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Distributed voltage unbalance mitigation in islanded microgrid using moth flame optimization and firebug swarm optimization

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ABSTRACT

In recent trends, hybrid renewable energy sources (HRES) provide a better solution to meet energy demand, maximizing the productivity of electricity network. Due to the above-mentioned features, several researchers have given more attention to PV-wind-based HRES systems. A stable energy supply must be added, including batteries, diesel generator (DG), to meet demand in the event of a grid failure. To meet the voltage unbalance in islanded mode, the sizes of DG have need to be selected sensibly and HRES requires additional energy storage. To examine the voltage unbalance problems of an islanded microgrid, a hybrid optimization approach known as moth flame optimization (MFO) and firebug swarm optimization (FSO) is introduced. Due to various loads, harmonic distortion causes the voltage to unbalance, which can result in voltage collapse. To deliver a quick response in an island mode, a comprehensive algorithm called MFO-FSO control is proposed. MATLAB software is used to validate the results which demonstrate that the proposed MFO-FSO outperforms the conventional decoupling double synchronous reference frame (DDSRF) methods by reducing total harmonic distortion (THD) up to 1.21% and voltage unbalance factor (VUF) up to 1.427%.

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1. INTRODUCTION

The introduction of the microgrid has received significant interest in a number of nations worldwide in recent years. A microgrid is a configurable system made up of local loads, energy storage appliances, tracking and protection equipment, and several distributed generating. Whenever storage devices and intermittent renewable energy sources are coupled in a hybrid inverter-interfaced distributed generation (DG) microgrid, the network's dependability improves [1]. The microgrid may function in both the islanded and grid-connected modes, giving crucial loads more dependable electricity. The majority of research on islanded microgrids focuses on correction for voltage imbalance, power management for various DGs and forms of energy storage, and parallel-inverter power sharing and circulation limitation [2]. In order to achieve effective functioning of the entire electric power system, distributed generation and the growing penetration of renewable energy sources are characteristics of the continuing transition in the electric power system [3]. Multiple elements have been created to address voltage imbalance compensation and improve the quality of the voltage waveform [4]. An unbalance compensation technique is suggested in the earlier work [5] by providing the local controllers of DGs with the appropriate control signals [6]. Since the voltage imbalance factor whose value is lowered by the positive sequence voltage is the primary control variable used by the microgrid central controller. To solve this problem, a hybrid green energy system that combines many energy sources is developed [7]. This article seeks to present and critically evaluate an in-depth review of hybrid renewable energy sources (HRES) [8]. Additionally, the article examines various approaches utilized in every category [9]. The battery charges to the average battery state of charge (SoC) state once the power generation surpasses the load requirement [10]. However, some research groups were particularly interested in the operation of islanded grids [11]. The system control method is complicated; the extraction of positive, negative, and zero-sequence components is required; decoupling requires the fundamental positive sequence active and reactive powers. Additionally, the imbalanced voltage drop throughout the system impedance is overlooked, which causes the output voltage to perform worse [12]. Nonetheless, one of the biggest technical difficulties in managing and operating grid-connected or islanded microgrid systems is power quality (PQ) issues. One of the problems with low voltage microgrids is voltage imbalance. Unbalanced loads associated to the microgrid are frequently the cause of it. To guarantee a microgrid operating efficiently, it must be compensated. In order to attain optimal unbalance compensation, this research suggests a tertiary control that uses HRES as distributed compensators rather than additional compensation equipment, which could result in additional costs.

To attain the required power quickly, Sharma *et al.* [13] presented 3IMPL (3 phase improved magnitude phase locked loop) controller. The suggested strategy has the following benefits, including removing DC offset and noise and providing quick dynamic reflexes in the presence of unbalance and variations in solar insolation. In the suggested grid, PV was connected to DC via a boost converter, and Incremental Conductance was used to extract the peak power from PV. However, when the load was uneven, the total power generated was larger, which increases the current and shortens the battery's life. A two-layer hybrid control approach for distribution networks combined with solar sources has been presented by Alghassab *et al.* [14]. Creating a self-tuning $H\infty$ controller with fuzzy logic controller (FLC) that dynamically modifies the weighted controller parameters. Next, by maximising the batteries' currents, the principal control level is used to mitigate the voltage violations. Finally, using on-load tap-changer or OLTC optimal tapping selection depending on the secondary control level to regulate voltage during extreme over- and under-voltage events. It was challenging to balance the voltage factor when running islanded microgrids with solar panels and wind turbines since these resources are stochastic. To make up for unbalanced bus voltage and improve the load current distribution effect, Wang *et al.* [15] developed a voltage unbalance correction technique for DGs in an island microgrid. The suggested voltage controller has two separate control branches that each individually control fundamental positive and negative sequence voltages. To improve the power distribution effect of the DGs, the positive sequence has been included. While the introduction of the negative sequence was made to offset the voltage drop caused by the line impedance and reduce the negative sequence circulating current. A cost-effective way to reduce voltage unbalance is to install a parallel compensator, but doing so obviously raises investment costs as well. An innovative control approach for decreasing voltage unbalance in an islanded mode was demonstrated by Kavitha and Kumar [16]. By regulating the fewest number of loads possible, voltage unbalance was intended to be completely eliminated. The bus with greatest influence on voltage has been identified using the suggested technique. The most efficient bus was found using the provided method, and loads were then handled to lower the voltage instability. When microgrids were not adequately managed, power quality problems increased.

The decoupling double synchronous reference frame (DDSRF) has been shown by Ahmadi and Karimi [17]. The suggested control technique is applied to decentralized power systems which interface with inverter circuits. DDSRF has been improved and served as the foundation for the suggested control method. The enhanced DDSRF may effectively separate the positive and negative sequence components. The suggested control provides a quicker dynamic reaction and a more effective voltage unbalance adjustment than the DSRF-based control scheme. A DDSRF-based method was used to lessen the instability of the negative sequence element. But the fluctuations remained unabated. To confirm the operation of the distribution system, an efficient EMS has been presented in Fathy *et al.* [18]. The primary goal was to provide consistent power to the load under diverse producing situations. The need to monitor the performance of battery storage and renewable energy conversion technologies were maintained constant for different levels of RES power generation. This observation will be challenging to perform if the load changes. A new Social Spider Optimizer has been put forth in Kumar *et al.* [19] to balance out the demand among various RES. A cost-effective way to reduce voltage unbalance is to install a parallel compensator, but doing so obviously raises investment costs as well. Grid integrated functioning of multiple sources was demonstrated by Maaruf *et al.* [20]. Higher amount of power is achieved for both RES using the control scheme, and the load and DC-bus voltages are stabilized regardless of disturbances, changes in requirement, differences in radiance, wind velocity, resulting in effective organization. Additionally, because the PV Panel is precisely connected to DC-bus, redundant interface boost converters are not required, which reduces costs and system inefficiencies. To demonstrate the stable operation and divergence of the overall system, a Lyapunov candidate variable is used. The overshoots and undershoots of the reactions under the regulator, however, are noticeably higher. From the overall analysis, an extra power converter is used in all of these compensatory techniques to introduce reactive power in the negative sequence. Very few studies use DG interface converters to correct the imbalance voltage. To balance the common bus voltage, inverter is programmed to inject negative sequence current. Nevertheless, in order to produce the negative sequence current, an excess converter capacity is required, and in cases of extreme unbalance, the injecting current may be excessive. In this section, the primary goals are to create the hybrid energy system's most practical system configuration and its number of components. MFO-FSO is used for EMS to satisfy load demand and accomplish decentralized power supply using PV, wind, battery, and diesel.

The research’s major contributions are specified as: i) The suggested MFO-FSO controller allocates energy among renewable sources to corrects the power factors and reduces the voltage unbalance; ii) The suggested MFO-FSO algorithm calculates the adequate number of harmonic attenuations to satisfy the total harmonic distortion (THD) criterion; and iii) In a noisy environment or with inter-harmonic elements of the system, the suggested MFO-FSO modulator operates satisfactorily. The proposed MFO-FSO compensator helps to alleviate the resonance condition. The structure of this study is given as: i) The description of the proposed method is given in section 2; ii) The mathematical formulation of hybrid MFO and FSO are outlined in section 3; iii) Section 4 presents the MFO-FSO simulation and comparison outcomes; and iv) Conclusion is stated in section 5.

2. PROPOSED METHOD

For islanded electrical networks, a hybrid MFO-FSO strategy is suggested in this study. The aim is to control the fewest number of loads necessary to achieve voltage balance. The best way to determine which bus has the biggest impact on the energy at premature chromosome condensation (PCC) to use the recommended MFO-FSO approach. In current history, the MFO-FSO approach has gained importance, particularly as a renewable source is introduced to the transmission network. By using this technique, the resources that increases the grid's consistency and power quality are connected to the buses with the highest thresholds. The overall block diagram is revealed in Figure 1.

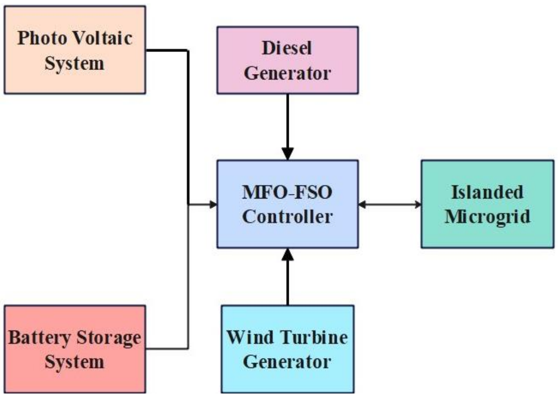

Figure 1. Overall block diagram

3. HYBRID MOTH FLAME OPTIMIZATION AND FIREBUG SWARM OPTIMIZATION

3.1. Moth flame optimization (MFO)

The employing of a moth population by MFO results in very high local optima rejection. Each moth is assigned a flame, and following every round, the order of the flames is changed to further explore the search space and lessen the possibility of local optimum stagnation. The flexibility and computational problems are resolved by the placement of the moth in the exploration area. MFO first determines the fitness values of each moth in the solution space by arbitrarily generating moths. The flame then serves to mark the ideal position. The moths' ability to update their position is controlled by the spiral movement function [21]. Subsequently using the location equation to decide where the flame should be placed optimally, MFO is modernized. MFO adopts the same procedures as the moth to modify its position and establish new locations [22]. Primarily, in (1) is constructed using a succeeding function.

$$M_i = S(M_i, F_j) \quad (1)$$

If M_i represents the i^{th} Moth, j^{th} flame is designated over F_j and S is quantified as spiral route. The moth route is characterized in (2).

$$S(M_i, F_j) = D_i . e^{bt} . cos(2\pi t) + F_j \tag{2}$$

D_i refers distance among the i^{th} and j^{th} flame. b denotes the constant; t states time boundary between [-1,1]. D_i is designed by (3).

$$D_i = |F_j - M_i| \tag{3}$$

In (3), M_i indicates i^{th} Moth, F_j indicates j^{th} flame; D_i shows nodes' distance which are stated in (4).

$$Flame\ no = round\ \left(N - 1 * \frac{N-1}{T}\right) \tag{4}$$

Where, the maximum flame number is specified as $N$and the maximum number of iterations are specified as T. MFO's results show that it can effectively solve a specific class of global optimization issues. For example, MFO was effectively used to solve a plan-related worldwide development issue. Predefined moth borders can cause early convergence and make it impossible to combine boundary sets. Hence, FSO is employed in conjunction with MFO to improve speed in anticipation of future enhancements to the traditional MFO that would result in more sophisticated execution.

3.2. Firebug swarm optimization (FSO)

The biological driving force behind the FSO approach is described in this article [23]. Firebugs possess two methods of acting: either they wander and examine alone or they act abundantly and create teams. These clusters are advantageous to the firebugs since it enables them to evade attackers and locate potential mating partners [24]. Due to the fact that each male bug swallows a group of N_F, the FSO procedure computes with $N_M$and $N_F$male and female bugs randomly dispersed throughout the candidate solutions. Let $m(m).F$ remain D via N_F, those segments associate to N_F. Therefore, as (5) and (6) are updated.

$$M_x \leftarrow repmat(m(m).x, 1, N_F) \tag{5}$$

$$M_y \leftarrow repmat(m(a).x, 1, N_F) \tag{6}$$

Where, random number is stated as a which considers in the range of 1 and NF. The repmat (A, m, n) offers a standard which includes m duplicates of A refers the row and n refers column. Thus, in case, A is taken as p by q, then repmat (A, m, n) produces mp by nq matrix which is stated as (7). Meanwhile these statistics in C_1 are chosen and better over C_2. When C_2 was kept lesser over C_1, FSO accomplished good results. The (8) displays the update rule which moves in the direction of toughest female.

$$m(m).F \leftarrow m(m).F + C_1 \odot (M_x - m(m).F) + C_2 \odot \left(M_y - m(m).F \right) \tag{7}$$

$$m(m).x \leftarrow m(m).x + C_3 \odot (g - m(m).x) \tag{8}$$

Correspondingly, FSO varies suggestively from other optimization methods such as GWO and PSO, where particle struggles for best results, therefore, in (9) is stated as,

$$m(m).x \leftarrow m(m).x + C_4 \odot (g - m(b).x) \tag{9}$$

The vector x is articulated on the basis of x^1 and x^2 which is stated in Equation (10).

$$x = x^1 + a(x^2 - x^1) = (1 - a)x^1 + ax^2 \tag{10}$$

The migration of male bug with position $\boldsymbol{m}(m).\boldsymbol{x}$) to fitting female bug that is reached over in (11). Additionally,the (11) is easy and comparatively inexpensive that is stated as (12). Similarly, in (13) is exploited to describe the feeble movement of female in the direction of several male bug.

$$m(m).x \leftarrow m(m).x + a(g - m(m).x) \tag{11}$$

$$m(m).x \leftarrow m(m).x + C_4 \odot (g - m(b).x) \tag{12}$$

$$m(m).F \leftarrow m(m).F + C_1 \odot (M_x - m(m).F) + C_2 \odot \left(M_y - m(m).F \right) \tag{13}$$

The two terms, $C_1 \odot(M_x - m(m).F)$ and $C_2 \odot(M_y - m(m).F)$ symbolizes the changes in direction of dominant and random male bug. Whereas maintaining the variety of potential solutions, this strategy facilitates the identification of the optimal response. The flowchart of MFO-FSO approach is revealed in Figure 2. Due to the impedance mismatch, the inverter and switches are placed under more strain, which will cause severe damage when there is heavy loading. The difference between the estimated and virtual impedances will then increase as a result of the adaptive method. The individual harmonic compensator evaluates each harmonic and accomplishes it at the appropriate level using the suggested MFO-FSO controller. Phase detection and harmonic component estimation are performed using the suggested MFO-FSO controllers [25]. The harmonics evaluation unit estimates both the fundamental and each individual harmonic component concurrently. The impedance adjustment element uses these approximations.

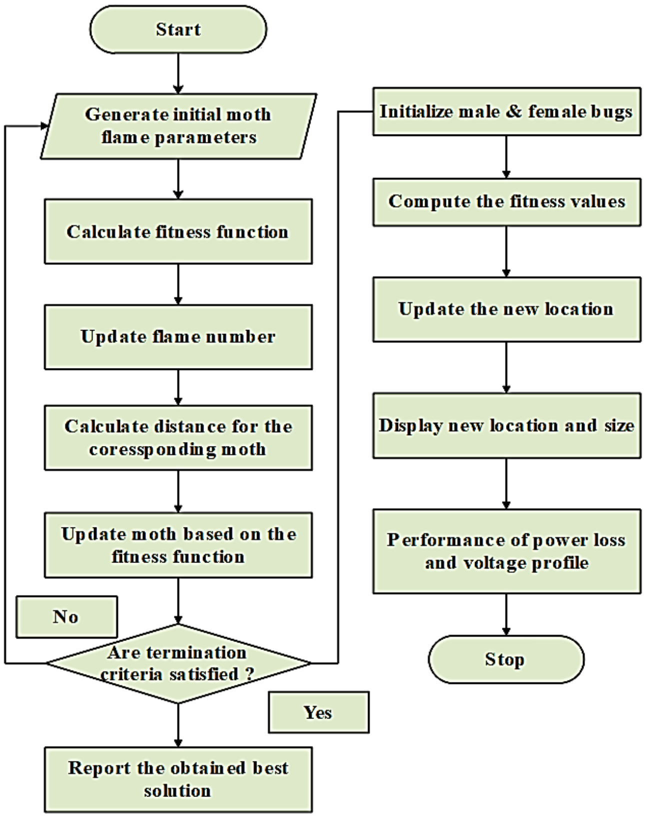

Figure 2. Flowchart of proposed MFO-FSO

4. RESULTS AND DISCUSSION

This research utilized MATLAB software to validate the findings. Utilizing MATLAB R2020a, which is powered by an intel core i5 CPU and 8 GB of RAM and runs on the Windows 11 computer system, the MFO-FSO is developed and simulated. The grid specifications including solar [25], wind [26], battery [27], diesel [28] and load values are shown in Table 1. While Table 2 shows the parameter ratings for proposed MFO-FSO. In some circumstances, a common grid-side filter inductor is included in the simulation. Figure 3 shows the simulation model of the proposed method.

Table 1. Specifications of the simulation model

L, R, C	Lf=6mH, 5 ohm & 10μF.
Load	R = 23.3 ohms, L = 85 mH.
Lead acid BES	253 V, 35 Ah.
Wind generator	3.7 kW, 3 phase 380 V, 5 0Hz, 4 Poles.
Solar photovoltaic array	Voc= 390 V, Isc = 5 A, Vpvmp = 335.87 V, 4.74 A and 1585 W.
Diesel generator (DG)	Fixed size = 40 W, Lifetime = 20 hrs

Table 2. Specifications of algorithm parameters

Parameters	Value
Number of search agent	30
Maximum iteration	500
Number of moth	20
Dimension	8
Lower and upper bounds	-100 and 100
Number of male and female firebugs	20 and 5
Population size	100

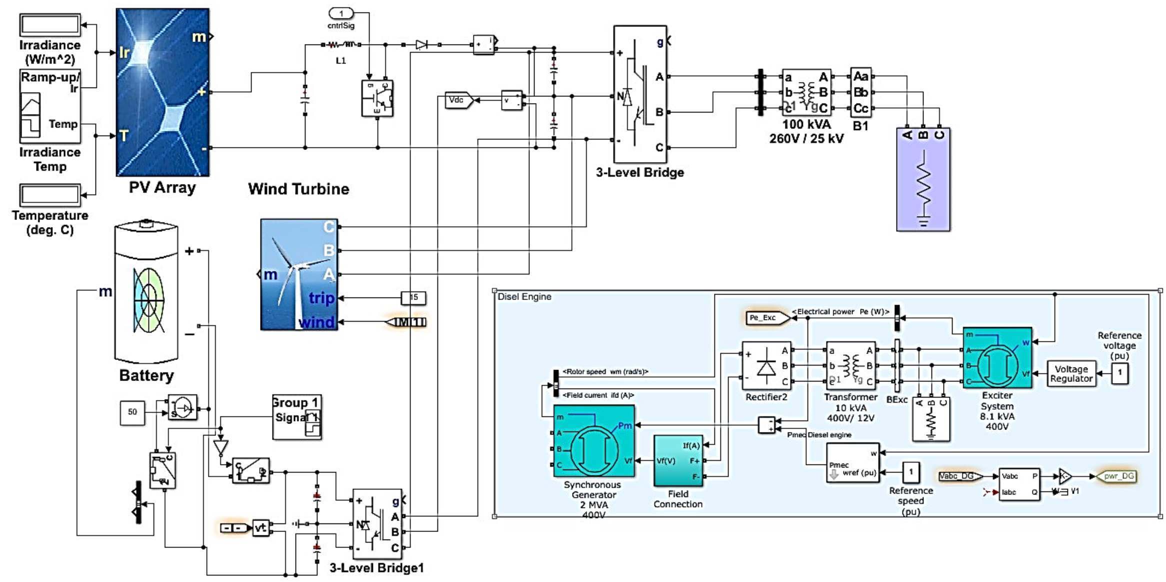

Figure 3. MATLAB representation for proposed model

4.1. Performance analysis

The proposed approach is discovered to be more efficient and to have a higher rate of convergence when contrasted with different current methods. A collection of multi-objective tests is resolved using the recommended methodology. The key objective is to produce electric energy by combining a battery, a standby power supply, and HRES. The innovative, quick, and highly precise MFO-FSO technique, that concurrently observes the MPP of PV under various illumination conditions, also maximizes the transformation of solar and wind into electricity.

4.1.1. MPPT voltage and current

Figure 4 and Figure 5 show the maximum power point tracking (MPPT) voltage and current results with respect to MFO, FSO and MFO-FSO methods. Individual MFO and FSO controllers lack the power of the recommended MFO-FSO controllers. The proposed MFO-FSO controller improved the outcomes by having higher MPPT current/voltage values, as shown in Figures 4 and 5.

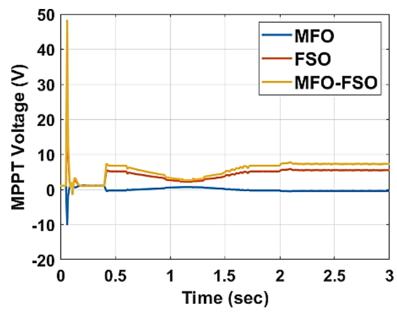

Figure 4. Graphical view of voltage

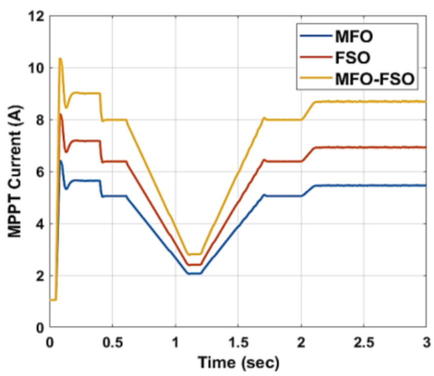

Figure 5. Graphical view of current

4.1.2. Grid voltage and current

The voltage from the grid is depicted graphically in Figure 6. On the other hand, the output voltage is lower than what is required for low radiation. The same graph shows this as having less power. The energy delivery from the PV system is represented as positive, whilst the power supply from the grid is represented as negative power. The voltage among 0.92s and 1.04s is shown in Figure 7. Figure 7 demonstrates unequivocally that while associated with conventional approaches for adjusting the demand, the proposed MFO-FSO delivers higher voltage levels. Figure 8 and Figure 9 depict the grid current and zoom elements of the suggested method.

4.1.3. Real and reactive power

Figure 10 and Figure 11 display the real/reactive power established by the grid respectively. As demonstrated in Figure 10 and Figure 11 The resulting MFO-FSO controller satisfies the grid's increased energy consumption. The wind turbine and batteries are switched under MFO-FSO control, which reduces harmonics carried by converters. The real and reactive power is increased with this MFO-FSO-based switching control without adding any distortions. Furthermore, surplus electricity from PV and wind generator is exploited to control battery backup, which is only exploited as reserve whenever the PV panel and wind generator will be unable to satisfy the load requirement simultaneously.

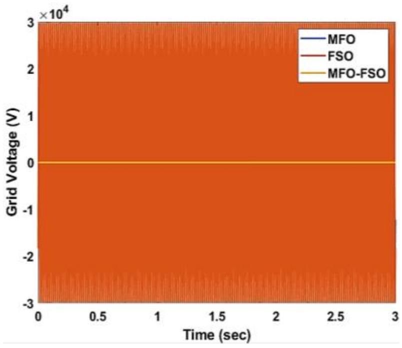

Figure 6. Grid voltage

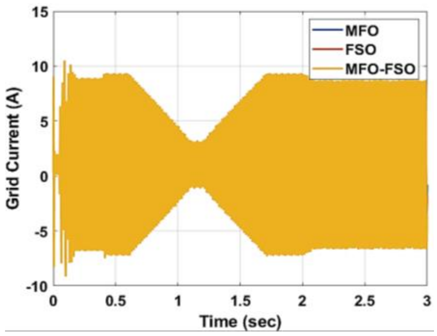

Figure 8. Grid current

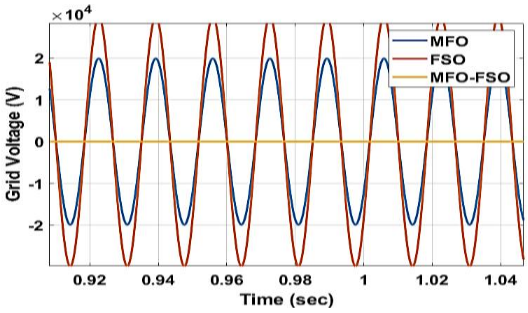

Figure 7. Zoom view of voltage variation

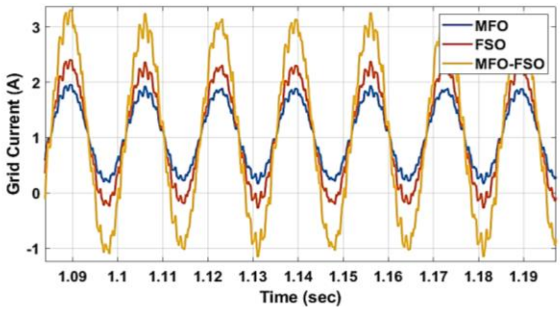

Figure 9. Zoom view of current variation

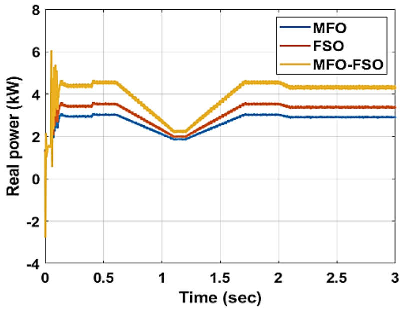

Figure 10. Real power

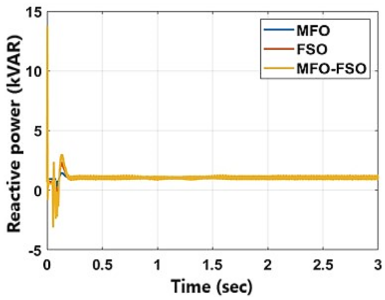

Figure 11. Reactive power

4.2. Analysis of voltage unbalance factor

For qualitative analysis, this study has implemented various swarm intelligence techniques such as crow swarm optimization (CSO), particle swarm optimization (PSO), glowworm swarm optimization (GSO) and cockroach swarm optimization (CRSO) to mitigate the voltage unbalance factor in islanded microgrid. The performances of proposed MFO-FSO algorithm with existing CSO, PSO, GSO and CRSO are tabulated in Table 3. From the Table 3, it clearly shows that proposed MFO-FSO outperformed the other swarm intelligence methods by achieving less VUF of 1.427%. While the CSO, PSO, GSO, CRSO, MFO and FSO has achieved VUF of 3.241%, 3.497%, 2.935%, 2.554%, 2.295% and 2.273% respectively.

Table 3. Performance analysis of various optimization methods

Optimization methods	VUF (%)
CSO	3.241
PSO	3.497
GSO	2.935
CRSO	2.554
MFO	2.295
FSO	2.273
Proposed MFO-FSO	1.427

4.3. Comparative analysis

The efficiency of RES with the MFO-FSO regulator is confirmed by contrasting it with earlier RES designs. The suggested MFO-FSO control is contrasted against the current LMS 3IMPL [13] to show the originality of control algorithms. The statistical assessment of THD is displayed in Table 4. From the Table 4, moth flame optimization with improved firefly algorithm (MFO-IFFA) has achieved a total harmonics distortion (THD) of 1.60% which is higher than proposed MFO-FSO.

Table 4. Comparison of THD

Method	THD (%)
BPF	5
LMS	6
SOGI	4
3IMPL [13]	3
MFO-IFFA	1.60
Proposed MFO-FSO	1.21

Whenever the phase 'a' of the demand is eliminated, the amplitude element of the LMS and SOGI regulation methods displays distortions only when input signal displays combined Switching losses and disturbance. However, as seen in Figure 12, fast Fourier transform (FFT) analysis of the suggested MFO-FSO control which estimates fewer harmonics of 1.21%. Voltage unbalance factor (VUF) comparative analysis is shown in Table 5. From the Table 5, it clearly shows that the suggested MFO-FSO obtains a superior VUF of 1.427 %, which is lower and better than MFO-IFFA (i.e.) achieved 1.748% only. The graphical illustration of VUF analysis is shown in Figure 13.

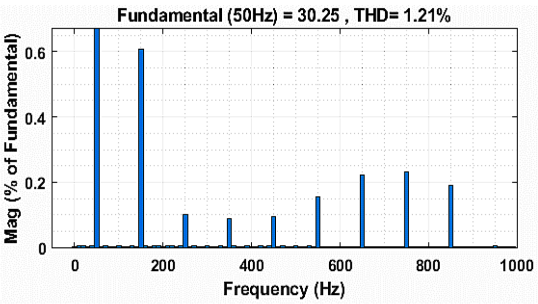

Figure 12. FFT analysis

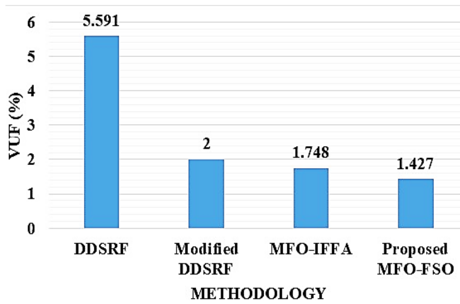

Figure 13. Graphical illustrations of VUF comparison [17]

Table 5. Evaluation of VUF

Method	VUF (%)
DDSRF [17]	5.591
Modified DDSRF [17]	2
MFO-IFFA	1.748
Proposed MFO-FSO	1.427

Table 6 compares the analysis of proposed method with the currently used MPPT approach [19]. Table 6 demonstrates that for all hybrid renewable sources, the proposed MFO-FSO achieves more power when compared to the current MPPT. The analysis takes into account a number of crucial factors, including how long each strategy takes to compute. Table 7 displays the computational time analysis for popular techniques including the social spider optimizer (SSO), grey wolf optimizer (GWO), and Harris Hawk's optimizer (HHO), along with the suggested MFO-FSO. In contrast, HHO uses renewable sources and completes its computation in 10416.69 seconds, compared to 4546.36 seconds for GWO and 4497.32 seconds for SSO. Table 7 demonstrates that the suggested MFO-FSO approach outperforms the HHO, GWO, and SSO [18] methods with a better computational time of 4193.54 seconds.

Table 6. Comparison of overall power

Environmental conditions	Time (Min)	PV (W)		Wind (W)		Battery (W)		Diesel (W)	
		MPPT [19]	Proposed MFO-FSO	MPPT [19]	Proposed MFO-FSO	MPPT [19]	Proposed MFO-FSO	MPPT [19]	Proposed MFO-FSO
PV	0	50	66.54	35	46.63	2	13.54	11.70	19.67
Irradiation –	10	54.26	67.78	42.18	48.59	-22.2	0.03	15.66	17.64
1000	20	54.26	68.48	42.18	50.28	-43.14	0.94	13.54	24.61
Temp – 35'	30	54.26	69.75	42.18	52.39	-43.14	4.08	15.46	27.31
Speed of wind –	40	54.26	71.44	42.18	54.24	-22.17	7.04	19.77	31.64
9 m/s	50	54.26	73.99	42.18	56.13	2.9	10.77	14.34	34.77
	60	54.26	74.96	42.18	57.99	16.13	21.05	18.75	30.14
	70	54.26	75.54	42.18	59.49	22.24	27.35	17.64	19.33

Table 7. Comparative analysis with existing methods

Approaches	Computational Time (sec)
HHO [18]	10416.69
GWO [18]	4546.36
SSO [18]	4497.32
Proposed MFO-FSO	4193.54

4.4. Discussion

Moth flame optimization (MFO) and firebug swarm optimization (FSO), a hybrid optimization technique is presented to investigate the voltage unbalance issues of an islanded microgrid. Voltage imbalance brought on by harmonic distortion from different loads can lead to voltage collapse. The current techniques, including the MPPT approach [19], DDSRF [17], SSO [18], and 3IMPL [13], were used for the comparison. The proposed MFO-FSO control is analyzed using the fast Fourier transform (FFT), which estimates 1.21% fewer harmonics. In addition, the proposed MFO-FSO is compared with the computational time analysis for common approaches such as the SSO [18], GWO [18], and HHO [18]. HHO, on the other hand, computes using renewable energy and finishes in 10416.69 seconds, whereas GWO and SSO take 4546.36 and 4497.32 seconds, respectively. The proposed MFO-FSO method has a better calculation time of 4193.54 seconds compared to the HHO, GWO, and SSO [18] methods.

4 CONCLUSION

In this study, an MFO-FSO controller is used to evaluate the concept of VUF in an island network. Generally, using solar power alone to stimulate rural regions can be expensive. To reduce the dependency on PV, wind power generation, DG is introduced which minimizes the overall cost. The chosen strategy involved improving each link in the chain one at a time. This system is equipped with a PV/wind/DG/battery system protection device that can respond to overvoltage, Undervoltage, and frequency changes. By using the proposed MFO-FSO, the impedance of negative sequence voltage drop is fixed, and the load current distribution is also improved with virtual resistivity. The simulation results demonstrate that the suggested MFO-FSO outperforms the current 3IMPL and DDSRF techniques, achieving a reduced THD of 1.21% and a greater VUF of 1.42%. According to the simulation results, the proposed control method efficiently corrects voltage unbalance and evenly distributes the load current. In, the future, these studies can be done to examine the characteristics of voltage unbalance using a variety of loads and situations.

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