ABSTRACT Unpredictable high renewable shares in a standalone microgrid (MG) system with stochastic load demands introduces an unavoidable mismatch among loads and sources. This mismatch directly impacts the system frequency, which can be mitigated via applying a suitable load frequency control (LFC) scheme. This brief proposes a maiden attempt of marine predator algorithm (MPA) assisted one plus proportional derivative with filter-fractional order proportional-integral ((1+PDF)-FOPI) controller to obtain the proper power flow management among loads and sources. The investigated MG system consists of a photovoltaic (PV) system, a wind turbine (WT) generator (WTG), and a diesel engine generator (DG) as the distributed energy sources, and an ultracapacitor (UC) and a flywheel are chosen as the energy storage elements (ESEs). Various system nonlinearities, such as governor dead-band (GDB) and generation rate constraint (GRC) are also considered to reflect the practical scenario. Five state-of-the-art optimization techniques and three traditional controllers, PID, FOPID, and PI-PD, are vividly compared to assess the proposed scheme’s performance. The parametric uncertainties are considered obtaining the robust performance of the proposed control scheme. An eigenvalues-based stability evaluation of the considered plant employing the proposed LFC scheme is also included in this work. In the worst situation, the maximum frequency deviation is obtained as $-0.016 \text{ Hz}$, which is entirely satisfactory and under the range of the IEEE standard. Finally, a modified New England IEEE-39 test bus system is chosen to perform the real power system validation via MATLAB/Simulink.

INDEX TERMS Microgrid, load frequency control, optimization technique, fractional cascade control, renewable energy sources, stability evaluation.

I. INTRODUCTION

A. BACKGROUND

Enhancing electricity demand requires employing hybrid generation units in standalone or interconnected power system networks. In the present era, renewable shares are enhancing the existing power system network due to the high emission of greenhouse gases, galloping oil prices, and sustainable development. Renewable energy (RE) sources, considered economical and clean energy sources, are likely to be interconnected to the MG power systems [1], [2]. Solar and wind are the most critical RE sources among all the energy sources due to their abundant availability [3]. The critical drawback of RE sources is their highly unpredictable nature.

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Due to the stochastic nature of RE sources, its efficacy is very low; with PV, the conversion efficacy is as low as it falls under the range of 7-19% [3]. Hence, in order to harvest the maximum obtainable power from the uninterrupted solar insolation, various maximum power point tracking (MPPT) schemes are employed [3], [4], [5]. The most commonly utilized MPPT schemes are perturbed & observe (P&O) and incremental conductance (IC) [5]. With wind energy conversion, the most common MPPTs are P&O and tip speed ratio [6]. In this investigated MG system, the maximum obtainable power from PV is harvested through the modified IC (MIC) MPPT scheme as presented in [7], and a nonlinear WTG modeling is employed to harvest maximum power from the stochastic wind speed. Due to the significant share of these RE sources in the MG system, the most interesting parameter of the power system, “frequency,” is affected [8]. The change in frequency deviation (CFD) severely affects the frequency-sensitive loads, and in the worst situation, a blackout may occur. To maintain the proper power flow management among loads and sources and to make CFD → 0, it is required to incorporate a supervisory LFC scheme in the MG system [9]. In other words, LFC allows the generating units to regulate their generations corresponding to load demands, resulting in a zero CFD under ideal situations. The system performance may undermine due to the improper design of LFC and also causing large oscillations in the system [10]. In order to the proper design of the LFC scheme, various meta-heuristics-based control approach is employed for various types of power system networks [7], [8]. The meta-heuristics handle the optimal performance of the designed frequency control scheme.

B. LITERATURE REVIEW

The apropos literature has witnessed various works on the novel controller design. Some of the recently published literature incorporates PI/PID structured controllers are dragonfly search algorithm [11], bacterial foraging optimization algorithm (BFOA) [12], particle swarm optimization (PSO) and hybrid BFOA (PSO-hBFOA) algorithm [13], lozi map-based chaotic algorithm [14], fire-fly algorithm tuned PI controller [15], PID2 control approach [16], ant colony optimization for hydrothermal power plant [17], flower pollination algorithm tuned PI-PD cascade control [18], genetic algorithm (GA)/differential evolution (DE) [19], bat algorithm tuned PD-PID cascade control approach [20], improved stochastic fractal search (SFS) algorithm [21], sine cosine algorithm based PI controller [22], DE tuned PI/PID [23], biogeography based optimization tuned I/P/I/PIDF [24], teaching learning based optimization algorithm based 2-degree of freedom (DOF) PID (2DOF-PID) [25], disrupted oppositional based gravitational search algorithm – pattern search based PID [26], symbiotic organism search algorithm tuned PID [27], hybrid SFS – local unimodal sampling (hSFS-LUS) based multistage PDF-(1+P-I) [28] and imperialist competition algorithm tuned PID controller for PV-thermal and hydrothermal based interconnected power system [29]. A GA-based LFC scheme with stability evaluation under solar, DG, and battery-based distributed energy sources is demonstrated in [7]. A (1+PD)-PID-based cascade control approach for the interconnected power system under RE contributions is briefed in [11]. Kumar and Hote [16] designed a robust PID2 controller to mitigate the frequency deviations in the interconnected power system. The authors have chosen Kharitonov’s theorem-based worst-case plant section model design. A sliding mode control approach is implemented to design a robust controller [16]. In order to improve the performance of the control scheme, other advanced control approaches based on H-infinity [30], sliding modes [31], fuzzy logic control [32], [33], artificial neural network-based [34], adaptive neuro-fuzzy inference system [35], disturbance observer-based fractional control [36], nonlinear disturbance observer [37], modified tilted control approach [38], delay-dependent control approach including electric vehicles, and constant and varying loads [39], [46] and fractional control approach [40] are discussed. In [33], an intelligent LFC scheme for a standalone MG system is demonstrated. In this, the authors have used an improved IC MPPT scheme to harvest power from PV, and a fuzzy observer-based control approach is chosen for the wind energy conversion system. The obtained results revealed the superior performance of the proposed controller over other considered control approaches. A double-stage controller design is proposed for a hybrid ocean-wind-based maritime MG system [47]. A grasshopper algorithm is used to tune the proposed PI-(1+PD) controller, and the obtained results revealed the enhanced performance of the proposed controller over PID and PID with filter-type controllers. A novel performance index criterion termed a hybrid peak area for the automatic generation control of two area power systems is revealed in [45], and the obtained results are compared with the existing performance indices. A lightning search tuned variable structure control approach for the frequency control of load following a nuclear reactor power system is briefed in [48], and the results are compared with a GA-based variable structure control scheme. An improved gray wolf optimization-based control approach for vision system-based autonomous vehicles is revealed in [49]. A PID controller design for two area power systems via an artificial bee colony is proposed in [50]. A black widow optimization algorithm-based PIDF – (1+I) cascade control approach for the LFC of the MG system is investigated in [51]. This P&O MPPT algorithm is used to harvest maximum obtainable power from PV, and the real-time benchmarking is performed via a modified New England IEEE 39 test bus system. A tilt integral derivative controller for the multi-MG system considering the electric vehicle is presented in [52]. Sensitivity analysis of the proposed control scheme is performed under ±30% of parametric uncertainties. The investigated system performances due to cascade control approaches are worth-appreciating control action in interest. Moreover, selecting an appropriate optimization approach for the LFC design is also challenging for
A. MODELING OF WTG

The rated wind speed \( V_w \) plays a critical role in the power production from WTG \( P_w \), and the \( V_w \) is dependent on base wind speed \( V_{wb} \), ramp speed \( V_{wr} \), gust speed \( V_{wg} \) and noise component of wind \( V_{wn} \) [42]:

\[
V_w = V_{wb} + V_{wr} + V_{wg} + V_{wn}
\]

The wind model incorporates its essential components as base fluctuation and randomness, which are represented as [43]:

\[
V_w = V_{wb} + V_{wn}
\]

The \( V_{wb} \) is a constant, and its presence is detected when WTG is in operation. Randomness of \( V_{wb} \) is expressed by the Heaviside step function as [42]:

\[
V_{wb} = C = 7.5H(t) + 4.5H(t-10) - 2.5H(t-15)
\]

In order to consider the practical scenario, variations in \( V_w \) is chosen from 2.5 m/s to 12.5 m/s. Moreover, the noise component of \( V_w \) is revealed as [43]:

\[
V_{wn} = 2\sigma^2 \sum_{i=1}^{n} \frac{S_v(\omega_i) \Delta \omega \cos(\omega_i t + \varphi_i)}{\pi^2 \left[1 + \left(\frac{F \omega_i}{\mu \pi}\right)^2\right]^{1/3}}
\]

where, \( \omega_i = (i - 1/2) \Delta \omega \) and \( \varphi_i \approx U(0, 2\pi) \). The noise variation is \( \sigma^2 \) and spectral density critical factor is \( \Delta \omega \). The spectral density component \( S_v(\omega_i) \) is given as [38]:

\[
S_v(\omega_i) = \frac{2k_n F^2 |\omega_i|}{\pi^2} \left[1 + \left(\frac{F \omega_i}{\mu \pi}\right)^2\right]^{-4/3}
\]

where, \( k_n, \mu \), and \( F \) denote surface drag coefficient, reference height, and base \( V_w \) at turbulence measure. A nonlinear WTG model is considered to harvest the power from unpredictable wind speed. The wind power generation modeling is revealed as [33]:

\[
P_W = \frac{1}{2} C_p(\lambda, \beta) \rho A_T V_w^3
\]

\[
T_W = \frac{P_W}{\omega_m}
\]

where WT angular speed and power output are \( \omega_m \) and \( P_W \). Swept area of the rotor is \( A_T \), air density is \( \rho \), and rotor blade coefficient is \( C_p \) that revealed as follows [33]:

\[
C_p(\lambda, \beta) = C_1 \times \left(\frac{C_2}{\lambda I} - C_3 \beta - C_4 \beta^2 - C_5\right) \times e^{-\frac{C_6}{\lambda T}} + C_7 \lambda_T
\]

where, \( C_1 \) to \( C_7 \) are WT’s coefficients for fixed and variable pitch, the pitch angle is \( \beta \), and the optimal tip speed ratio is \( \lambda_T \) that demonstrated as [33]:

\[
\lambda_T = \lambda_T^{OP} = \frac{\omega_T \times r_T}{V_W}
\]

where the radius of the rotor blade is \( r_T \) and \( \lambda_T \) is the intermittent tip speed ratio briefed as [33]:

\[
\frac{1}{\lambda_T} = \frac{1}{\lambda_T^{OP} + 0.08 \beta} = \frac{0.035}{\beta^3 - 1}
\]
B. MODELING OF PV SYSTEM

The governing relation of I-V for PV is as follows [44]:

\[
I = I_{ph} - I_0 \left( e^{\frac{(V_{pv}+R_sI_{pv})}{AKT}} - 1 \right) - \frac{V_{pv} + R_sI_{pv}}{R_{sh}}
\]

where,
- \(I_{ph}\) = light-generated current (A)
- \(R_{sh}\) and \(R_s\) = shunt and series resistances (\(\Omega\))
- \(T\) = cell temperature in Kelvin (K)
- \(I_o\) = reverse saturation current (A)
- \(q\) = electron charge (1.6022 \(\times\) 10\(^{-19}\) C)
- \(V_{pv}\) = solar cell output voltage
- \(R_{pv}\) = solar cell output voltage
- \(A\) = the p-n ideality factor
- \(K\) = the Boltzman’s constant (1.38 \(\times\) 10\(^{-23}\) J/K)

The output power of the PV system is briefed as [38]:

\[
P_{PV} = \eta S \phi \{1 - 0.005 (T_a + 25)\}
\]

where \(\eta\) is conversion efficacy, \(S\) is the measured surface area, \(\phi\) is input insolation on the surface area, and \(T_a = 25^\circ\) C is atmospheric temperature. The solar insolation \(\phi\) is expressed as the heavy step function as [38]:

\[
\phi = 0.5H (t) - 0.03H (t - 25) + 0.3H (t - 75) - 0.3H (t - 150) + \phi_d (t)
\]

where, \(\phi_d\) is in the range (-0.1, 0.1). In this proposed work, the actual PV power through the MIC MPPT scheme is injected into the investigated MG system at the insolation level varying from 400 W/m\(^2\) to 1000 W/m\(^2\) in a ramp variation form. Hence all the nonlinearities of the system are already considered. The obtained maximum power from PV is shown in Fig. 7. The simulation parameters of the PV system are depicted in Table 1.

C. MODELING OF DG

In this proposed work, first order governor model is chosen and revealed as [33]:

\[
T_g \frac{dP_G}{dt} = -P_G - u - \frac{1}{R_d} (\Delta f)
\]

where power output and time constant of the governor are \(P_G\) and \(T_g\) respectively, the control signal is \(u\), and the droop coefficient is \(R_d\). Moreover, the first-order turbine model is chosen and revealed as [33]:

\[
T_t \frac{dP_{DG}}{dt} = P_G - P_{DG}
\]

where power output and time constant of DG are \(P_{DG}\) and \(T_t\) respectively. The overall open loop transfer function (OLTF) of DG and WTG by assuming other inputs as zero are revealed by (16) and (17) as:

\[
1 + R_d \left( \frac{T_W s + 1}{(T_s s + 1)(2Hs + D)} \right) = \frac{R_d}{1} \left( T_g s + 1 \right)
\]

where WTG’s time constant is \(T_W\), the inertia constant is \(H\), and the MG system’s damping coefficient is \(D\).
while considering no tie-line power exchange in MG and \( \beta \) as frequency bias factor, the \( ACE \) is as:

\[
ACE = \beta \Delta f
\]  

(21)

and

\[
CFD = \Delta E (t) = \int_0^t ACE (\tau) d\tau
\]  

(22)

Equations (21) and (22) reveal the integral of \( CFD \rightarrow 0 \) at a steady state. The linearized model of governor valve position due to \( ACE \) delay is as:

\[
\Delta P_v (t) = -\frac{\Delta f (t)}{R_d T_g} - \frac{\Delta P_v (t)}{T_g} - \frac{\Delta E (t - d (t))}{T_g} + \frac{u (t)}{T_g}
\]  

(23)

where, \( d (t) \) denotes the system’s delay, which is neglected in the present study. In summarized form, (18) is written as:

\[
\begin{bmatrix}
\dot{x} (t) \\
\dot{y} (t)
\end{bmatrix} = \begin{bmatrix}
A & \Delta f \\
0 & 0
\end{bmatrix} \begin{bmatrix}
P_G \\
P_v
\end{bmatrix} + \begin{bmatrix}
B \\
0
\end{bmatrix} u (t) + \begin{bmatrix}
F \\
0
\end{bmatrix} \Delta P_d (t)
\]  

(24)

where,

\[
\begin{align*}
A &= \begin{bmatrix}
\frac{-D}{2H} & \frac{1}{2H} \\
0 & -1
\end{bmatrix} \\
B &= \begin{bmatrix}
0 & \frac{1}{T_g} \\
0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix} \\
F &= \begin{bmatrix}
-1 \\
0
\end{bmatrix} \\
C &= [1 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0]
\end{align*}
\]  

(25)

where \( \Delta f \) is frequency deviation, \( \Delta P_G \) is valve position and \( \Delta P_d \) is the change in load demand. The dynamics of the MG system’s frequency are demonstrated as [33], [45]:

\[
2H \frac{d \Delta f (t)}{dt} = P_{PV} + P_{WTG} + P_{DG} \pm P_{FW} (t) \pm P_{UC} (t) - P_d (t) - D \Delta f (t)
\]  

(26)

The (18) is written in the “s” domain and revealed as:

\[
\frac{\Delta f (s)}{P_v (s)} = \frac{1}{2H s + D + D}
\]  

(27)

where power error \( P_e = P_s - P_d \pm P_{FW} \pm P_{UC} \), and \( P_s = P_{PV} + P_{WTG} + P_{DG} \) The output power of the PV, WTG, and DG, respectively. The \( \pm P_{FW} \) and \( \pm P_{UC} \) reveal the power provided and absorbed by the flywheel and UC, respectively.
F. CONTROL STRATEGY
This section reveals the design consideration of the proposed (1+PDF)-FOPI cascade controller used for the droop control in the considered MG system. The output of the (1+PDF) controller is working as the input of the FOPI controller in a series manner; hence, it is considered the cascade control approach. The structure of the (1+PDF)-FOPI controller is shown in Fig. 1 and revealed as:

\[
u = \left(1 + k_1 \Delta f + k_2 s + \frac{k_3}{s + k_3} \Delta f \right) \times \left(\frac{k_4 + k_5}{s^2}\right)\]

where, \(k_1 - k_5\) and \(\lambda\) are the parameters of the (1+PDF)-FOPI controller, and \(u\) is the controller’s output. The total tuning parameters of the proposed controller are six. This is the optimization problem and can be reduced by minimizing the objective function \(J_s\). The different types of objective functions that are used in the LFC of the power system are IAE, ITAE, ISE, and ITSE. The ISE tuned controller reduces significant errors very fast, but the minor errors remain for a long duration [45]. The IAE tuned controller gives a slow dynamic response, and significant deviations remain compared to ISE [45]. The controller tuned via ITAE and ITSE give a dynamic response with less settling time (ST) [45]. The critical shortcoming of ITAE and ITSE is that the initial dynamic response is slow [45]. Hence, to ramp up the dynamic and steady-state performance (faster convergence with lesser divergence from the final value), an excellent combination is ISE and ITAE, which is considered in this work and given as:

\[
J_s = \min \left( w_1 \times ISE + w_2 \times ITAE \right) = \int_0^{t_s} \left( w_1 |\Delta f|^2 + w_2 |\Delta f| \cdot t \right) \times dt
\]

where, \(t_s\) is simulation time, \(w_1\) and \(w_2\) are the weights and chosen as 50% each. The critical aim of this work is to reduce \(J_s\) via MPA because reduced \(J_s\) provides excellent performance of (1+PDF)-FOPI cascade controller for LFC of considered MG system. Minimize \(J_s\) subject to:

\[
\begin{align*}
k_1^{\min} &\leq k_1 \leq k_1^{\max}, & k_2^{\min} &\leq k_2 \leq k_2^{\max}, & k_3^{\min} &\leq k_3 \leq k_3^{\max}, \\
k_4^{\min} &\leq k_4 \leq k_4^{\max}, & k_5^{\min} &\leq k_5 \leq k_5^{\max}, & \lambda^{\min} &\leq \lambda \leq \lambda^{\max}
\end{align*}
\]

III. PROPOSED MPA FOR LFC OF CONSIDERED MG SYSTEM
This is a population-based algorithm in which the solution is uniformly distributed as follows [41]:

\[
X_o = X_{\min} + \text{rand} \left( X_{\max} - X_{\min} \right)
\]

where the lower and upper bounds of variables are \(X_{\min}\) and \(X_{\max}\), and \(\text{rand}[0, 1]\). The fittest predators are in the form of a matrix and searches for prey according to the prey’s positional
TABLE 2. Performance evaluation of different schemes.

| Indices     | PSO:(1+PDF)-FOPI | CS:(1+PDF)-FOPI | GSA:(1+PDF)-FOPI | SSA:(1+PDF)-FOPI | Proposed controller |
|-------------|------------------|-----------------|------------------|------------------|---------------------|
| IAE         | 0.000243         | 0.000188        | 0.000158         | 0.000149         | 0.000137            |
| ITAE        | 0.001993         | 0.001945        | 0.001647         | 0.001568         | 0.001439            |
| ISE         | $2.34 \times 10^{-7}$ | $7.56 \times 10^{-8}$ | $8.63 \times 10^{-9}$ | $5.98 \times 10^{-9}$ | $4.21 \times 10^{-9}$ |
| ITSR        | $4.22 \times 10^{-8}$ | $4.13 \times 10^{-8}$ | $2.52 \times 10^{-8}$ | $1.89 \times 10^{-8}$ | $1.32 \times 10^{-9}$ |
| Max. $\delta f$ (Hz) | $-0.113$ | $-0.060$ | $-0.059$ | $-0.051$ | $-0.013$ |
| ST (sec.)   | 0.24             | 0.26            | 0.18             | 0.17             | 0.02                |

FIGURE 6. Frequency response of controllers under SLP of 45%.

FIGURE 7. Extracted PV power via MIC MPPT scheme.

FIGURE 8. (a) stochastic wind speed, and (b) Extracted wind power.

information as \[41\]:

\[
\text{Elite} = \begin{bmatrix}
X^l_{1,1} & X^l_{1,2} & X^l_{1,d} \\
X^l_{2,1} & X^l_{2,2} & X^l_{2,d} \\
... & ... & ...
\end{bmatrix}_{n \times d}
\]

\[
\text{Prey} = \begin{bmatrix}
X_{1,1} & X_{1,2} & X_{1,d} \\
X_{2,1} & X_{2,2} & X_{2,d} \\
... & ... & ...
\end{bmatrix}_{n \times d}
\]

where, $X^l$ presents the top predator, which replicates $n$ several times to make $\text{Elite}$ matrix, search agents, and dimensions are $n$ and $d$. $\text{Elite}$ is updated if a better predator replaces the top predator. The $\text{Prey}$ matrix is the same as $\text{Elite}$ and represented as \[41\]:

When prey and predator move in the same search space, they search for their food. This scenario presents the immediate phase of optimization and exploration that tries to convert into exploitation. Hence, half of the population is designated for exploration, and half is designated for exploitation. In this
TABLE 3. Performance of controller under $\delta_1$, $\delta_2$ and $\delta_3$.

| Schemes                  | IAE     | ITAE    | ISE       | ITSE     | Max. $\Delta f$ (Hz) |
|--------------------------|---------|---------|-----------|----------|-----------------------|
| PSO:(1+PDF)-FOPI         | 0.000261| 0.002071| $2.470 \times 10^{-7}$ | $4.883 \times 10^{-8}$ | $-0.220$ |
| CS:(1+PDF)-FOPI          | 0.000192| 0.002006| $8.870 \times 10^{-8}$ | $4.312 \times 10^{-9}$ | $-0.110$ |
| GSA:(1+PDF)-FOPI         | 0.000166| 0.001791| $9.396 \times 10^{-9}$ | $3.613 \times 10^{-9}$ | $-0.048$ |
| SSA:(1+PDF)-FOPI         | 0.000157| 0.001671| $7.606 \times 10^{-9}$ | $2.925 \times 10^{-9}$ | $-0.040$ |
| MPA: PID                 | 0.008480| 0.049832| $8.34 \times 10^{-6}$  | $4.883 \times 10^{-7}$ | $-0.300$ |
| MPA: FOPID               | 0.004572| 0.008643| $3.32 \times 10^{-6}$  | $9.779 \times 10^{-6}$ | $-0.285$ |
| MPA: PI-PD               | 0.000223| 0.001651| $1.940 \times 10^{-7}$ | $4.425 \times 10^{-8}$ | $-0.147$ |
| Proposed controller      | 0.000146| 0.001630| $4.970 \times 10^{-7}$ | $6.654 \times 10^{-8}$ | $-0.016$ |

TABLE 4. Proposed controller performance under varying MG parameters.

| Parameters               | IAE     | ITAE    | ISE ($\times 10^6$) | ITSE ($\times 10^6$) |
|--------------------------|---------|---------|---------------------|----------------------|
| (3 x 2H, D)              | 0.0001535| 0.0001704| 7.926              | 3.914                |
| (2H, 3 x D)              | 0.0001520| 0.0001682| 7.735              | 3.699                |
| (2H, 3 x D/2)            | 0.0001475| 0.0001630| 7.428              | 3.186                |
| (2H, 2 x D/3)            | 0.0001521| 0.0001683| 7.737              | 3.693                |
| (3 x 2H, 3 x D)          | 0.0001474| 0.0001631| 7.426              | 3.193                |

Multiplication of $\vec{R}_L$ and Elite imitates the predator’s movement in Lévy type while adding step size to Elite position imitates the predator’s movement for updating of prey position. Another critical factor that affects the MPA is environmental impacts such as fish aggregating devices (FADs) effects. FADs are considered local-optimal points, and there is a chance to trap these points. The FADs effect is mathematically presented as [41]:

$$
\vec{Prey}_i = \begin{cases} 
\vec{Prey}_i + CF \left[ \vec{X}_{min} + \vec{R} \otimes (\vec{X}_{max} \otimes \vec{X}_{min}) \right] \otimes \vec{U} & \text{if } r \leq \text{FADs} \\
\vec{Prey}_i + [\text{FADs} (1-r)+r] \left( \vec{Prey}_{r1} - \vec{Prey}_{r2} \right) & \text{if } r > \text{FADs}
\end{cases}
$$

where FADs = 0.2 is the impact of FADs on optimization. Binary vector is $\vec{U}$ including an array with one and zero. Vectors containing maximum and minimum bounds are $\vec{X}_{max}$ and $\vec{X}_{min}$. Random indexes of the Prey matrix is $r_1$ and $r_2$. The flowchart of the MPA is depicted in Fig. 4.
IV. RESULTS AND DISCUSSION

A. CONSTANT LOAD CONDITION

The convergence rate of the proposed MPA:(1+PDF)-FOPI controller is shown in Fig. 5. From Fig. 5, the minimum $J_s$ is obtained as 0.000789, and the final convergence is obtained in 60 iterations. In order to investigate the performance of all the applied optimization schemes on the (1+PDF)-FOPI controller, a step load perturbation (SLP) of 45% is given as a load at constant wind speed and constant solar insolation. Hence, an SLP of 45% and without $\delta_1$ (uncertainty in the wind) and $\delta_2$ (uncertainty in solar insolation), The performance of the designed PSO, CS, GSA, SSA and MPA tuned (1+PDF)-FOPI controllers is depicted in Fig. 6 and tabulated in Table 2.

By observing Fig. 6 and Table 2, it can be noted that the maximum $\Delta f$ is obtained as -0.113 Hz with an ST of 0.24 sec. for PSO:(1+PDF)-FOPI controller. The minimum $\Delta f$ as $-0.013$ Hz with a minimum ST of 0.02 sec. is obtained with the proposed MPA:(1+PDF)-FOPI controller. For CS, GSA and SSA tuned (1+PDF)-FOPI controllers, the maximum CFD obtained are $-0.06$ Hz, $-0.059$ Hz, and $-0.051$ Hz with STs are 0.26 sec., 0.18 sec., and 0.17 sec., respectively.
From Table 2, it can be concluded that the error rates are minimum for the proposed controller as IAE(0.000137), ITAE (0.001439), ISE (4.21 × 10⁻⁹) and ITSE (1.32 × 10⁻⁹). So, in this considered state performance, the MPA:(1+PDF)-FOPI controller is superior to other control schemes.

The controller’s performance in more practical scenarios by applying a constant SLP of 55% with δ₁ and δ₂ is considered for further analysis. The considered δ₁ is in between 400 W/m²-1000 W/m², and the harvested MPP via MI MPPT is depicted in Fig. 7. Which shows that the maximum obtained power is 100 kW (0.067 pu) at the maximum insolation of 1000 W/m².

The considered δ₂ is in between 2.5 m/s-12.5 m/s, and the extracted MPP via the nonlinear WTG model is depicted in Figs. 8(a)&(b) respectively, the maximum obtained WTG power is 750 kW (0.5 pu). The CFD response of the controllers PSO, CS, GSA, SSA, and MPA tuned (1+PDF)-FOPI is revealed in Figs. 9(a)-(e) respectively. The controller’s performance is summarized in Table 3, and from Table 3, the maximum Δf appeared with PSO as −0.22 Hz with IAE (0.000261), ITAE (0.002071), ISE (2.470 × 10⁻⁷), and ITSE (4.883 × 10⁻⁸). For CS, it is −0.11 Hz with IAE (0.000192), ITAE (0.002006), ISE (8.870 × 10⁻⁸), and ITSE (4.312 × 10⁻⁸).

For GSA and SSA, the maximum Δf are −0.048 Hz and −0.40 Hz. The enhanced performance of the proposed MPA:(1+PDF)-FOPI is obtained as −0.016 Hz CFD with IAE (0.000146), ITAE (0.001630), ISE (4.970 × 10⁻⁹), and ITSE

FIGURE 11. (1+PDF)-FOPI controller tuned via (a) PSO (b) CS (c) GSA (d) SSA (e) MPA under varying load condition.
In this considered test case, the contribution of all the distributed energy sources with load demand is in Fig. 13(a). Moreover, PID, FOPID, and cascade PI-PD controllers are chosen to assess the proposed controller’s superior performance over other traditional controllers, as depicted in Fig. 10. From Fig. 10 and Table 3, the maximum CFD has appeared in MPA: PID controller with valued $-0.3$ Hz and for MPA: FOPID and MPA: PI-PD controllers CFDs are $-0.285$ Hz and $-0.147$ Hz. The maximum error rates appeared for MPA: PID controller compared to MPA: FOPID, PI-PD, and the proposed controller. From the above discussion and Table 3, it can be concluded that the proposed technique surpasses MPA: PID, MPA: FOPID, and MPA: PI-PD controllers under transient and steady-state performance.

### B. VARYING LOAD CONDITION

A varying load demand as SLP of 50%, 60%, and 70% with $\delta_1$ and $\delta_2$ are considered for benchmarking the $(1+PDF)$-FOPI controller tuned via PSO, CS, GSA, SSA, and MPA. The response of CFD for all the designed control schemes are revealed in Figs. 11(a)-(e), and the performance is summarized in Table 3. The maximum CFD has appeared with PSO as $-0.04$ Hz with IAE $(0.0020770)$, ITAE $(0.002089)$, ISE $(1.345 \times 10^{-8})$, and ITSE $(1.976 \times 10^{-7})$ With CS tuned $(1+PDF)$-FOPI controller, the maximum CFD is $-0.038$ Hz with IAE $(0.0001668)$, ITAE $(0.001958)$, ISE $(7.736 \times 10^{-9})$, and ITSE $(5.110 \times 10^{-8})$. With GSA and SSA, the maximum CFDs are $-0.025$ Hz and $-0.033$ Hz, respectively; with the proposed MPA:$(1+PDF)$-FOPI controller, the maximum CFD is minimum and valued as $-0.08$ Hz with IAE $(0.0001510)$, and ITAE $(0.000169)$, ISE $(4.792 \times 10^{-9})$, and ITSE $(5.185 \times 10^{-9})$. The comparative analysis of the MPA: PID, MPA: FOPID, MPA: PI-PD, and proposed controllers are tabulated in Table 3 and depicted in Figs 11(e) and 12. The maximum CFD is obtained for MPA: PID with a value of $-0.079$ Hz, whereas for MPA: FOPID and MPA: PI-PD are $-0.062$ Hz and $-0.022$ Hz. The error rates are higher for MPA: PID, MPA: FOPID, and MPA: PI-PD controllers...
In order to boost the dynamic performance of an LFC technique, it is required to have enough stability. Various schemes are available to assess the stability of a system and the eigenvalues-based stability approach is one of them. To obtain the eigenvalues, first, the fractional order term of the page. The obtained eigenvalues for MPA:(1+PDF)-FOPI controlled considered MG system are as follows:

\[
G(s) = 5.316 \times 10^3 s^{10} + 6.478 \times 10^2 s^9 + 2.632 \times 10^2 s^8 + 1.564 \times 10^1 s^7 + 1.926 \times 10^0 s^6 + 4.494 \times 10^{-1} s^5 + 1.680 \times 10^{-1} s^4 + 1.080 \times 10^{-1} s^3 + 8.243 \times 10^{-2} s^2 + 1.008 \times 10^{-2} s^1 + 7.942 \times 10^{-3} s^0
\]

\[
G(s) = \frac{34470s^3 + 56770s^2 + 12680s^1 + 405.6s + 1}{6300s^4 + 5493s^3 + 3880s^2 + 4074s + 52.66}
\]

where, \( s^{0.6} \) and revealed by as in (42), shown at the bottom of the page. The obtained eigenvalues for MPA:(1+PDF)-FOPI controlled considered MG system are as follows:

\[
C(s) = \left( 1 + k_1 + \frac{k_2 k_3 s}{s + k_3} \right) \left( k_4 + \frac{k_5 s}{s^6} \right)
\]

\[
= \left( 1 + 823.51 + \frac{189.3965}{s + 100} \right) \left( 17.95 + \frac{405.19}{s^{0.6}} \right)
\]

(41)

\[
\text{FIGURE 14. (a) load variations, and (b) CFD for the proposed controller.}
\]

\[
\text{FIGURE 15. Modified New England IEEE-39 bus system [44].}
\]

compared to the proposed control scheme. Hence, it can be concluded that the proposed controller surpasses the other designed controller for the considered test case.

To assess the robustness performance of the proposed controller, parametric variations are considered. The various components of parametric uncertainties will primarily affect the parameters of the MG system. Hence, a large perturbation order of 300% change in 2H and 300% change in D is considered for the robustness evaluation of the proposed controller.

In this scenario, the controller’s performance in terms of the error rates is summarized in Table 4, which is reasonably satisfactory. In order to investigate the robustness analysis of the proposed controller in a harsh situation, a rigorous load variation is also considered, as depicted in Fig. 14(a), and the performance of the MPA:(1+PDF)-FOPI controller is revealed in Fig. 14(b). Considering the challenging scenario, the performance of the proposed controller is entirely satisfactory, with a maximum CFD of \(-0.014\) Hz, which is under the permissible limit of the IEEE standard.

**C. STABILITY EVALUATION**

In order to boost the dynamic performance of an LFC technique, it is required to have enough stability. Various schemes are available to assess the stability of a system and the eigenvalues-based stability approach is one of them. To obtain the eigenvalues, first, the fractional order term of the page. The obtained eigenvalues for MPA:(1+PDF)-FOPI controlled considered MG system are as follows:

\[
G(s) = 5.316 \times 10^3 s^{10} + 6.478 \times 10^2 s^9 + 2.632 \times 10^2 s^8 + 1.564 \times 10^1 s^7 + 1.926 \times 10^0 s^6 + 4.494 \times 10^{-1} s^5 + 1.680 \times 10^{-1} s^4 + 1.080 \times 10^{-1} s^3 + 8.243 \times 10^{-2} s^2 + 1.008 \times 10^{-2} s^1 + 7.942 \times 10^{-3} s^0
\]

\[
G(s) = \frac{34470s^3 + 56770s^2 + 12680s^1 + 405.6s + 1}{6300s^4 + 5493s^3 + 3880s^2 + 4074s + 52.66}
\]

where, \( s^{0.6} \) and revealed by as in (42), shown at the bottom of the page. The obtained eigenvalues for MPA:(1+PDF)-FOPI controlled considered MG system are as follows:

\[
C(s) = \left( 1 + k_1 + \frac{k_2 k_3 s}{s + k_3} \right) \left( k_4 + \frac{k_5 s}{s^6} \right)
\]

\[
= \left( 1 + 823.51 + \frac{189.3965}{s + 100} \right) \left( 17.95 + \frac{405.19}{s^{0.6}} \right)
\]

(41)
standard IEEE-39 bus system [45]. In this work, out of three areas, only one area, i.e., area 1, is chosen to assess the proposed control scheme. The modification is done in area 1, where one conventional generator is replaced by the solar and wind as generating units and a flywheel as a storage unit. The considered modified IEEE-39 bus system is depicted in Fig. 15. The related simulation parameters are given in Table 1.

The effect of GRC nonlinearity is also incorporated in this study. The frequency response, supply, and demand power for SLP 65% pu are depicted in Fig. 16 (a) and (b). Maximum \( \Delta f \) is obtained in the order of -0.148 Hz, which is reasonably satisfactory and within the permissible range. The performance is tested by employing the varying power demand of SLP 80%, 30%, and 65%, and responses are depicted in Figs. 17(a) and (b); with varying power demand, the maximum obtained \( \Delta f \) is +0.169 Hz, which is in the permissible frequency range. The idea of the proposed MG system may be implemented for the places which are not accessible to the conventional grid but enriched with RE sources, for rural electrification, hospitals, agricultural fields, etc. The proposed control scheme may be applied to control interconnected power systems and hybrid electric vehicles.

V. CONCLUSION

The study made in this paper has been directed toward a novel MPA:(1+PDF)-FOPI fractional cascade LFC for a 1.5 MW standalone MG system. The maximum PV power is successfully harvested via a modified IC MPPT technique, and the optimal power is extracted from the wind via a designed nonlinear WTG model. The results of the proposed controller are vividly compared with four state-of-the-art optimization techniques, PSO, CS, GSA, SSA, and three controllers, PID, FOPID, and cascade PI-PD. The obtained performance indices and maximum CFD show the effectiveness and superiority of the proposed LFC scheme over the other designed control schemes. For the robustness assessment of the proposed LFC scheme, huge parametric uncertainties are considered in the MG system’s parameters, and rigorous load demand in triangular format is also considered. Under the worst situation, the maximum frequency deviation is -0.016 Hz, which is under the permissible limit. The controller has performed well, and CFD is under the permissible limit of the IEEE standard. Eigenvalues-based stability analysis shows the stable performance of the proposed control scheme. Finally, a modified New England IEEE-39 test bus system is successfully implemented to assess the proposed control scheme’s actual power system implementation in an off-line scenario. This work’s future scope may focus on designing of intelligent control scheme for renewable-rich multi-area power systems.

REFERENCES

[1] M. Ramesh, A. K. Yadav, and P. K. Pathak, “An extensive review on load frequency control of solar-wind based hybrid renewable energy systems,” Energy Sources A, Recovery, Utilization, Environ. Effects, pp. 1–25, Jun. 2021.
[2] Z. Zhuo, N. Zhang, J. Yang, C. Kang, C. Smith, M. J. O’Malley, and B. Kroposki, “Transmission expansion planning test system for AC/DC hybrid grid with high variable renewable energy penetration,” IEEE Trans. Power Syst., vol. 35, no. 4, pp. 2597–2608, Jul. 2020.
[3] P. K. Pathak, A. K. Yadav, and P. A. Alvi, “A state-of-the-art review on shading mitigation techniques in solar photovoltaics via meta-heuristic approach,” Neural Comput. Appl., vol. 34, no. 1, pp. 171–209, Jan. 2022.
[4] S. M. Sousa, L. S. Gusman, T. A. S. Lopes, H. A. Pereira, and J. M. S. Callegari, “MPPT algorithm in single loop current-mode control applied to DC–DC converters with input current source characteristics,” Int. J. Electr Power Energy Syst., vol. 138, Jun. 2022, Art. no. 107909.
[5] P. K. Pathak, A. K. Yadav, and P. A. Alvi, “Advanced solar MPPT techniques under uniform and non-uniform irradiance: A comprehensive review,” J. Sol. Energy Eng., vol. 142, no. 4, Aug. 2020, Art. no. 040801.
[6] C. Huang, F. Li, and Z. Jin, “Maximum power point tracking strategy for large-scale wind generation systems considering wind turbine dynamics,” IEEE Trans. Ind. Electron., vol. 62, no. 4, pp. 2530–2539, Apr. 2015.

[7] P. K. Pathak, S. Padmanaban, A. K. Yadav, P. A. Alvi, and B. Khan, “Modified incremental conductance MPPT algorithm for SPV-based grid-tied and stand-alone systems,” IET Gener. Transmiss. Distrib., vol. 16, no. 4, pp. 776–791, Feb. 2022.

[8] P. Mercier, R. Cherkaoui, and A. Oudalov, “Optimizing a battery energy storage system for frequency control application in an isolated power system,” IEEE Trans. Power Syst., vol. 24, no. 3, pp. 1469–1477, Aug. 2009.

[9] M. Ma, C. Zhang, X. Liu, and H. Chen, “Distributed model predictive load frequency control of the multi-area power system after deregulation,” IEEE Trans. Ind. Electron., vol. 64, no. 6, pp. 5129–5139, Jun. 2017.

[10] F. Liu, Y. Li, Y. Cao, J. She, and M. Wu, “A two-layer active disturbance rejection controller design for load frequency control of interconnected power system,” IEEE Trans. Power Syst., vol. 31, no. 4, pp. 3320–3321, Jul. 2016.

[11] E. Çelik, N. Öztürk, Y. Arya, and C. Ocak, “(1+P)D-PID cascade controller design for performance betterment of load frequency control in diverse electric power systems,” Neural Comput. Appl., vol. 33, pp. 15433–15456, Jun. 2021.

[12] E. S. Ali and S. M. Abd-Elazim, “Bacteria foraging optimization algorithm based load frequency controller for interconnected power system,” Int. J. Electr. Power Energy Syst., vol. 33, no. 3, pp. 633–638, 2011.

[13] S. Panda, B. Mohanty, and P. K. Hotá, “Hybrid BFOA—PSO algorithm for automatic generation control of linear and nonlinear interconnected power systems,” Appl. Soft Comput., vol. 13, no. 12, pp. 4718–4730, 2013.

[14] M. Farahani, S. Ganjefar, and M. Alizadeh, “PID controller adjustment using chaotic optimisation algorithm for multi-area load frequency control,” IET Control Theory Appl., vol. 6, no. 3, pp. 1984–1992, 2012.

[15] S. M. Abd-Elazim and E. S. Ali, “Load frequency controller design of a two-area system composing of PV grid and thermal generator via firefly algorithm,” Neurocomput., Appl. Vol., 30, no. 2, pp. 607–616, Jul. 2018.

[16] M. Kumar and Y. V. Hote, “Robust PIDD2 controller design for perturbed load frequency control of an interconnected time-delayed power systems,” IEEE Trans. Control Syst. Technol., vol. 29, no. 6, pp. 2662–2669, Nov. 2021.

[17] M. Omar, M. Soliman, A. A. Hany, and F. Bendary, “Optimal tuning of PID controllers for hydrothermal load frequency control using ant colony optimization,” Int. J. Electr. Eng. Inform., vol. 5, no. 3, pp. 340–348, 2013.

[18] S. Padhy and S. Panda, “A hybrid stochastic fractal search and pattern search technique based cascade PI-PD controller for automatic generation control of multi-source power systems in presence of plug in electric vehicles,”CAAJ Trans. Intell. Technol., vol. 2, no. 1, pp. 12–15, 2017.

[19] S. K. Saoho, “Control techniques in AC, DC, and hybrid AC–DC microgrid: A review,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 6, no. 2, pp. 739–759, Jun. 2018.

[20] P. Dash, L. C. Saikia, and N. Sinha, “Automatic generation control of multi area thermal system using Bat algorithm optimized P–D–PID cascade controller,” Int. J. Electr. Power Energy Syst., vol. 68, pp. 364–372, Jun. 2015.

[21] E. Čelik, “Improved stochastic fractal search algorithm and modified cost function for automatic generation control of interconnected electric power systems,” Eng. Appl. Artif. Intell., vol. 88, Feb. 2019, Art. no. 103407.

[22] P. Satapathy, M. K. Debnath, and P. K. Mohanty, “Design of PD–PID controller with double derivative filter for automatic generation control of power system,” IEEE Trans. Industrial Informatics, vol. 15, no. 1, pp. 112–117, 2019.

[23] P. K. Hota and B. Mohanty, “Automatic generation control of multi source thermal system using Bat algorithm optimized PD–PID cascade controller,” Int. J. Electr. Power Energy Syst., vol. 11, pp. 205–214, Feb. 2016.

[24] A. Rahman, L. C. Saikia, and N. Sinha, “Automatic generation control of an interconnected two-area hybrid thermal system considering dish-stirring solar thermal and wind turbine system,” Renew. Energy, vol. 105, pp. 41–54, May 2017.

[25] R. K. Sahu, S. Panda, U. K. Rout, and D. K. Sahoo, “Teaching learning based optimization algorithm for automatic generation control of power system using 2-DOF PID controller,” Int. J. Electr. Power Energy Syst., vol. 77, pp. 287–301, May 2016.

[26] R. K. Khadanga and A. Kumar, “Hybrid adaptive ‘ghost’-guided gravitational search and pattern search algorithm for automatic generation control of multi-area power system,” IET Gener. Transmiss. Distrib., vol. 11, no. 13, pp. 3257–3267, 2017.
M. Elsisi and H. Abdelfattah, “New design of variable structure control based on lightning search algorithm for nuclear reactor power system considering load-following operation,” *Nucl. Eng. Technol.*, vol. 52, no. 3, pp. 544–551, Mar. 2020.

M. Elsisi, “Improved grey wolf optimizer based on opposition and quasi learning approaches for optimization: Case study autonomous vehicle including vision system,” *Artif. Intell. Rev.*, pp. 1–24, Jan. 2022.

M. Elsisi, M. Soliman, M. A. S. Aboelela, and W. Mansour, “ABC based design of PID controller for two area load frequency control with nonlinearities,” *TEKOMNIKA Indonesian J. Elect. Eng.*, vol. 16, no. 1, pp. 58–64, 2015.

P. K. Pathak, A. K. Yadav, A. Shastry, and P. A. Alvi, “BWOA assisted PIDF(1+1) controller for intelligent load frequency management of stand-alone micro-grid,” *ISA Trans.*, pp. 1–15, Jun. 2022.

B. Khokhar, S. Daihya, and K. P. S. Parmar, “Load frequency control of a multi-microgrid system incorporating electric vehicles,” *Electric Power Compon. Syst.*, vol. 49, nos. 9–10, pp. 867–883, Jun. 2021.

F. N. Deniz, B. B. Alagoz, N. Tan, and D. P. Atherton, “An integer order approximation method based on stability boundary locus for fractional order derivative/integrator operators,” *ISA Trans.*, vol. 62, pp. 154–163, May 2016.

A. X. R. Irudayaraj, N. I. A. Wahab, M. G. Umamaheswari, M. A. M. Radzi, N. B. Sulaiman, V. Eerasamy, and R. Ramachandran, “A Matignon’s theorem based stability analysis of hybrid power system for automatic load frequency control using atom search optimized FOPID controller,” *IEEE Access*, vol. 8, pp. 168751–168772, 2020.

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