Design a novel fractional order controller for smart microgrid using multi-agent concept

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Abstract

A microgrid system deploys various components such as solar, wind, diesel generator, fuel cell, flywheel, aqua electrolyser, ultra-capacitor, and storage batteries etc. A microgrid system operates through a centralized control system that works on the current condition of the sources and loads. The status of renewable and non renewable sources as well as load is obtained through the multi-agent system (MAS) to regulate a controllable source as per the deficit between demand and supply. The message interchange in the MAS is considered to be compatible with a user data gram protocol/internet protocol-based network. The present study implements the application of MAS to control a smart microgrid in a Matlab/simulation environment. The simulation results reveal that the present MAS can provide the persistent transition from microgrid when disturbances occur. This indicates the effectiveness of MAS as a technology for controlling the microgrid process. A fractional order (FO) based controller is employed and its parameters are optimized through gravitational search algorithm. The FO controller demonstrates enhanced performance in contrast to the integer order controller under linear as well as nonlinear operating conditions. Furthermore, the proposed controller additionally exhibits its superiority in terms of robustness against parameter changes and disconnection of various components.

Keywords Fractional PID controller · Microgrid · Renewable energy · Multi agent system · GSA

1 Introduction

For the recent hundreds of years, Fossil fuel is the principle source to create power. As we realize that fossil fuel isn't accessible in plenteous. It gives the trouble flag to create and utilize new sustainable power sources. Energy condition in developing countries is exceptionally crucial and most of the power units are operated by natural gas or other natural resources. Therefore, the natural reserve has tumbled to its impediments and it might keep going for further couple of years. So the age of power from elective sources has turned into the need for world. One of the essential requirements for financial advancement in any country on the planet is the accessibility of reliable power supply system with low carbon impression levels. Microgrid system which utilizes sustainable sources may be a

compelling arrangement of this power emergency. Solar and wind energies are considered as the most suitable solution to the present situation. As both are pollution free and available in abundance. Renewable energy sources nowadays play an important role in eco friendly electric power generation systems. Microgrid is a viable solution to incorporate renewable sources into distributed network [1]. Besides controlling of non controllable sources is the challenging assignment. Inferable from the presence of non controllable power sources, there is dependably an issue of demand and supply in a microgrid. The solution for such problem, one is to furnish microgrid with diesel generator/gas alternator/battery/energy component to cross over any barrier between the power created by the sustainable sources and loads [2]. However the working expense and emission level of such system are altogether

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high contrasted with environmentally friendly power sources. Hence microgrid should employ control schemes to resolve the power quality issues like stability due to the practical varying input energy and load while augmenting the utilization of the sustainable resources. The performance of microgrid is influenced by the controller parameters and indulgence of renewable energy sources. Recently, optimal control of microgrid has become the challenging field in research area. Various optimization search methods like genetic algorithm [3], particle swarm intelligence [4], self-organizing migrating algorithm [5], and electromagnetism algorithm [6] have been used for controller tuning in microgrid to suppress interruption. Intelligent frequency control techniques using fuzzy logic too shows tremendous improvement in system performance against load changes and disturbances [7]. Research based on fractional calculus has been gaining attention due to its flexibility and effective solution to the control design application [8, 9]. Podlubny [10] proposed a fractional controller where the fractional integral and fractional differential terms with controller gain were used. Since then, there is lot of research work has been done on fractional order PIDs (FOPIDs) and employed in numerous domains [11–14]. Various research papers for tuning of FOPID can be found in the literature such as Ziegler–Nichols-type rules [15, 16], optimal tuning [17], tuning for robustness control [18, 19], auto-tuning [20, 21], and tuning based on reducing the number of parameters [22]. In the same line, various advanced control strategy based on FOPID controllers were proposed. For example, Smith indicators structures [23], internal mode controller [24, 25], hybrid control [26], gain scheduling [27] and many others. Latest surveys in the evolution of FOPIDs can be viewed in [28–31]. Furthermore, some usages of fractional calculus are also reported in field of Biomedical [32], electro-hydraulic system [33], robotic manipulators [34, 35], Pneumatic position servo system [36], Industrial process [37] and water level control [38]. Incorporation of computational intelligence with fractional calculus has led to considerable attention of many researchers in the field of power system [39].

The fundamental operation of any power system depends upon control design. The control design comprising of hardware and software units is used for communicating system status and control signals. In ordinary electric power system, this is executed by Supervisory Control and Data Acquisition (SCADA) system. In recent time, the controlling and supervision activity of electric power system are done by automated agent system, which is commonly known as a multi-agent system. A MAS is a combination of few agents working together to achieve the objective of the system. The MAS has now turned into

a useful tool in creating complex frameworks owing to the properties of autonomy, sociality, reactivity and proactivity. The MAS is self-governing in the sense that they work without human interventions. The MAS also has social ability as they are associated with different agents by means of some sort of operator communication protocol. The agents see and respond to their conditions. Finally, the MAS are proactive because they can show objective oriented behaviour by taking activities. The exhaustive details of centralized microgrid control operation of multi agent system (MAS) can be found in [40, 41]. A centralized microgrid control system is economical because it reduces the number of individual controller for each energy storage system and hence improves the performance which declines due to complex loop connections. Further, there is no need of tuning each controller separately.

This research work has proposed a centralized fractional order frequency controller based on the concept of MAS. Different components of microgrid interact through user data gram protocol/internet protocol (UDP/IP). The five parameters of FOPID controller, namely proportional gain constant, integral time constant, differentiator time constant, integral order, and differentiator order has been considered for tuning. The proposed controller parameters have been optimized by gravitational search algorithm (GSA). Moreover, GSA has been successfully implemented in many fields like AGC of interconnected power systems [42] and in optimal controlling of DC microgrid [43]. Since it needs just two parameters and has capability to discover global optimum, therefore it gives better outcomes when compared with other nature enlivened algorithms. Inferences from the above points of interest make this research work actualize the GSA for tuning the parameters of controller. The outcomes as far as performance indices, robustness against parametric variations, nonlinearities and disconnection of different components exhibit the viability of FOPID controller when contrasted with standard FOPI/PID/PI controller.

This study is structured as in the subsequent way. Section 2 presents details the components of microgrid model. Section 3 briefly introduces the FO controller. Sect. 4 describes the optimization technique. Objective function and simulation results of FOPID controller structure along with FOPI/PID/PI are presented in Sect. 5 followed by conclusion in Sect. 6.

2 Microgrid central controller (MGCC)

The schematic of proposed microgrid with central controller is represented in Fig. 1. In this study, microgrid consists of WTG (0.5 p.u), SPV (0.15 p.u), AE (0.002 p.u),

Fig. 1 Block diagram of smart microgrid

FESS (0.01 p.u), UC (0.7 p.u), BESS (0.003 p.u), DEG (0.003 p.u), and FC (0.01 p.u). This study considered $(1 - K_n)$ fraction of total power of wind source and solar source is used by AE and rest of power given to microgrid where K_n is equal to 0.6. The total load is estimated to be 1.0 p.u. under nominal circumstances and isolated microgrid is operated in 100% self sufficient mode. To accomplish the main objective of frequency control, we have employed the Multi Agent System concept into the microgrid. Each component of microgrid has been considered as an agent with IP address as given in Table 1. The designated IP address assists the server utilized as microgrid central controller (MGCC) to create a bidirectional data path between agents and the MGCC. Information collection from each load and source is achieved through multiple sensor and internet. MGCC works as a server, which gets the information from each source/load and generates the appropriate control

signal according to the available information. The MGCC also maintains the status of loads as well as sources. The UDP/IP is used for information exchange between MGCC and the components of microgrid. Each agent sends and receives information through UDP send and UDP receive module. UDP send module conveys an input vector as a UDP message over an IP network. It also contains the information regarding receiver IP address as well as port address by which information will pass to the concerned agent. In the same way UDP receiver module contains the information regarding sender IP address as well as port address by which information are to be obtained by the receiving agent. The observed data are detected utilizing reasonable sensors and changed over to a digital data by analog to digital (A/D) converters and transmitted to the communication channel. On the other hand than a digital to analog (D/A) converter will interpret the information conveyed by the MGCC to the agents.

Table 1 IP addresses of different agents of microgrid system

Microgrid component as agent	Sending port address	Receiving port address
System agent	10.64.5.601/40101	–
Load agent	10.64.5.601/40102	–
Solar photo voltaic system agent	10.64.5.601/40103	–
Wind turbine generator agent	10.64.5.601/40104	–
Aqua Electrolyser (AE)	10.64.5.601/40301	–
<i>Control unit</i>		
Fuel cell (FC)	10.64.5.601/40401	–
Diesel engine generator (DEG)	10.64.5.601/40501	10.64.5.601/40203
Flywheel energy storage system (FESS)	10.64.5.601/40601	10.64.5.601/40204
Ultra capacitor (UC)	10.64.5.601/40701	10.64.5.601/40205
Battery energy storage system (BESS)	10.64.5.601/40801	10.64.5.601/40206

The values of parameters of the various sources of microgrid are presented in Table 2.

2.1 Wind turbine generator

The WTG is represented in first order transfer function as

$$G_{WTG}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} = \frac{P_{WTG}}{P_W} \quad (1)$$

Here all the non linearity is neglected.

2.2 Solar voltaic system

In this study, solar photovoltaic is realised by a first order transfer function as [2]

$$G_{PV} = \frac{K_{PV}}{1 + sT_{PV}} \quad (2)$$

2.3 Ultra capacitor

Ultra-capacitors are used here as an energy storage device. It accumulates energy by polarizing the electrolytic solution as no chemical reaction takes place. Thus ultra capacitors can process thousands of charging cycles without any deterioration. They have high energy density due to large surface area of micro-porous carbon and small charge separation (10 angstroms) between electrodes. Ultra capacitor generates capacitances in range of thousands of farad at 2.5 V. The transfer function of ultra capacitor is given as [39]

$$G_{UC}(s) = \frac{K_{UC}}{1 + sT_{UC}} \quad (3)$$

2.4 Diesel engine power generation system

In general, renewable energy sources are stochastic in nature; therefore it is essential to incorporate conventional energy sources to deliver a consistent power output. Diesel generator works as substantial source of power. The design

specification of DG systems is considered according to the requirement of demand and supply. The diesel engine generator is expressed in first order transfer function as [2]

$$G_{DEG}(s) = \frac{K_{DEG}}{1 + sT_{DEG}} \quad (4)$$

2.5 Fuel cell

It is an electrochemical apparatus to generate electricity by mixing hydrogen fuel with oxygen. Fuel cells produce power without combustion. It has high efficiency due to direct conversion of fuel into electricity. Due to non movable parts, fuel cell is free from noise and pollutant. The fuel cell is expressed in first order transfer function as [2]

$$G_{FC}(s) = \frac{K_{FC}}{1 + sT_{FC}} \quad (5)$$

2.6 Aqua electrolyser

Aqua electrolyser is basically used to absorb the fluctuation produced due to stochastic nature of renewable energy sources. Secondly it is utilized to produce hydrogen which is needed in fuel cell to produce electricity. In aqua electrolyser, electrolysis process generates oxygen and hydrogen gases. The electrolysis unit consists of electrochemical cell, which has two electrodes separated by aqueous electrolyte. When current is passing through electrodes, decomposing of water takes place and produces hydrogen and oxygen gases. The amount of gases produced is directly proportional to current. The aqua electrolyser is expressed in first order transfer function as [39]

$$G_{AE}(s) = \frac{K_{AE}}{1 + sT_{AE}} = \frac{\Delta P_{AE}}{((\Delta P_{WTG} + \Delta P_{STPG})(1 - K_n))} \quad (6)$$

where $K_n = \frac{P_t}{P_{WTG} + P_{STPG}}$.
It uses $K_n = 0.6$.

2.7 Flywheel energy storage system

Flywheels are storage devices which can accumulate large amount of energy for short duration. Conceptually they should be in good match with wind turbine based micro system for smoothing out power fluctuations induced by the turbulence. The flywheel works in the following ways: when the wind power exceeds the load by some specific amount, the diesel generator is disconnected from the engine, which is then assumed to stop and flywheel continues to spin. The fly wheel accelerates/decelerates as energy is absorbed/transmitted back to the system. The fly wheel is expressed in first order transfer function as [39]

Table 2 Microgrid components with their nominal parameter values [39]

Block name	Nominal values
Wind turbine generator (WTG)	$K_{WTG} = 1, T_{WTG} = 1.5$
Solar photo voltaic system (SPV)	$K_{PV} = 1, T_{PV} = 1.8$
Diesel engine generator (DEG)	$K_{DEG} = 1/300, T_{DEG} = 2$
Battery energy storage system (BESS)	$K_{BESS} = -1/300, T_{BESS} = 0.1$
Flywheel energy storage system (FESS)	$K_{FESS} = -0.01, T_{FESS} = 0.1$
Ultra capacitor (UC)	$K_{UC} = -0.7, T_{UC} = 0.9$
Aqua electrolyser (AE)	$K_{AE} = -0.002, T_{AE} = 0.5$
Fuel cell (FC)	$K_{FC} = 0.01, T_{FC} = 4.0$

$$G_{FESS}(s) = \frac{K_{FESS}}{1 + sT_{FESS}} \quad (7)$$

2.8 Power and frequency deviation

With the objective to give substantial power, it is required that generated power must be efficacious controlled and provides balanced supply. Since renewable power sources are stochastic in nature. The power control strategies are required to mitigate the deviation of supply (P_s) and load (P_L). It is represented by the equation

$$\Delta P_e = P_s - P_L \quad (8)$$

P_s donates the total power generation by different components of microgrid and P_L denotes the demanded load. The net power deviation causes the system frequency variation. Thus system frequency variation f is considered as

$$\Delta f = \frac{\Delta P_e}{K_{sys} + D} \quad (9)$$

K_{sys} represents system frequency characteristics constant of the microgrid. Thus transfer function representation of microgrid is given by

$$G_{sys}(s) = \frac{\Delta f}{\Delta P_e} = \frac{1}{Ms + D} \quad (10)$$

Here M (inertia constant)/ D (damping constant) has been considered to 0.4/0.03 for the proposed study [39].

2.9 Uncontrollable energy sources

To study the impact of stochastic components (wind power, solar power, and load) on proposed micro grid's performance, following methodologies are adopted.

2.9.1 Modeling of wind speed

The practical wind speed is generated by auto-regressive and moving average (ARMA) time-series model [44].

The ARMA time series model y_t is given by

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \dots + \phi_n y_{t-n} + \beta_t - \varphi_1 \beta_{t-1} - \varphi_2 \beta_{t-2} - \dots - \varphi_m \beta_{t-m} \quad (11)$$

where ϕ_i ($i = 1, 2, \dots, n$), φ_j ($j = 1, 2, \dots, m$), and β_t are the autoregressive parameter, moving average parameter, and white noise process with zero mean individually.

This study, adopted the ARMA (3, 2) model for generating wind speed, [44]:

$$y_t = 1.7901y_{t-1} + 0.9087y_{t-2} + 0.0948y_{t-3} + \beta_t - 1.0929\beta_{t-1} + 0.2892\alpha_{t-3} \quad (12)$$

Here the average wind speed has been considered as 5.5 m/s between 0 and 41 s, 7.5 m/s between 41 and 81 s, and 4.5 m/s between 81 and 120 s.

2.9.2 Modeling of SPV radiation and load

The power output of the SPV can be represented by (13) and detailed description is given in [2]

$$P_{PV} = \eta S \phi \{1 - 0.005(T_a + 25)\} \quad (13)$$

Here considered area of the SPV array is equal to 4084 m² with 10% of conversion efficiency, ϕ (14) is the input radiation on the surface of the SPV cells and $T_a = 25$ °C is the surrounding temperature.

For the SPV radiation

$$\phi = 0.15h(t) - 0.043h(t - 40) + 0.08h(t - 80) + \phi_n(t), \quad (14)$$

$$\phi_n(t) \sim U(-0.1, 0.1),$$

For the demanded load

$$P_L = 0.91h(t) + 0.01h(t - 40) + 0.06h(t - 75) - 0.06h(t - 82) + NL, \quad (15)$$

$$NL \sim U(-0.05, 0.05)$$

Here $h(t)$ symbolizes Heaviside step function. Figure 2 demonstrates the randomly generated power output (P_w , P_{PV} , and P_L) and net power produced from renewable sources to microgrid.

3 Mathematical formulation of fractional order (FO) controller

3.1 Fractional calculus

This technique extends to the n th sorted consecutive differentiation/integration of arbitrary functions, possessing a real valued order. It is represented by an operator D^α and is mathematically expressed as [8, 9]

$$D^\alpha = \begin{cases} \frac{d}{dt^\alpha} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_0^t (d\tau)^{-\alpha} & \alpha < 0 \end{cases} \quad (16)$$

Here ' α ' is the order of integrator and differentiator. The few definitions employed in fractional calculus are:

1. Riemann–Liouville definition

$$D^\alpha f(t) = \frac{1}{\Gamma(n - \alpha)} \frac{d^n}{dt^n} \int_0^t \frac{f(\tau)}{(t - \tau)^{\alpha+1-n}} d\tau \quad (17)$$

$$\alpha \in \mathbb{R}^+, n \in \mathbb{Z}^+, n - 1 \leq \alpha < n$$

Fig. 2 Power profile of stochastic component and demand load

2. Caputo's definition

$$D^\alpha f(t) = \frac{1}{\Gamma(n-\alpha)} \int_0^t \frac{d^n f(\tau)}{(t-\tau)^{\alpha+1-n}} d\tau \quad (18)$$

$$\alpha \in \mathbb{R}^+, n \in \mathbb{Z}^+, n-1 \leq \alpha < n$$

3. Grunwald–Letnikov definition

$$D^\alpha f(t) = \lim_{h \rightarrow 0} \frac{1}{h^\alpha} \sum_{i=0}^{\left(\frac{t}{h}\right)} (-1)^i \binom{\alpha}{i} f(t-ih) \quad (19)$$

$$\text{where } \binom{\alpha}{0} = \frac{\Gamma(\alpha+1)}{\Gamma(i+1)\Gamma(\alpha-i+1)}; \binom{\alpha}{0} = 1 \text{ for } i=0,$$

Here h is step size.

3.2 Fractional order PID controller (FOPID)

The FOPID controller is realized using transfer function [10] as

$$C_{FOPID}(s) = K_p + K_i s^{-\lambda} + K_d s^\mu (\lambda > 0, \mu > 0) \quad (20)$$

This controller has five parameters i.e. three gain constants as K_p, K_i, K_d and two fractional operator λ and μ .

Actually, FO differentiator/integrator are linearised filter of infinite ranges [45]. Hence its band limited implementation is necessary for practical application. Rational approximations of fractional integrators and differentiators are done by Outstaloup's method and order of rational transfer function is decreased by sub-optimum H_2 approximation technique. For the selected frequency band (w_b, w_h), the transfer function of the filter is given as [46]

$$G_{Outstaloup_{filter}}(s) = K \prod_{l=-n}^n \frac{s + w'_l}{s + w_l} \quad (21)$$

Now zeros, poles, and gain of above filter can be computed as

$$w'_l = w_b (w_h/w_b)^{\frac{l+N+\frac{1(1-\beta)}{2}}{2N+1}} \quad (22)$$

$$w_l = w_b (w_h/w_b)^{\frac{l+N+\frac{1(1+\beta)}{2}}{2N+1}}, \quad (23)$$

$$K = w_h^\beta \quad (24)$$

where β is the order of integrator/differentiator and ' $2N+1$ ' represents the order of filter.

4 Outline of gravitational search algorithm (GSA)

GSA is supported by Newton's theory of gravity and motion [47]. In GSA each agent assumed as an object and their efficiency based on their masses. These agents interact with each other through gravity force.

$$Z_k = (z_k^1, \dots, z_k^d, \dots, z_k^N) \text{ for } k = 1 \text{ to } N \quad (25)$$

where z_k^d is the corresponds to the position of k th mass in the d th dimension and N represents the search space.

At time ' t ', the force acting on mass ' k ' from mass ' j ' is given as

$$F_{kj}^d(t) = G(t) \frac{M_{passivek} * M_{activej}}{R_{kj} + \epsilon} (z_j^d - z_k^d) \quad (26)$$

where $M_{activej}/M_{passivek}$ is the active/passive gravitational mass related to agent j/k , $G(t)$ is the gravitational constant

at time t , ϵ is small constant, and $R_{kj}(t)$ is the Euclidian distance between two agents k/j given by

$$R_{kj}(t) = \left\| Z_k(t), Z_j(t) \right\|_2 \quad (27)$$

The summation of force acting on agent k in the dimension d is calculated by Eq. (28)

$$F_j^d(t) = \sum_{j=1, j \neq k}^N \text{rand}_j F_{kj}^d(t) \quad (28)$$

where rand_j is a random number in the limit of $[0, 1]$. In view of law motion, acceleration of the agent ' k ' at the time t and in the direction d_{th} , is calculated as

$$a_k^d(t) = \frac{F_k^d(t)}{M_{\text{inertiak}}(t)} \quad (29)$$

where $M_{\text{inertiak}}(t)$ is the inertia mass of k_{th} agent. The next velocity of an agent is considered as fraction of current velocity and it's added to current acceleration as written in (30)

Minimize J

Subject to

$$K_p^{\min} \leq K_p \leq K_p^{\max}, K_i^{\min} \leq K_i \leq K_i^{\max}, K_D^{\min} \leq K_D \leq K_D^{\max}, \lambda^{\min} \leq \lambda \leq \lambda^{\max}, \mu^{\min} \leq \mu \leq \mu^{\max}$$

$$V_k^d(t+1) = \text{rand}_k * V_k^d(t) + a_k^d(t) \quad (30)$$

and the next position of an agent can be calculated by using equation

$$z_k^d(t+1) = z_k^d(t) + V_k^d(t+1) \quad (31)$$

$V_k^d(t)$ is current velocity and rand_k is a uniform random variable in the range $(0, 1)$. Gravitational constant G at iteration ' t ' is computed by using Eq. (32)

$$G(t) = G_0 e^{\frac{-\alpha t}{T}} \quad (32)$$

G_0 and α are constant, T is the total number of iterations. The masses of the agents are figured out utilizing fitness evaluation. A heavier mass represents proficient agent. Taking the equivalent gravitational/inertial mass, the values of masses are found out by the fitness map. The updated gravitational/inertial masses are determined as

$$M_{\text{activek}} = M_{\text{passivek}} = M_{\text{inertiak}} = M_{ki}, \quad i = 1, 2, 3 \dots n \quad (33)$$

$$m_k(t) = \frac{\text{fit}_k(t) - \text{worst}(t)}{\text{best}(t) - \text{worst}(t)} \quad (34)$$

$$M_k(t) = \frac{m_k(t)}{\sum_{j=1}^N m_j(t)} \quad (35)$$

At a particular time t , $\text{fit}_k(t)$ presents the fitness value of the agent ' k '. Best (t) is characterized as

$$\text{Best}(t) = \min_{j \in (1 \dots n)} \text{fit}_k(t) \quad (36)$$

To enumerate the results, 25 independent experiments be performed for each parameter variation and got finest values for constant as $\alpha = 20$, gravitational constant $G_0 = 100$, population size $N = 20$ and number of iteration $T = 100$ (Fig. 3).

5 Simulation result and analysis

The objective function to implement GSA algorithm on our proposed controller is defined as

$$J = \int_0^T \left[w(\Delta f)^2 + (1-w)/K(\Delta u)^2 \right] dt \quad (37)$$

Here Δf denotes frequency deviation, T is simulation time period denotes the weight age of each objective function and its value considered here is equal to 0.7. The K is the normalizing constant to scale every signal (frequency deviation and control motion) in uniform scale. The decision of w as 0.7 in the present case shows that the proposed study gives more significance to the quick concealment of the microgrid frequency fluctuations in contrast with the higher value of control signal. The typical range of design variables $\{K_p, K_i, K_D, \lambda, \mu\}$ are $\{0-250, 0-250, 0-250, 0-1, 0-1\}$. The microgrid system shown in Fig. 4 is implemented on MATLAB software

Fig. 3 Fractional order PID controller

Fig. 4 Smart microgrid in MATLAB/Simulink

version 7.12.0 (R2011a). The nominal parameters values of microgrid components are specified in Table 2 [2].

5.1 Performance of the controller under linear operating conditions

The Gravitational search algorithm has been adopted to obtain the optimized values of gains of PI/PID/FOPID and FOPID controllers. Table 3 shows the five parameters of studied controllers corresponding to the best objective function (J_{min}) for 25 random generation runs. A comparative analysis of the proposed controller (FOPID) with PI, FOPID and PID controllers is shown in Fig. 5. It illustrates the frequency deviation and actuating control signals for PI/PID/FOPID/FOPID controllers. The graph clearly indicates that the oscillations as well overshoot are less in PID controller as compared to PI controller.

Although PI/FOPID controllers offer negligible error but it is insensitive to interference of the measurement channel. The main disadvantage of PI control is slow reaction to disturbances. Figure 5 reveals that the overshoot is more visible in PI/FOPID controller than PID/FOPID controller when undue load variations occur during period $t=77$ s to 85 s. It reveals that PID controller makes fast reaction to disturbances. Although from frequency deviation curve, it is difficult to find which controller is doing better than the other. Numerical values of J_{min} associated with FOPID/PID/FOPID/PI are 2.45/2.5660/2.981/3.098 respectively as

given in Table 3. It clearly indicates that FOPID is performing better than PI/PID/FOPID controllers. Moreover, control signal fluctuation is less in FOPID controller than PI/PID/FOPID controllers. As we know that the continuous variation in control signal reduces the life time and performance of mechanical parts. Table 4 shows the transient characteristics of present controllers. It is now evident that the performance of FOPID controller is better in all aspects (overshoot/under shoot/settling time) in comparison to PID/FOPID/PI controllers.

Power produced through individual components of the microgrid corresponding to PID/FOPID controllers is illustrated in Fig. 6. It is evident that the highest power supply is given by ultra capacitor of microgrid. The power generation curve of diesel generator shows positive magnitude because it is energy producing component while ultra capacitor, battery system, and flywheel have negative power magnitude curves as they are energy absorbing components.

5.2 Robustness against ultra capacitor parameter variation

From Fig. 6, it is clear that ultra capacitor has contributed the maximum power as compared to other components of the grid. Hence investigation of controller's robustness against increase or decrease of ultra capacitor's gain and time constant is essential. Figure 7 illustrates the control

Table 3 Controller's parameter after optimization

Controller structure	Optimized parameters					
	J_{min}	K_p	K_I	K_D	λ	μ
PI	3.098	0.92	0.512	–	–	–
PID	2.5660	0.8856	0.56	0.0678	1	1
FOPID	2.981	0.845	0.458	–	0.512	–
FOPID	2.4508	0.7959	0.7937	0.0341	0.2662	0.9919

Fig. 5 Frequency deviations and control signals with studied controllers

Table 4 Transient characteristics of PI/FOPI/PID/FOPID controller

Controllers	Overshoot (p.u)		Undershoot (p.u)		Settling time (s)	
	Δf	Control signal	Δf	Control signal	Δf	Control signal
PI	0.9567	2.11	-0.04	0	Not settle down to final set point	Not settle down to final set point
FOPI	0.9505	2.09	-0.02	0	Not settle down to final set point	Not settle down to final set point
PID	0.895	2.04	-0.017	0	8	66
FOPID	0.8567	2.01	-0.012	0	5	64

Fig. 6 Power output of each component of microgrid

signal and frequency deviation with variations in gain and time constant of ultra capacitor for the both controller. Table 5 lists the performance measurement for different condition of ultra capacitor parameters. Table 5 demonstrates that in all the cases FOPID gives better result as compared to PID controller.

5.3 Robustness against eliminating different components

Robustness of obtained result of proposed system is tested by disconnecting three components, namely DEG, FESS, and BESS at a time. The outcomes in terms of performance index are shown in Table 6. It is remarkably noticed that performance measure (ISE) is significantly lower in case of FOPID controllers or in other words, performance deterioration is less in FOPID controller than PID controller. It

is also evident that detaching the DEG has impact on the execution pursued by FESS and BESS.

5.4 Performance of the controller under non-linear operating conditions

To test the sturdiness of the control methodology, generation rate constraint (GRC) type nonlinearity is added in system. For implementation of GRC, four components, namely flywheel, battery, ultra capacitor, and diesel generator are taken. In all these components, subsequent constraints of $|\dot{P}_{FESS}| < 0.02$, $|\dot{P}_{BESS}| < 0.005$, $|\dot{P}_{UC}| < 1.5$, and $|\dot{P}_{DEG}| < 0.001$ are considered [39]. Figure 8 demonstrates the variation of power output of energy storing and energy generating components with and without GRC. The inclusion of GRC increases the value of performance index for both controllers as shown in Fig. 8.

Fig. 7 Frequency deviations and control signal with variation in time and gain constant of ultra capacitor

Table 5 Performance Index of controller for parameter variation of ultra capacitor

Condition	Performance (ISE)	
	FOPID	PID
Nominal	2.4089	2.566
Increase 30%	2.3902	2.5238
Increase 50%	2.3711	2.4931
decrease 30%	2.483	2.601
decrease 50%	2.5481	2.7612

Table 6 Robustness against eliminating different components of microgrid

Component open	Performance Index-ISE	
	PID	FOPID
Nominal	2.4089	2.566
Diesel	2.511	2.621
Battery	2.421	2.575
Flywheel	2.443	2.591

The optimum value of the performance index (with GRC) in case of FOPID controller ($J_{\min} = 2.4544$) again demonstrates its effectiveness in comparison to the PID ($J_{\min} = 2.6214$) controller. Figure 9 illustrates that the effects of GRC on energy storing and generating

elements for both controllers. It is evident that FOPID gives better results than PID.

5.5 Performance of controller under uncertainty in data transmission using UDP/IP

The ADC are used with sample and hold circuit to get digital data in smart micro grid. As mentioned in [41] if considered sampling time is less than smallest time constant then system output will have same response in both continuous and discrete. Thus this study adopted sampling time equal to 0.1 s which is smallest time constant of components employed in the microgrid (in proposed study flywheel system has smallest time constant).

As we know that UDP does not support affirmation of receipt mechanism and packet loss is impalpable under ordinary conditions. In UDP a few packets will be lost or tainted through the span of the session. In the exhibited case we have considered that when there is an information lost, the past information will keep on going about as the reference as appeared in Fig. 10. It shows that information transmitted from diesel engine generator is lost at 20.6 s and don't achieve the receiver then diesel engine generator output will remains same from 20.6 to 20.8 s and information is received at 20.9 s and formed wrong sequence. Although there is no significant effect of wrong sequence on frequency deviations due to small time delay. In real time application of UDP, there will be

Fig. 8 Effect of GRC on energy storage/generating elements

Fig. 9 Power profile of the energy storage and generation components with and without GRC

a time stamping that implies if information isn't come to inside the stipulated period then receiver won't recipient it at all and Fig. 11 demonstrates that no significant impact of wrong sequence or data loss has been appeared on frequency deviation due to of small time delay.

6 Conclusion

MAS-based centralized control scheme with FOPID controller for islanded microgrid has been investigated in this research work. The GSA has been employed to search the optimized values of parameters of the

Fig. 10 Control signal from MGCC to diesel engine generator

Fig. 11 Frequency deviation with/without data-loss

controllers. It is discovered that the dynamic execution of the microgrid with FOPID controller is superior to PID controller for variation in renewable power generation. The study has been done in terms of deviation in frequency, control signal, robustness against parameter variations of ultra capacitor, robustness against by disconnecting the different components of micro-grid. The system performance has also been observed by including the nonlinearities like GRC in energy storing and generating components. The reliability of the system is substantiated by the fact that only one time controller is tuned under nominal condition. It is also apparent from the results that the multi agent based microgrid control system can fully meet the requirements of supply and demand.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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