{tie12} = \frac{|V_1| \cdot |V_2|}{(X_{12})} \left[ \cos(\delta^0_1 - \delta^0_2) \right] [(\Delta \delta_1 - \Delta \delta_2)]$$

$$\Delta P_{tie12} = \frac{|V_1| \cdot |V_2|}{(X_{12})} \left[ \cos(\delta^0_1 - \delta^0_2) \right] [\sin(\delta^0_1 - \delta^0_2)]$$ (18)

Let us consider

$$T_{12} = \frac{|V_1| \cdot |V_2|}{(X_{12})} \left[ \cos(\delta^0_1 - \delta^0_2) \right]$$

$$K_{12} = \frac{|V_1| \cdot |V_2|}{(X_{12})} \left[ \sin(\delta^0_1 - \delta^0_2) \right]$$ (19)

$$\Delta P_{tie12} = [T_{12}(\Delta \delta_1 - \Delta \delta_2)] + \frac{\Delta K_c}{1 - K_c} [K_{12}]$$ (20)

Hence

$$\Delta \delta_1 = 2\pi \int \Delta f_1 dt$$ (21)

$$\Delta \delta_2 = 2\pi \int \Delta f_2 dt$$ (22)

By substituting values of Eq (21) and (22) into Eq (20) and also taking Laplace Transform, Eq. (20) can be written as:

$$\Delta P_{tie12}(s) = \frac{2\pi T_{12}}{s} [\Delta f_1(s) - \Delta f_2(s)] + \frac{\Delta K_c}{1 - K_c} [K_{12}]$$ (23)

In Eq (23) the tie-line power can be controlled by $\Delta K_c$ and can be written as:

$$K_c = \frac{K_{Tcsc}}{1 + ST_{Tcsc}}$$ (24)

where $K_{Tcsc}$ and $T_{Tcsc}$ represent gain and time constant of TCSC. If the input signal to the TCSC damping controller is assumed to be the change in error and TF of the signal conditioning circuit as:

$$\Delta K_c(s) = \frac{K_{Tcsc}}{1 + ST_{Tcsc}} [\Delta Error(s)]$$ (25)

$$\Delta K_c(s) = \frac{K_{Tcsc}}{1 + ST_{Tcsc}} [\Delta f_1(s)]$$ (26)

C. RFB MODELLING IN AGC

Redox flow batteries (RFBs) are made of electrolytes conta-ining the active redox species contained in external tanks. Usually, cells are organised in bipolar stacks, in which the electrolytes flow during charge and discharge. Subsequently, the storage capacity is then calculated with respect to electrolyte tank size and the reactant concentration, while the energy is determined by the number, configuration and choice of component of cell stacks. The soluable flow batteries gained attention over other devices to work efficiently without a cell separation membrane. RFBs are power devices which can be used as a frequency fluctuations stabilizer besides a fast energy compensation source. RFB can be considered as an energy storage device to reduce fluctuation in frequency and tie-line power of an IPS [21], [22], [39]. RFB is used more frequently as compared to other storage devices like SMES owing to its simple operation under normal temperature, low losses and long lifespan and maintenance. During abrupt changes in load, the RFB device delivers energy to the system and also charged constantly during system operation. RFB model of the system output versus frequency variation is expressed as follows:

$$\Delta P_{RFB} = \frac{K_{RFB}}{1 + T_{RFB}} [\Delta f]$$ (27)

where $T_{RFB}$ shows time constant and $K_{RFB}$ denote gain of RFBs.
III. CONTROLLERS DESIGN AND FITNESS FUNCTION

Various controllers have been designed and implemented for AGC in literature. However, fractional-order controller attained considerable attention in the last few decades as compared to traditional controllers due to better disturbance rejection ratio, low noise effect and reduction of calculation time [28], [36]. In this section, a modified FOPID controller known as FOI-PD controller is designed and developed for AGC problem in a deregulated environment. The structure of FOPID and FOI-PD controllers are shown in Figure 2 and 3 respectively, which consist of five parameters, integral gain \((K_i)\), derivative gain \((K_d)\), proportional gain \((K_p)\), fractional integrator order \((\lambda)\) and fractional derivative order \((\mu)\). In FOPID controller all the parameters are put in feedforward direction while, in FOI-PD controller, the integral parameter \((K_i)\) with integrator order \((\lambda)\) is put in a forward direction and the remaining parameters are put in feedback [37]. The output of FOPID and FOI-PD controllers in terms of a differential equation is specified by Eq (28) and Eq (29) respectively.

\[
u(t) = k_pe(t) + K_iD^{-\lambda}e(t) + K_dD^{\mu}e(t) \tag{28}
\]

\[
u(t) = K_iD^{-\lambda}e(t) - [k_p]e(t) + K_dD^{\mu}y(t) \tag{29}
\]

where \(u(t)\) represent control signal, \(e(t)\) denotes error signal, which is ACE in this case and \(y(t)\) is the output of the system. A step-change in the reference input \(R(s)\) of the FOPID controller will cause an instant spike change in the output of control signal \(U(s)\). This spike in the controller output is called as proportional or derivative kick which effects rapidly change the command signal to the actuator and can cause a serious problem in the plant \(G_p(s)\). To overcome these drawbacks the modified structure of FOPID controller is introduced. In this structure, the integral gain responds on error signal \(E(s)\). An instant change in the reference input will not affect the derivative and proportional gains, since these two gains work on the output process \(Y(s)\) [38], [39].

The Transfer Function (TF) of the closed-loop system by considering a plant \(G_p(s)\) with FOPID and FOI-PD controllers are given by Eq (29) and (30) respectively.

\[
\frac{Y(s)}{R(s)} = \frac{G_p(s)[K_pS^\lambda + K_i + S^\lambda K_d S^\mu]}{S^\lambda + G_p(s)[K_pS^\lambda + K_i + S^\lambda K_d S^\mu]} \tag{30}
\]

Eq (30) shows that there are two zeros with FOPID controller which is tough to adjust the response of the system with these zeros. Their impact takes place as higher overshoot or an earlier peak. The proposed modified FOPID controller known as FOI-PD controller gets over these effect of zeros as shown in Eq (31) and enhances the response of the system by adding derivative and proportional terms of FOPID on feedback path instead of feedforward. Therefore, the response of the system with FOI-PD controller is achieved better as compared to FOPID controller which will be evident in the section of results and discussion.

To evaluate the performance of the proposed I-FDO method, Integral of Time-weighted Squared Error (ITSE) [23], [29], [30] and [39] is used as cost function to optimize AGC problem. ITSE expression can be written as:

\[
J_1 = ITSE = \int_0^t \left[ \Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie12}^2 \right] dt \tag{32}
\]

IV. OPTIMIZATION TECHNIQUES

A. FITNESS DEPENDENT OPTIMIZER (FDO)

In recent years, researchers are trying to develop a new meta-heuristic algorithm for optimization problems. In this aspect, Abdullah and Tarik developed a new algorithm in 2019 that is inspired by nature-based bee swarming reproductive process. This algorithm has been tested on 19 classical benchmark functions and three practical problems which shows outstanding performance as compared to other recent techniques [40]. Furthermore, the efficiency of the algorithm has also been evaluated on AGC problem [30] and also for the optimization of one-dimensional bin packing combinatorial problem [41]. FDO algorithm has fewer parameters comparing to other algorithms, this makes FDO much simpler, less complex, and faster. FDO algorithm consists of the following four steps:

1) STEP 1 (INITIALIZATION OF POPULATION)

In this step, a population of scout bee in search space \(X_k\) \((1, 2 \ldots n)\) is initialized randomly. The number of the scout bees were equal to population size and each scout contains five parameters known as \(K_i\), \(K_p\), \(K_d\), \(\lambda\) and \(\mu\) denotes the gains of FOI-PD/FOPID controllers. Where each scout signifies the potential of solution and is trying to search a better hive (solution) by probing more positions randomly.

2) STEP 2 (FITNESS WEIGHT OF SCOUT BEE)

Fitness weight \(F_w\) of the scout bee can be evaluated as:

\[
F_w = \left| \frac{\mathcal{f}(X_{k,i}^*)}{\mathcal{f}(X_k^*)} \right| - \gamma \tag{33}
\]

where \(\mathcal{f}(X_{k,i}^*)\) denotes the current value of fitness at iteration \((t)\), \(\mathcal{f}(X_k^*)\) represents fitness value for the global best solution and \(\gamma\) represents weight factor and its value is either 1 or 0. In most cases, its value is 0 for a stable
search. However, this value also depends on a case by case problem.

3) STEP 3 (MOVEMENT OF SCOUT BEE)
The movement of scout bee from their current position to a next position by adding pace \((P)\) to explore better position can be expressed as follows:

\[ X_{k}^{t+1} = X_{k}^{t} + P \] (34)

where \(X_{k}^{t+1}\) represents the next position, \(X_{k}^{t}\) denotes the current position and \(P\) represents the moment of scout bees. Pace \((P)\) depends on \(F_w\) for a different case as given in Eq (35) and also its direction is based on random phenomena.

\[ P = \begin{cases} \gamma (X_{k}^{t} - X_{k}^{*}) - 1; & \text{If } 0 < \gamma < 1 \text{ and } \Gamma < 0 \\ \gamma (X_{k}^{t} - X_{k}^{*}); & \text{If } 0 < \gamma < 1 \text{ and } \Gamma \geq 0 \\ \Gamma X_{k}^{t}; & \text{If } \gamma = 1 \text{ or } \gamma = 0 \text{ or } f(X_{k}^{t}) = 0 \end{cases} \] (35)

where \(\Gamma\) belongs to random values in the range of \([-1, 1]\).

4) STEP 4 (STOPPAGE CRITERIA)
The fitness value of each scout bee is calculated until a solution is achieved or a termination criterion is reached.

B. IMPROVED-FITNESS DEPENDENT OPTIMIZER (I-FDO)
I-FDO is the improved form of FDO which was recently developed by Danieal et al. [42] and has been tested on 19 classical benchmark functions and shows its superiority from FDO and other recent metaheuristic algorithms. The concept of algorithm is based on the collective decision-making and generative process used by bees. Our proposed I-FDO algorithm differs from FDO algorithms which consist of two phases including position updates of scout bees and randomization of weight factor \((\gamma)\).

1) UPDATING THE SOUT BEE POSITION
In I-FDO algorithm, the position of the scout’s bee is updated by adding two parameters that are Alignment \((A)\) and Cohesion \((C)\) to original FDO. These two parameters are important signifiers of group motion; alignment \((A)\) which shows pace matching of individuals in the neighbourhood or group to that of other individuals whereas, cohesion \((C)\) is the tendency of scouts towards the centre of mass of the neighbourhood. The new position of artificial scout’s bee can be articulated as follows:

\[ X_{k}^{t+1} = X_{k}^{t} + P + (A \times \frac{1}{C}) \] (36)
TABLE 2. Parameters setting for controller under Poolco Based Transaction (PBT) considering different cases.

| Controller Gains | Case-1 | Case-2 | Case-3 |
|------------------|--------|--------|--------|
| FDL-PD (FDO)     | 1.176  | 1.323  | 1.190  |
| FDL-PD (TLBO)    | 1.010  | 1.012  | 1.011  |
| FDL-PD (FA)      | 1.130  | 1.200  | 1.490  |
| FDL-PD (FOPID)   | 1.290  | 0.232  | 1.890  |
| FDL-PD (FOPID)   | 1.405  | 1.012  | 0.110  |
| FDL-PD (FOPID)   | 1.032  | 1.012  | 0.110  |
| FDL-PD (FOPID)   | 0.998  | 0.110  | 0.220  |
| With RFB & TCSC  | 1.678  | 1.989  | 1.110  |
| TCSC             | 1.340  | 1.988  | 1.101  |
| RFB              | 1.458  | 1.543  | 1.120  |
| Without RFB & TCSC| 1.069  | 1.101  | 1.069  |

TABLE 3. Parameters setting for controller with Bilateral Based Transaction (BBT) and Contract Violation Based Transaction (CVBT).

| Controller Gains | Bilateral Based Transaction | Contract Violation Based Transaction |
|------------------|------------------------------|-------------------------------------|
| FDL-PD (I-FDO)   | 1.678                        | 2.904                               |
| FDL-PD (I-FDO)   | 1.989                        | 2.207                               |
| FDL-PD (I-FDO)   | 1.010                        | 1.011                               |
| FDL-PD (I-FDO)   | 1.120                        | 1.101                               |
| FDL-PD (I-FDO)   | 1.064                        | 1.001                               |
| FDL-PD (I-FDO)   | 1.001                        | 1.010                               |
| FDL-PD (I-FDO)   | 1.064                        | 1.001                               |
| FDL-PD (I-FDO)   | 0.988                        | 1.010                               |
| FDL-PD (I-FDO)   | 0.998                        | 1.069                               |
| FDL-PD (I-FDO)   | 1.101                        | 1.069                               |
| FDL-PD (I-FDO)   | 1.101                        | 1.069                               |
| FDL-PD (I-FDO)   | 1.069                        | 1.069                               |


where $X_{t+1}^i$ represents the next position, $X_t^i$ denotes the current position, $P$ represents the moment of scout bees, $A$ represents alignment and $C$ represents the cohesion of scouts bee. Whereas alignment and cohesion are expressed in Eq (37) and (38) respectively.

$$A_i = \sum_{i=1}^{N} P_i$$  \hspace{1cm} (37)

$$A_i = \sum_{i=1}^{N} X_i^i - X$$  \hspace{1cm} (38)

where $P_i$ represents the pace of i-th neighbouring scouts bee, $N$ represents the neighbourhood number, $X$ is the position of current individuals and $X_i$ is the position of i-th neighbouring scout.

2) RANDOMIZATION OF WEIGHT FACTOR

In I-FDO algorithm weight factor ($\gamma$) is generated in the range of [0, 1] by using random phenomenon to control the fitness weight ($F_W$) instead of original FDO in which weight factor is considered to be 0 or 1. However in FDO, for most cases, the weight factor is used to be 0. In I-FDO algorithm improvement in terms of fitness weight can be written as below:

$$F_w = \frac{f(X_{t+1}^i)}{f(X_t^i)}$$  \hspace{1cm} (39)
Figure 5. Two areas multi-generation deregulated power system with non-linearities including TD, GRC, BD and GDB.
V. IMPLEMENTATION AND RESULTS

In this section, the model as shown in Figure 5 is developed in Matlab/Simulink using the values from Appendix (Table-10) and I-FDO algorithm is written in m. file. ITSE criteria are used as an objective function to tune the gains of the proposed controller. For the optimization of controller gains, the values of I-FDO parameters were taken from Appendix (Table 11). The optimization process has been performed 20 times for each algorithm, and the best optimal values among the 20 iterations are chosen as the controller’s final gains. The optimal values for two areas six-generation unit in the deregulated environment under the Poolco Based Transaction (PBT) considering different cases are provided in Table 2. While the optimum values under Contract Violation Based Transaction (CVBT) and Bilateral Based Transaction (BBT) is presented in Table 3. The results attained from the proposed approach are associated with other algorithms such as FDO, FA and TLBO based FOI-PD algorithm. ITSE based convergence diagram of different algorithm is depicted in Figure 7. In order to evaluate the controller’s efforts, the control signal of FOPID and FOI-PD controllers using ITSE criteria are shown in Figure 9 which indicate that FOI-PD controller has high control signal as compared to FOPID controller.

A. POOLCO BASED TRANSACTION (PBT)

In PBT, Discos have a power contract with Gencos in their same control area. It is presumed that the two discos demands of 0.05 p.u.MW ($P_{L1} = P_{L2} = 0.05$ p.u.MW) power in control area1 from the Gencos of the similar control area. In the control area, 2 Discos have not any contract with Gencos i.e ($P_{L3} = P_{L4} = 0.00$ p.u.MW). Hence, the total load disturbance in area 1 is ($P_{d1} = 0.1$ p.u.MW) and in area 2 is ($P_{d2} = 0.0$ p.u.MW). A specific case of PBT between Gencos and Discos is simulated by considering
Three cases have been considered under PBT. The first case is the validation of the proposed I-FDO technique, which is compared with other optimized techniques such as FDO, TLBO and FA. In the second case, the performances of the novel proposed controller have been compared with the performance of other conventional controllers like FOPID, I-PD and PID. In the third case, the performance of the system has been evaluated with and without RFB and TCSC with prosed methods.

1) CASE-1
In case-1 the superiority of the proposed I-FDO technique has been validated by comparing the result with other optimization techniques including FDO, TLBO and FA. The dynamic response profile of the system with proposed techniques for 1% step load in area 1 under PBT is presented in Figure 6(a-c). It can be observed from Fig 6 (a-c) that I-FDO based optimization method quickly suppressed oscillation for frequency variation in area 1 ($f_1$), area 2 ($f_2$) and variation in tie-line power ($P_{tie}$). A comprehensive comparative results for various algorithms in terms of Settling time ($T_s$), Overshoot ($O_s$) and Undershoot ($U_s$) for $f_1$, $f_2$ and $P_{tie}$ are given in Table 4. From Fig 6 (a-c) it can be observed that FOI-PD controller tuned with I-FDO algorithm has nearly same peak overshoot as compared with FOI-PD tuned with FDO techniques but improved settling time by 11.95% for change in area-1 and 16.63% for change in area-2. Similarly, FOI-PD controller tuned with I-FDO improved settling time by (47.56%, 10.88% and 0.20%) and effectively reduced overshoot by (97.10%, 56.20%, and 69.41%) for $f_1$, $f_2$ and $P_{tie}$ respectively as compared to FOI-PD controller tuned with FA. From Table 4, it can be observed that I-FDO based tuned FOI-PD controller as compared to hDE-PS based MID controller provides a

### TABLE 4. Comparison performance of various algorithms under PBT for case-1 in terms of $T_s$, $O_s$ and $U_s$.  

| Controller with Algorithms | $T_s$ (Settling time) | $O_s$ (Overshoot) | $U_s$ (Undershoot) |
|---------------------------|----------------------|------------------|-------------------|
|                           | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie}$ | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie}$ |
| FOI-PD (FDO)              | 4.42     | 13.1     | 9.97       | 0.000017 | 0.000240 | 0.000378 | -0.00094 | -0.00448 | -0.00199 |
| FOI-PD (FDO)              | 5.02     | 15.9     | 9.81       | 0.000682 | 0.00126 | 0.00651 | -0.00135 | -0.00888 | -0.00507 |
| FOI-PD (TLBO)             | 6.53     | 14.8     | 12.7       | 0.000363 | 0.000424 | 0.000542 | -0.00664 | -0.00178 | -0.00162 |
| FOI-PD (FA)               | 8.43     | 14.7     | 9.99       | 0.000813 | 0.000548 | 0.001236 | -0.00922 | -0.00156 | -0.01012 |
| TID (hTLBO-PS) [12]       | 9.53     | 13.75    | 10.36      | 0.007222 | 0.007040 | 0.003500 | -0.18888 | -0.24010 | -0.06330 |
| MID (hDE-PS) [20]         | 19.07    | 18.09    | 12.69      | 0.000800 | 0.001700 | 0.006600 | -0.00100 | -0.01500 | -0.00800 |

### TABLE 5. Comparison performance of the proposed algorithm with different controllers under PBT for case-2 in terms of $T_s$, $O_s$ and $U_s$. 

| Controller with Algorithms | $T_s$ (Settling time) | $O_s$ (Overshoot) | $U_s$ (Undershoot) |
|---------------------------|----------------------|------------------|-------------------|
|                           | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie}$ | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie}$ |
| I-FDO with FOI-PD         | 6.23     | 10.9     | 8.23       | 0.000041 | 0.000044 | 0.000272 | -0.00628 | -0.00061 | -0.00178 |
| I-FDO with FOPID          | 7.93     | 11.1     | 8.46       | 0.000048 | 0.000174 | 0.000509 | -0.00104 | -0.00056 | -0.00500 |
| I-FDO with I-PD           | 8.61     | 11.0     | 9.02       | 0.000406 | 0.000153 | 0.003254 | -0.00179 | -0.00062 | -0.00651 |
| I-FDO with PID            | 10.9     | 12.2     | 10.4       | 0.000813 | 0.000409 | 0.006035 | -0.00922 | -0.00105 | -0.01376 |

### TABLE 6. Comparison performance under PBT for case-3 in terms of $T_s$, $O_s$ and $U_s$. 

| Controller with Algorithms | $T_s$ (Settling time) | $O_s$ (Overshoot) | $U_s$ (Undershoot) |
|---------------------------|----------------------|------------------|-------------------|
|                           | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie}$ | $\Delta f_1$ | $\Delta f_2$ | $\Delta P_{tie}$ |
| I-FDO with RFB& TCSC      | 8.10     | 6.23     | 10.8       | 0.000115 | 0.000039 | 0.00116 | -0.00446 | -0.00527 | -0.00681 |
| I-FDO with TCSC           | 9.80     | 7.80     | 11.2       | 0.000508 | 0.000318 | 0.00223 | -0.00912 | -0.00441 | -0.00685 |
| I-FDO with RFB            | 9.90     | 8.20     | 11.8       | 0.000557 | 0.000319 | 0.00224 | -0.00691 | -0.00568 | -0.00812 |
| FDO without RFB&TCSC      | 11.8     | 12.4     | 12.1       | 0.001410 | 0.001641 | 0.00363 | -0.01023 | -0.00695 | -0.00823 |
significance improvement of 76.85%, 26.42% and 21.43% for both areas and in tie-line power, while effectively reduced peak overshoot of 97.80%, 85.88%, and 37.00% and undershoot of 6.00%, 70.13% and 75.00% for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively. Similarly, I-FDO based FOI-PD controller also provides an improvement of 53.62%, 4.96%, and 6.37% in $T_s$ for load frequency of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively as compared to TLBO-PS based TID controller. From Fig 7 it can be seen that I-FDO algorithm converge rapidly by using ITSE criteria and obtained the value of (ITSE = 0.000168) as compared to FDO (ITSE = 0.000290), TLBO (ITSE = 0.000410) and FA (ITSE = 0.000513).

2) CASE-2
In this case, the performance of FOI-PD controller optimized with I-FDO algorithms have been compared with FO-PID, I-PD and PID controllers tuned with the same algorithm for two area multi-source IPS under poolco based transaction. The results obtained from the proposed techniques are shown in Figure 8(a-c) and Table 5. From Table 5 it can be seen that FOI-PD controller with I-FDO tuned method superiorly performs in respect of settling time by (2.80%, 16.56%, and 23.87%), overshoot by (69.36%, 62.55%, and 88.35%) for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively as compared to FOPID controller tuned with I-FDO techniques. From Fig 8(a-c) and Table 5 it can be observed that FOI-PD controller improved settling time by (42.84%, 10.65%, and 20.86%), effectively reduced peak overshoot by (49.56%, 89.24% and 95.40%) and reduced undershoot by (31.88%, 41.90% and 87.0%) for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively, when compared with PID controller optimized with similar algorithms.

Hence, it can be inferred that our proposed controller outperforms in respect of $T_s$, $O_s$ and $U_s$ as compared to PID
and I-PD controllers optimized with a similar algorithm i.e. I-FDO.

3) CASE-3
In case 3, the effect of introducing RFB and TCSC unit on AGC is investigated. RFB unit is incorporated in each area and TCSC is considered in tie-line of the system. The performance of the system is evaluated with I-FDO based FOI-PD controller considering the effect of RFB, TCSC, both RFB and TCSC and without RFB and TCSC. The results attained for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ are shown in Figure 10 (a-c).
for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively as compared to a system without considering the effect of RFB and TCSC unit. From Fig 10 (a-c) and Table 6 it is seen that the response of the system considering the individual effect of TCSC and RFB is improved in respect of $T_s$, $O_s$ and $U_s$ as compared to without including the effect of TCSC and RFB unit for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$. Hence, it can be concluded from Table 6 that our proposed techniques perform outstanding incorporating with RFB and TCSC.

**B. BILATERAL BASED TRANSACTION (BBT)**

In BBT, Discos have a power contract with Gencos in their same or different control area. It is presumed that each Discos demand of 0.05 p.u.MW ($\Delta P_{L1} = \Delta P_{L2} = \Delta P_{L3} = \Delta P_{L4} = 0.05$ p.u.MW) power in both areas and hence, the entire load disturbance in area 1 is ($\Delta P_{d1} = 0.1$ p.u.MW) and in area 2 is ($\Delta P_{d2} = 0.1$ p.u.MW). All Gencos participated in AGC task can be represented by below DPM.

$$DPM = \begin{bmatrix} 0.2 & 0.10 & 0.3 & 0.00 \\ 0.2 & 0.25 & 0.1 & 0.16 \\ 0.1 & 0.25 & 0.2 & 0.16 \\ 0.2 & 0.10 & 0.2 & 0.36 \\ 0.1 & 0.20 & 0.1 & 0.16 \\ 0.1 & 0.10 & 0.1 & 0.16 \end{bmatrix}$$ (41)

The response of the system under BBT is given in Figure 11 (a-c) and the overall comparison of mentioned techniques in terms of $T_s$, $O_s$ and $U_s$ for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively is shown in Table 7. When comparing the settling time ($T_s$) of Fig 11 (a-c), the proposed I-FDO tuned FOI-PD controller has quickly reached the $T_s$ as 12.63%, 34.56% and 23.67% is compared to FOI-PD controller tuned with FA algorithm. When comparing the undershoot ($U_s$) of FA tuned FOI-PD controller, the proposed FOI-PD controller optimized with I-FDO techniques has efficiently reduced the $U_s$ as 78.30%, 45.67% and & 49.30% as compared to FA tuned FOI-PD controller tuned with FA algorithm. When comparing the overshoot ($O_s$) of Fig 11 (a-c), the proposed I-FDO optimized FOI-PD controller has efficiently reduced the overshoot as 56.03%, 78.06% and 48.69% is compared to FOI-PD controller tuned with FA algorithm. Hence, it can be inferred, that I-FDO based FOI-PD controller has better performance in terms of $T_s$, $O_s$ and $U_s$ for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ respectively as compared to FOPID controller optimized with FDO/TLBO/FA.

**C. CONTRACT VIOLATION BASED TRANSACTION (CVBT)**

In contract violation, Discos need more power than a specified contract which is not contracted out to any Gencos. This uncontracted power must be provided by Gencos to Discos in the similar area. In this scenario, a poolco based transaction is again considered with modification of 10% excess uncontracted power i.e ($\Delta P_{uc1} = 0.1$ p.u.MW) demanded by Disco-1 from area-1 and ($\Delta P_{uc2} = 0.0$ p.u.MW) from area 2. So, the total load demand ($\Delta P_{d1}$) in Area 1 = $\Delta P_{L1} + \Delta P_{L2} + \Delta P_{uc1} = 0.1 + 0.1 + 0.1 = 0.3$ p.u.MW. Whereas $\Delta P_{d2} = \Delta P_{L3} + \Delta P_{L4} + \Delta P_{uc2} = 0.1 + 0.1 + 0 = 0.2$ p.u.MW.

![Figure 12. Results under contract violation based transaction for (a) $\Delta f_1$, (b) $\Delta f_2$ and (c) $\Delta P_{tie}$.](image-url)
FIGURE 13. The response of the system with a variation of (a) R with $\Delta f_1$ b) R with $\Delta f_2$ c) R with $\Delta P_{tie}$ (d) Tg with $\Delta f_1$ e) Tg with $\Delta f_2$ (f) Tg with $\Delta P_{tie}$ (g) $T_r$ with $\Delta f_1 \Delta P_{tie}$.
TABLE 7. Comparison performance under BBT in terms of $T_s$, $O_s$ and $U_s$.

| Controller with Algorithms | $T_s$ (Settling time) | $O_s$ (Overshoot) | $U_s$ (Undershoot) |
|----------------------------|-----------------------|-------------------|--------------------|
| FOI-PD (FDO)              | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ |
| 17.6                      | 18.3                  | 11.7              | 0.000085           | 0.000257           | 0.00171         | -0.00410         | -0.00060         | -0.0151          |
| FOI-PD (FDO)              | 18.2                  | 19.4              | 12.8              | 0.000168           | 0.0000326         | 0.00262         | -0.00117         | -0.00080         | -0.0151          |
| FOI-PD (TLBO)             | 21.1                  | 19.9              | 13.2              | 0.000151           | 0.0000276         | 0.00429         | -0.00137         | -0.00098         | -0.0180          |
| FOI-PD (FA)               | 23.2                  | 12.1              | 14.1              | 0.000225           | 0.0000765         | 0.00741         | -0.00149         | -0.00111         | -0.0195          |
| TID (hTB0-PS)[12]         | 27.99                 | 26.17             | 12.8              | 0.0599             | 0.05910           | 0.00116         | -0.39500         | -0.42160         | -0.0123          |
| MID (hDE-PS) [20]         | 20.15                 | 18.58             | 14.22             | 0.00010           | 0.001600          | 0.00090         | -0.00100         | -0.00150         | -0.0800          |

TABLE 8. Comparison performance under contract violation in terms of $T$.

| Controller with Algorithms | $T_s$ (Settling time) | $O_s$ (Overshoot) | $U_s$ (Undershoot) |
|----------------------------|-----------------------|-------------------|--------------------|
| FOI-PD (FDO)              | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ |
| 11.00                     | 13.8                  | 12.80             | 0.000000           | 0.00273           | 0.000000         | -0.00097         | -0.00681         | -0.00097         |
| FOI-PD (FDO)              | 11.09                 | 13.9              | 13.30             | 0.000000           | 0.00335           | 0.000021         | -0.00088         | -0.00685         | -0.00049         |
| FOI-PD (TLBO)             | 16.4                  | 17.3              | 14.47             | 0.000631           | 0.00442           | 0.000028         | -0.00468         | -0.00812         | -0.00052         |
| FOI-PD (FA)               | 16.9                  | 17.7              | 15.36             | 0.000241           | 0.00473           | 0.000060         | -0.00448         | -0.00823         | -0.00053         |
| TID (hTB0-PS)[12]         | 24.50                 | 24.62             | 18.78             | 0.023100           | 0.03520           | 0.039000         | -0.54960         | -0.68980         | -0.07590         |
| MID (hDE-PS) [20]         | 24.31                 | 22.72             | 19.05             | 0.001600           | 0.00210           | 0.001000         | -0.00234         | -0.00956         | -0.01890         |

TABLE 9. Results of Sensitivity analysis for proposed I-FDO based FOI-PD controller considering PBT.

| Parameter | % Change | $T_s$ (Settling time) | $O_s$ (Overshoot) | $U_s$ (Undershoot) |
|-----------|----------|-----------------------|-------------------|--------------------|
|           |          | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ | $\Delta f_1$ $\Delta f_2$ $\Delta P_{ne}$ |
| R         | +25      | 6.78                  | 6.38              | 12.72              | 0.00064           | 0.00068           | 0.000323         | -0.00610         | -0.00240         | -0.00315         |
|           | -25      | 7.90                  | 8.01              | 12.73              | 0.00054           | 0.00047           | 0.000276         | -0.00600         | -0.00236         | -0.00313         |
| Tg        | +25      | 6.74                  | 6.38              | 13.01              | 0.00094           | 0.00037           | 0.000296         | -0.00693         | -0.00713         | -0.00489         |
|           | -25      | 7.91                  | 8.03              | 13.03              | 0.00098           | 0.00030           | 0.000289         | -0.00678         | -0.00913         | -0.00482         |
| Tt        | +25      | 6.14                  | 6.10              | 12.80              | 0.00083           | 0.00014           | 0.000310         | -0.00731         | -0.00780         | -0.00361         |
|           | -25      | 8.10                  | 7.80              | 12.79              | 0.00075           | 0.00017           | 0.000311         | -0.00725         | -0.00740         | -0.00361         |
| T12       | +25      | 6.17                  | 6.09              | 13.10              | 0.00063           | 0.00032           | 0.000315         | -0.00623         | -0.00830         | -0.00251         |
|           | -25      | 8.10                  | 7.82              | 13.08              | 0.00061           | 0.00031           | 0.000316         | -0.00618         | -0.00840         | -0.00257         |

Under contract violation, the dynamic profile of the system is shown in Figure 12 (a)-(c). From Table 8 it can be seen that FOI-PD controller with I-FDO tuned method superiorly performs in respect of $T_s$ by (10.34%, 9.54%, and 31.76%), $O_s$ by (78.77%, 57.76%, and 89.36%) and $U_s$ by (14.56%, 3.09%, and 19.56%) for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{ne}$ respectively as compared to FOI-PD controller tuned with FDO optimization techniques. Similarly, when comparing the overshoot ($O_s$) of Fig 12 (a-c) , the proposed I-FDO optimized FOI-PD controller has efficiently reduced the overshoot as 76.22%, 28.16% and 83.32% is compared to FOI-PD controller tuned with FA algorithm. The settling time of I-FDO optimized FOI-PD controller is improved by (39.12%, 12.08%, and 41.63%) for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{ne}$ respectively as compared to FOI-PD controller tuned with FA algorithm.

D. SENSITIVITY ROBUSTNESS ANALYSIS

Sensitivity analysis is performed to examine the uncertainty of power system in dynamic behaviour under a nominal condition concerning a certain change in a few of the essential parameters of the system. The purpose of this analysis is to study the robust performance of the controller by varying system parameters. This paper has carried out a sensitivity analysis of the some of the system parameters with nominal value by varying the turbine time constant ($T_g$), synchronizing coefficient ($T_{12}$), droop constant (R) and governor time constant ($T_t$) in the range of ±(25%). The results obtained by varying system parameters in the range of ±(25) % are shown in Figure 13 (a) - (g). The comparison of various parameters in terms of settling time, undershoot and overshoot with a change of ±(25) % from their nominal values are provided.
The efficacy of I-FDO based FOI-PD controller exhibits the reset when the system parameters or load conditions changed. Table 9. From Fig 13 (a-g), it can be observed that the response of the system plotted for various parameters are almost similar to the nominal values which show that the proposed I-FDO based FOI-PD controller provides a robust performance within a range of ±(25)% of the system parameters. Furthermore, the optimized values of the proposed controller don’t need to be re-tuned for wide-ranging parameters attained at nominal load with nominal parameters.

VI. CONCLUSION
In this paper, FOI-PD controller is designed and developed for AGC of two areas, six-generation units under the deregulated environment with the inclusion of various non-linearities including GDB, BD, TD and GRC. Improved–Fitness Dependent Optimizer (I-FDO) meta-heuristic algorithm is used to optimize the parameters of the proposed controller. In addition, the dynamic response of the system is improved by Incorporating RFB in each area and TCSC in series with the tie-lines. From simulation results, it can be observed that I-FDO based tuned FOI-PD controller as compared to hDE-PS based MID controller provides a significant improvement of 76.85%, 26.42% and 21.43% respectively as compared hTLBO-PS based TID controller. Finally, the improved performance within a range of ±(25)% of the system parameters. Table 11. Values of I-FDO parameters.

Table 10. Parameter setting for two-area interconnected power system [39].

| Parameters | Values | Parameters | Values | Parameters | Values |
|------------|--------|------------|--------|------------|--------|
| f1 and f2 | 0.4312 p.u. MW/Hz | Rci, Rcz, Rsys, Rhyd, Rgi, Rw | 2.4 Hz/p.u | Tm | 0.08 s |
| T1 | 0.3 s | Kf | 0.3 | Tt | 10 s |
| Kp | 68.956 | Tp | 11.49 s | Tt2 | 0.0453 |
| a1 | -1 | Tg, Ty | 1 s | Tns | 5 s |
| b1 | 28.75 s | Tg, Ty, TDC | 0.2 s | x1 | 0.6 s |
| Kp DC | 0.130438 | KDC, xDC | 1 | b0 | 0.05 s |
| Kp1 | 0.543478 | T1 | 0.01 s | Tr | 0.23 s |
| Kp2 | 1.25 | Kp2 | 1.4 | Tp1 | 0.6 |
| Kp3 | 0.041 | KFBD | 0.67 | TpFBD | 0 s |
| Kp4 | 0.85 | Kp4 | 0.8243 | |
| Kp5 | 0.8 | |

under a deregulated environment promptly with sustained oscillations.

APPENDIX
See Table 10 and 11.

REFERENCES
[1] K. S. Rajesh, S. S. Dash, and R. Rajagopal, “Hybrid improved firefly-pattern search optimized fuzzy aided PID controller for automatic generation control of power systems with multi-type generations,” Swarm Evol. Comput., vol. 44, pp. 200–211, Feb. 2019.
[2] Y. Arya, “Improvement in automatic generation control of two-area electric power systems via new fuzzy aided optimal PID–FOI controller,” ISA Trans., vol. 80, pp. 475–490, Sep. 2018.
[3] Z. Bingul and O. Karahan, “A novel performance criterion approach to optimum design of PID controller using cuckoo search algorithm for AVR system,” J. Franklin Inst., vol. 355, no. 13, 2018, pp. 534–559. [Online]. Available: https://doi.org/10.1016/j.jfranklin.2018.05.056.
[4] N. Mahendra, C. K. Shiva, and V. Mukherjee, “TCSC based automatic generation control of deregulated power system using quasi-oppositional harmony search algorithm,” Eng. Sci. Technol. Int. J., vol. 20, no. 4, pp. 1380–1395, 2017.
[5] A. Pappachen and A. P. Fathima, “NERC’s control performance standards-based load frequency controller for a multi-area deregulated power system with ANFIS approach,” Ain Shams Eng. J., vol. 9, no. 4, pp. 2399–2414, 2017.
[6] U. Raj and R. Shankar, “Deregulated automatic generation control using novel opposition-based interactive search algorithm cascade controller including distributed generation and electric vehicle,” Iranian J. Sci. Technol., Trans. Electr. Eng., vol. 44, no. 3, pp. 1233–1251, Sep. 2020.
[7] A. Daraz, S. A. Malik, and A. ul Haq, “Review of automatic generation control for multi-source interconnected power system under deregulated environment,” in Proc. Int. Conf. Power Gener. Syst. Renew. Energy Technol. (PGSRET), Islamabad, Pakistan, Sep. 2018, pp. 1–5.
[8] V. Donde, M. A. Pai, and I. A. Hiskens, “Simulation and optimization in an AGC system after deregulation,” IEEE Trans. Power Syst., vol. 16, no. 3, pp. 481–491, Aug. 2011.
[9] K. P. S. Parmar, S. Majhi, and D. P. Kothari, “LFC with ANFIS approach,” J. Franklin Inst., vol. 355, no. 13, 2018, pp. 534–559. [Online]. Available: https://doi.org/10.1016/j.jfranklin.2018.05.056.
[10] A. Demiroren and H. L. Zeynelgil, “GA application to optimization of AGC in three-area power system after deregulation,” Int. J. Electr. Power Energy Syst., vol. 29, no. 3, pp. 230–240, Mar. 2007.
J. Morsali, K. Zare, and M. Tarafdar Hagh, “A novel dynamic model
P. C. Pradhan, R. K. Sahu, and S. Panda, “Firefly algorithm optimised
H. M. Hasanien, “Whale optimisation algorithm for automatic genera-
R. Shankar, A. Kumar, U. Raj, and K. Chatterjee, “Fish algorithm-
based automatic generation control of multi-area interconnected power
system with FACTS and AC/DC links in deregulated power environment,”
Int. Trans. Electr. Energy Syst., vol. 29, pp. 1–25, Jan. 2019.
C. K. Shiva and V. Mukherjee, “A novel quasi-optimisation harmony
search algorithm for AGC optimization of three-area multi-unit power
system after deregulation,” Eng. Sci. Technol., Int. J., vol. 19, no. 1,
p. 395–420, Mar. 2016.
R. J. Abraham, D. Das, and A. Patra, “Effect of TCPS on oscillations in
tie-power and area frequencies in an interconnected hydrothermal power
system,” IET Gener., Transmiss. Distrib., vol. 1, no. 4, pp. 632–639, 2007.
S. Padhan, R. K. Sahu, and S. Panda, “Automatic generation control with
thyristor controlled series compensator including superconducting mag-
netic energy storage units,” Ain Shams Eng. J., vol. 5, no. 3, pp. 759–774,
Sep. 2014.
M. Ponnuasamy, B. Banakara, S. S. Dash, and M. Veerasamy, “Design
of integral controller for load frequency control of static synchronous
series compensator and capacitive energy source based multi area system
consisting of diverse sources of generation employing imperialistic compe-
tition algorithm,” Int. J. Electr. Power Energy Syst., vol. 73, pp. 863–871,
Dec. 2015.
P. C. Pradhan, R. K. Sahu, and S. Panda, “Firefly algorithm optimized
fuzzy PID controller for AGC of multi-area multi-source power sys-
tems with UPFC and SMES,” Eng. Sci. Technol., Int. J., vol. 19, no. 1,
p. 338–354, Mar. 2016.
Y. Arya and N. Kumar, “Optimal AGC with redox flow batteries in multi-
area restructured power systems,” Eng. Sci. Technol., Int. J., vol. 19, no. 3,
p. 1145–1159, Sep. 2016.
R. K. Sahu, T. S. Gorripotu, and S. Panda, “A hybrid DE–PS algorithm for
load frequency control under deregulated power system with UPFC and
RFB,” Ain Shams Eng. J., vol. 6, no. 3, pp. 893–911, Sep. 2015.
I. A. Chidambaram and B. Paramasivam, “Optimized load-frequency sim-
ulation in restructured power system with redox flow batteries and interline
power flow controller,” Int. J. Electr. Power Energy Syst., vol. 50, pp. 9–24,
Sep. 2013.
T. S. Gorripotu, R. K. Sahu, and S. Panda, “AGC of a multi-area power
system under deregulated environment using redox flow batteries and interline
power flow controller,” Eng. Sci. Technol., no. 18, no. 4, pp. 555–578,
2015.
K. Zare, M. T. Hagh, and J. Morsali, “Effective oscillation damping of an
interconnected multi-source power system with automatic generation con-
trol and TCSC,” Int. J. Electr. Power Energy Syst., vol. 65, pp. 220–230,
Feb. 2015.
M. Deepak and R. J. Abraham, “Load following in a deregulated power
system with thyristor controlled series compensator,” Int. J. Electr. Power
Energy Syst., vol. 65, pp. 136–145, Feb. 2015.
E. Sahin, “Design of an optimized fractional high order differential feed-
back controller for load frequency control of a multi-area multi-source power
system with nonlinearity,” IEEE Access, vol. 8, pp. 12327–12342,
2020, doi: 10.1109/ACCESS.2020.2966261.
H. M. Hasanien, “Whale optimisation algorithm for automatic genera-
tion control of interconnected modern power systems including renew-
able energy sources,” IET Gener., Transmiss. Distrib., vol. 12, no. 3,
p. 607–614, Feb. 2018.
W. Tasnin and L. C. Saikia, “Maiden application of an sine–cosine algo-
rithm optimised FO cascade controller in automatic generation control of
multi-area thermal system incorporating dish-stirling solar and geothermal
power plants,” IET Renew. Power Gener., vol. 12, no. 5, pp. 585–597,
Apr. 2018.
Y. Arya, “A novel CFFOFI-FOPID controller for AGC performance
enhancement of single and multi-area electric power systems,” ISA Trans.,
vol. 100, pp. 126–135, May 2020.
J. Morsali, K. Zare, and M. Tarafdar Hagh, “A novel dynamic model and
control approach for SSCS to contribute effectively in AGC of a
deregulated power system,” Int. J. Electr. Power Energy Syst., vol. 95,
p. 239–253, Feb. 2018.
A. Daraz, S. A. Malik, H. Mokhli, I. U. Haq, G. F. Laghari,
and N. N. Mansor, “Fitness dependent optimizer-based automatic
generation control of multi-source interconnected power system with
non-linearities,” IEEE Access, vol. 8, pp. 100089–101003, 2020,
doi: 10.1109/ACCESS.2020.2998127.
G. Chen, Z. Li, Z. L. Zhang, and S. Li, “An improved ACO algorithm
optimized fuzzy PID controller for load frequency control in multi area
interconnected power systems,” IEEE Access, vol. 8, pp. 6429–6447,
2020, doi: 10.1109/ACCESS.2020.2960380.
H. M. Hasanien and A. A. El-Fergany, “Salp swarm algorithm-based
optimal load frequency control of hybrid renewable power systems with
communication delay and excitation cross-coupling effect,” Elec. Power
Syst. Res., vol. 176, Nov. 2019, Art. no. 105938.
V. Veerasamy, N. I. A. Wahab, R. Ramachandran, M. L. Othman,
H. Hizam, A. X. R. Idrayayaraj, J. M. Guerrero, and J. S. Kumar, “A Hankel
matrix based reduced order model for stability analysis of hybrid power
system using PSO-GSA optimised cascade PI-PD controller for automatic
load frequency control,” IEEE Access, vol. 8, pp. 71422–71446, 2020,
doi: 10.1109/ACCESS.2020.2987387.
P. C. Sahu, R. C. Prusty, and S. Panda, “Improved-GWO designed FO
based type-II fuzzy controller for frequency awareness of an AC microgrid
under plug in electric vehicle,” J. Ambient Intell. Hum. Comput., 2020,
doi: 10.1007/s12652-020-02260-z.
A. Prakash, S. Murali, R. Shankar, and R. Bhushan, “HVDC tie-link
modeling for restructured AGC using a novel fractional order cascade
controller,” Electr. Power Syst. Res., vol. 170, pp. 244–258, May 2019,
doi: 10.1016/j.epsr.2019.01.021.
Z. Bingu and O. Karahan, “Comparison of PID and FOPID controllers
controlled by PSO and ABC algorithms for unstable and integrating sys-
tems with time delay,” Optim. Control Appl. Methods, vol. 39, no. 4,
p. 1431–1450, Jul. 2018.
D. Sain, S. K. Swain, A. Saha, S. K. Mishra, and S. Chakraborty,
“Real-time performance analysis of FOI-PD controller for twin rotor
MIMO system,” IEEE Tech. Rev., vol. 36, no. 6, pp. 547–567, Nov. 2019,
doi: 10.1108/0264662018.1528190.
V. Rajinikanth and K. Latha, “I–P/D controller tuning for unstable system
using bacterial foraging algorithm: A study based on various error crite-
rion,” Appl. Comput. Intell. Soft Comput., vol. 2012, pp. 1–10, Jan. 2012,
doi: 10.1155/2012/329389.
S. M. Nosratabadi, M. Bornapour, and M. A. Gharaei, “Grasshopper
optimization algorithm for optimal load frequency control considering pre-
dictive functional modified PID controller in restructured multi-resource
multi-area power system with redox flow battery units,” Control Eng.
Pract., vol. 89, pp. 204–227, Aug. 2019.
M. Abdullah and T. Ahmed, “Fitness dependent optimizer: Inspired by
the bee swarming reproductive process,” IEEE Access, vol. 7,
p. 43473–43486, 2019.
D. S. Abdul-Minaam, W. M. E. S. Al-Mutairi, M. A. Awad,
and W. H. El-Ashmawi, “An adaptive fitness-dependent optimizer for the one-
dimensional bin packing problem,” IEEE Access, vol. 8, pp. 97595–97974,
2020, doi: 10.1109/ACCESS.2020.2985752.
D. A. Mohammed, S. A. M. Saed, and T. A. Rashid, “Improved fitness-
dependent optimizer algorithm,” IEEE Access, vol. 8, pp. 19074–19088,
2020, doi: 10.1109/ACCESS.2020.2968064.

AMIL DARAZ was born in Pakistan, in 1989. He received the B.E. degree in electronics engi-
neering from COMSATS University Islamabad, Pakistan, in 2012, and the M.S. degree in power
and control engineering from International Islamic University Islamabad (IIU), Pakistan, where he is
currently pursuing the Ph.D. degree in electrical engineering. His research interests include control
systems, power system operation and control, and the optimization of solving nonlinear problems.
SUHEEL ABDULLAH MALIK (Member, IEEE) received the B.E. degree in electrical & electronics from Bangalore University, Bengaluru, India, in 1997, the M.S. degree in electronic engineering from Muhammad Ali Jinnah University (MAJU), Pakistan, and the Ph.D. degree in electronic engineering from International Islamic University Islamabad (IIUI), Pakistan. Since 2007, he has been with IIUI, where he is currently serving as the Chairman/Associate Professor for the Department of Electrical Engineering (DEE). He has authored more than 30 journal and conference publications. His research interests include control systems, the numerical investigation of nonlinear problems, and the application of nature-inspired metaheuristic algorithms for solving nonlinear problems. He is also the reviewer of some journals and has served as a member/chair for some international conferences.

HAZLIE MOKHLIS (Senior Member, IEEE) received the B.Eng. and M.Eng.Sc. degrees in electrical engineering from the University of Malaya (UM), Malaysia, in 1999 and 2002, respectively, and the Ph.D. degree from The University of Manchester, Manchester, U.K., in 2009. He is currently a Professor with the Department of Electrical Engineering, University of Malaya (UM), and also the Head of the UM Power and Energy System (UMPES) research. His research interests include fault location, distribution automation, power system protection, and renewable energy. He is also a Chartered Engineer in the U.K. and a Professional Engineer in Malaysia.

IHSAN UL HAQ (Member, IEEE) received the M.S. degree in electronics from Quad-i-Azam University, Islamabad, Pakistan, in 2004, and the Ph.D. degree in electronics and information engineering from Beihang University, Beijing, China, in 2009. He has been an Associate Professor with the Department of Electrical Engineering, Faculty of Engineering and Technology, International Islamic University Islamabad, Islamabad, Pakistan. He has supervised 25 M.S. and 6 Ph.D. students. He has published 35 journal and 15 proceeding articles. His research interests include image processing, hyperspectral image processing, medical image processing, signal processing, deep learning, and meta-heuristic techniques.

FARHAN ZAFAR was born in Pakistan, in 1975. He received the M.Sc. degree and the M.Sc. degree in physics from the University of Sindh, Jamshoro, Pakistan, in 1999 and 2006, respectively, and the M.S. degree in electronic engineering from International Islamic University Islamabad (IIUI), Pakistan, in 2013, where he is currently pursuing the Ph.D. degree in electrical engineering. His research interests include control systems, under actuated systems, and the optimization and application of nature-inspired metaheuristic algorithms for solving nonlinear problems.

NURULAFIQAH NADZIRAH MANSOR (Member, IEEE) received the B.Eng. degree from Vanderbilt University, USA, in 2008, the M.Eng. degree in power system engineering from the University of Malaya (UM), Malaysia, in 2013, and the Ph.D. degree from The University of Manchester, U.K., in 2018. From 2008 to 2014, she was a Process Engineer with Texas Instruments Malaysia Sdn. Bhd. She is currently a Senior Lecturer with UM. Her research interests include distribution system modeling and optimization, distribution system planning and operation, the integration of renewable energy, and smart grids.