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Mayfly Algorithm for Optimal Integration of Hybrid Photovoltaic / Battery Energy Storage / D-STATCOM System for Islanding Operation

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Abstract: In today's power system design studies, autonomous and self-healing capabilities are becoming increasingly important. Renewable energy (RE) integration, on the other hand, is geared at long-term sustainability. In this regard, a hybrid energy system consisting of a photovoltaic (PV) source, battery energy storage (BESS), and distribution-static synchronous compensator (D-STATCOM) is proposed for optimal design and integration in the electrical distribution network (EDN) when short-term islanding operational requirements are taken into account. When considering grid-connected mode, the PV system is initially optimally allocated towards loss minimization. Following that, the capacities of BESS and D-STATCOM are assessed in the context of a short-term islanding scenario. The optimization problem is tackled utilising a recent meta-heuristic mayfly optimization algorithm (MOA) in both stages. The simulations are run on an IEEE 33-bus EDN network. By having optimal PV system in grid-connected mode, it is observed that real power losses are reduced to 111.03 kW from 210.998 kW and reactive power losses are reduced to 81.684 kVAr from 143.033 kVAr. In addition, the minimum voltage in the network is raised to 0.9424 p.u. from 0.9038 p.u. On the other hand, by designing hybrid energy systems using PV, BESS, and D-STATCOM, the network is able to serve the entire load even under islanding conditions. MOA's competitiveness in solving difficult non-linear multi-variable optimization problems was demonstrated in comparative research with literature publications. In addition, the proposed hybrid energy system can cope with the uncertainties and other requirements of current grids.

Keywords: Electrical distribution network, Photovoltaic system, Mayfly algorithm, Battery energy storage system, D-STATCOM, Islanding operation, Loss minimization.

1. Introduction

The increasing threat of global warming has prompted a number of countries to construct 100 percent renewable energy (RE) systems [1]. In addition, for reliable supply, remote places and stand-alone applications are receiving a lot of attention [2]. Techno-economic benefits and the high pace of depletion of conventional fuel sources become important motivators to create RE-based hybrid energy systems in this scenario. Photovoltaic (PV) and wind turbine (WT) technologies are highly adapted and employed to construct hybrid energy systems among other forms of RE [3]. However, because of their reliance on weather conditions, these technologies are unreliable, necessitating the use of energy storage systems (ESS) [4]. On the other hand, around 70-80 percent of power system components are inductive and operate as reactive power sinks. Reactive power transfer over greater distances is known to create increased losses and low voltage, which can lead to voltage collapse. Reactive power correction in transmission systems and at load sites becomes critical in terms of stability to avoid this [5]. Capacitor banks (CBs) and D-STATCOM are such major feasible reactive power sinks at distribution side.

In literature, integration of various active and reactive power sources at distribution side are highly highlighted as optimal allocation of distributed generation (OADG) [6]. In [7], the gbest-guided artificial bee colony (GABC) algorithm is presented for determining the optimum allocation of different types of DGs considering different loading levels and different types of loads. The impact of DGs is examined for technical and economic improvements in distribution system operation. In [8] stud krill herd algorithm (SKHA), a new meta-heuristic algorithm is introduced for multiple DG allocation and sizing in two different radial systems and one real time system for improving loss minimization and hence voltage stability achievement under different loading conditions. In [9], a new meta-heuristic algorithm, the hybrid grey wolf optimizer (HGWO), is used. The objective function is to reduce the losses and consequently enhance the voltage profile on each bus. The results acquired are compared with those of other algorithms and matched to the best feasible outcome. Different numbers of DGs are emulated using the IEEE-33, 69, and 85 bus systems. Whale optimization algorithm (WOA) is a multi-objective optimization algorithm introduced in [10], which seeks to identify the best placement and size for DGs while reducing power loss, voltage profile improvement, and operational expenses. Comprehensive teaching learning-based optimization (CTLBO) algorithm is proposed to allocate multiple DGs and also for network loadability enhancement by reconfiguring them, reduction of active power losses, enhanced voltage profile, voltage stability index, and qualified loadability index under all constraints in different radial networks [11]. In [12], moth search optimization (MSO) based OADGP is presented with on-load-tap-changer (OLTC) controls for improving EDN performance under light, normal, and peak loading scenarios in order to achieve techno-economic advantages. In [13], WOA is used as an optimization technique for various locations of DGs to reduce power loss, enhance voltage profile, and increase economic benefits. The results are tested on two different radial systems and are compared with other heuristics methods. QODELFA combines the quasi-opposition-based learning concept (QOBL) and differential evolution (DE) with Lévy flights, and it is implemented for OADGP by aiming multi-objectives loss, voltage deviation, and voltage stability index [14]. The genetic moth swarm algorithm (GMSA) is a hybrid approach for evaluating the appropriate position and scale of renewable DG sources on EDN to reduce loss [15]. A novel hybrid technique that combines IHHO and particle swarm optimization (PSO) is presented to optimize the integration of renewable DGs in EDN operations for techno-economic benefits [16]. The harris hawks optimizer (HHO) and its improved form based on the rabbit location rather than the random position (IHHO) are provided in [17] for solving the OADG problem as a single objective function of real power loss reduction. When implementing a multi-objective function, voltage and voltage stability index are taken into account in addition to loss reduction. In [18], a novel hybrid approach based on monarch butterfly optimization (MBO) and a technique for order of preference by similarity to ideal solution (TOPSIS) is proposed for minimizing annual energy loss, mean node voltage deviation, average branch loadability limits, and RE fluctuations while solving OADGP with dispatchable and non-dispatchable type DG mix. In [19], Pathfinder Algorithm (PFA) is proposed for optimal allocation of PV system in multi-later distribution network considering resilience requirement. The manta ray foraging optimization approach (MRFO) [20] is used to enhance the performance of EDN in terms of loss, VD, and VSI-1 reduction by optimizing the integration of various types of DGs. In [21], a new bio-inspired algorithm, manta ray foraging optimization (MRFO), is employed, considering reduction of losses as the major target by determining a suitable size and ideal placement. Simulation results of three different radial systems with three different numbers of DGs are implemented and results are compared with various heuristic algorithms.

Optimal DG integration, according to the reviewed works, can improve EDN performance in both technological and environmental aspects. These methods are efficient while EDN is connected to the grid, but not when islanding. This causes instability or load restrictions when islanding mode is used. For efficient functioning, energy storage systems and reactive power sources must be integrated [22]. There is also the no-free-launch (NFL) theorem, which says that many heuristic methods have local bests and may not work for all optimization tasks.

As a result, researchers are still motivated to create simple and efficient meta-heuristic algorithms. Mayfly Optimization Algorithm (MOA) is one such meta-heuristic algorithm introduced in 2020 by drawing inspiration from the foraging and mating behaviour of mayflies [24]. In this context, the following are the major contributions of this paper:

1. At first, the problem of optimal allocation of PV system is solved for loss minimization under grid connected mode.
2. In the second stage, optimal hybrid energy system with PV, BESS, and D-STATCOM is proposed for sustaining the network even under islanding conditions.

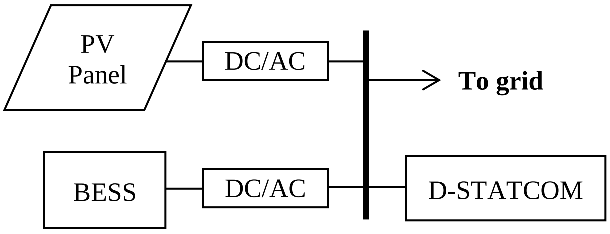

Figure. 1 Schematic diagram of proposed hybrid PV/ BESS/ D-STATCOM system

3. Recent meta-heuristic MOA algorithm is used to solve the proposed optimization problem with a lot of different types of variables and constraints.
4. The simulations were performed on IEEE 33-bus RDN and compared the computational efficiency of MOA with literature work.

The rest of the paper is organized as follows. The mathematical modelling of proposed hybrid energy system components like PV, BESS, and D-STATCOM is explained in Section 2. In Section 3, an optimization problem is formulated for real power loss minimization. In Section 4, the concept of MOA is explained mathematically. In Section 5, simulation results obtained on IEEE 33-bus EDN by using MOA are explained. At the end, the major contributions and research findings are summarized in Section 6.

2. Proposed hybrid system modelling

In this section, the modelling of proposed hybrid energy system using photovoltaic (PV), battery energy storage system (BESS) and distribution-static synchronous compensator (D-STATCOM) is explained. The schematic diagram of PV/ BESS/ D-STATCOM is shown in Fig. 1.

2.1 Photovoltaic system

The power generation by a PV system is dependent on two major parameters namely solar radiation and cell temperature. By considering these factors, the following model is presented.

$$PV_{a(t)} = N_s \times N_p \times PV_{(t)} \times \varphi_{loss} \quad (1)$$

$$PV_{(t)} = PV_m \frac{G_{(t)}}{G_r}\left[1 + \rho_{pv}\left(T_{c(t)} - T_r\right)\right] \times \varphi_{in} \quad (2)$$

$$T_{c(t)} = T_{a(t)} + \left[\frac{(T_{NOCT}-20)}{0.8}\right] \quad (3)$$

where $PV_{a(t)}$ and PV_m are the actual power generation by PV system and panel rated power in kW; N_s and N_p are the number panels in series and parallel connections; G_r and $G_{(t)}$ are the radiation at SCT and in a location; T_{NOCT}, $T_{a(t)}$ and T_r are the cell nominal operation, ambient and reference temperatures; φ_{in} is the inverter efficiency, φ_{loss} is the factor for cable resistance, dust and other losses.

2.2 Battery energy storage system

The deficit energy beyond PV system generation is proposed to meet by battery energy storage system (BESS). For this, first, daily average deficit power is determined for a typical day and later, the required BESS capacity is evaluated considering time of islanding mode, as follows:

$$P_{df} = \left\{\frac{1}{24}\sum_{t=1}^{24}\left[P_{d(t)} - PV_{a(t)}\right]\right\} \quad (4)$$

$$BESS_c = \frac{P_{df} \times t_i}{D_d \times V_b \times \tau_b \times \rho_a} \quad (5)$$

where $BESS_c$ is the BESS capacity in kAr, P_{df} is the daily average deficit power in kW, $P_{d(t)}$ is the network demand at hour-t in kW, D_d is the battery depth of discharge, ρ_a is the ageing factor, V_b is the battery nominal voltage in volts, τ_b is the battery temperature correction factor.

2.3 D-STATCOM

D-STATCOM is a flexible AC transmission system (FACTS) device suitably integrated at distribution network known as D-FACTS that may inject or absorb reactive current at the linked bus. It comprises of a three-phase voltage source converter (VSC)/ current source converter (CSC), a DC capacitor/DC voltage source/energy storage system (ESS) and an AC filter, which is often connected to the distribution network through a coupling transformer. In general, D-STATCOM functions as a synchronized voltage source that can manage the magnitude and angle of AC bus/ grid bus voltages, allowing it to effectively handle active and reactive power exchanges from/to grids by working in either inductive or capacitive mode. The reactive power from D-STATCOM is modelled by,

$$Q_{ds} = -|V_{ds}|^2 b_{ds} + |V_{ds}||V_g| b_{ds} \quad (6)$$

where Q_{ds} is the D-STATCOM reactive power in kVAr, $|V_{ds}|$ and $|V_g|$ are the VSC voltage of D-STATCOM and grid-bus voltages, respectively; b_{ds} is the susceptance of the D-STATCOM interface between grid-bus and VSC.

Under ideal conditions, D-STATCOM cannot be able to provide active power support to the utility. Also, it can able to generate reactive power to the grid if $|V_g| > |V_{ds}|$ for which Q_{ds} becomes negative. On the other hand, it absorbs reactive power from grid if $|V_g| < |V_{ds}|$ for which Q_{ds} becomes positive.

3. Problem formulation

The location and sizing of hybrid PV/ BESS/ D-STATCOM system is optimized by considering loss minimization as major objective.

$$F = min\{P_{loss}\} = \sum_{k=1}^{n_{br}} |I_{b(k)}|^2 r_{b(k)} \quad (7)$$

The objective function constrained by bus voltage, branch current, active and reactive power balance, radial configuration, as defined by,

$$|V_{(i)}^{min}| \leq |V_{(i)}| \leq |V_{(i)}^{max}|, \forall i = 1: N_b \quad (8)$$

$$|I_{b(k)}| \leq |I_{b(k)}^{max}|, \forall k = 1: N_{br} \quad (9)$$

$$P_{D(t)} + P_{loss} \leq PV_{a(t)} + P_{grid} + BESS_c \quad (10)$$

$$Q_{D(t)} + Q_{loss} \leq Q_{ds} + Q_{grid} \quad (11)$$

$$N_{br} = N_b - 1 \quad (12)$$

where $|V_{(i)}|$ and $|I_{b(k)}|$ are the voltage magnitude of bus-*i* and current of branch-*k*, respectively; $P_{D(t)}$ and $Q_{D(t)}$ are the total real and reactive power demand, respectively; P_{grid} and Q_{grid} are the active and reactive powers from grid, respectively; N_b and N_{br} are the number of buses and number of branches, respectively.

4. Mayfly algorithm

Zervoudakis K and Tsafarakis S are developed the Mayfly Optimization Algorithm (MOA) in 2020, by inducing mating behaviour in Mayflies [24], which are insects belonging to the order Ephemeroptera, which is part of an ancient group of insects known as Palaeoptera. In comparison to other popular algorithms, by process itself, it behaves like an hybrid algorithm by combining the features of particle swarm optimization (PSO), genetic algorithm (GA), and flower pollination algorithm (FPA). This section provides a mathematical explanation of the MOA process, as well as the sequential stages involved in solving the proposed optimization problem of this research.

In the initial phase, MOA, like all population search algorithms, creates random search spaces for the solution candidates, which are a group of male mayflies, and similarly, the position vector for all search agents, which is given by $M = [m_1: m_D]^T$, $m_{i,min} \leq \forall m_i \leq m_{i,max}$. Through evaluation of initial position vector performance in relation to the proposed objective function *F* described in Eq. (7), it is possible to determine the velocity vector $V = [v_1: v_D]^T$ that will be used to update the position of mayflies in search space based on their social and individual experiences in searching. Thus, the search agents move to new position based their own fitness (m_{best}), and the fittest position among the entire swarms/ mayflies ($m_{b,best}$) is processed.

4.1 Characterization of male mayflies' stochastic behaviour

The search agents migrate to a new position based on their individual fitness (m_{best}), and the position that is considered to be the fittest among the complete swarms/ mayflies ($m_{b,best}$) is then processed. For the next phase, the new position of male mayflies $m_i(k+1)$ is determined by its current position $m_i(k)$ and updated velocity for the next step $v_i(k+1)$, which are calculated according to the following relationship:

$$m_i(k+1) = v_i(k+1) + m_i(k) \quad (13)$$

Due to the fact that the male mayfly's nuptial dance continues at a height of many metres, the algorithm provides them with a constant speed, which is determined using Eq. (14).

$$\begin{aligned} v_{id}(k+1) = {} & v_{id}(k) + \\ & c_1 \times exp(-\vartheta D_x^2)[m_{id,best}(k) - m_{id}(k)] + \\ & c_2 \times exp(-\vartheta D_g^2)[m_{id,gbest}(k) - m_{id}(k)] \end{aligned} \quad (14)$$

where, c_1 and c_2 are the two positive attraction constants which scale the proportion of cognitive and social factors, respectively; ϑ reduces mayfly visibility in relation to one another, D_x and D_g are the distances between (m_{id} and $m_{id,best}$), (m_{id} and $m_{id,gbest}$), $v_{id}(k)$ and $v_{id}(k+1)$ are the velocity of *i*th mayfly in *d*-dimension for the current and next iterations respectively.

$$\|D_x\| = \sqrt{\sum_{j=1}^{D} (m_{ij} - M_{ij})^2} \quad (15)$$

where m_{ij} is the *j*th element of *i*th mayfly and M_{ij} corresponds to either $m_{id,best}$ and $m_{id,gbest}$. For the minimization problem, the local best and global best populations $m_{id,best}$ and $m_{id,gbest}$ for the current iteration is computed as follows:

$$\begin{aligned} & if\ F\big(m_{id}(k+1)\big) < F\big(m_{id,best}\big), \\ & \qquad m_{id,best} = m_{id}(k+1) \\ & else,\ m_{id,best} = m_{id,best} \end{aligned} \tag{16}$$

$$m_{id,best} = min\{F\big(m_{id,best}\big)\forall i \in D\} \tag{17}$$

For a successful mating process, the mayflies in the swarm should maintain their unique nuptial dance characteristic. In this, their up-and-down movements are modelled by,

$$v_{id}(k+1) = v_{id}(k) + n_d \times r_i \tag{18}$$

where n_d and r_i are the nuptial dance coefficient and a random variable between [-1, 1], respectively. This dance feature creates a stochastic behaviour to the algorithm.

4.2 Characterization of female mayflies' stochastic behaviour

In opposition to the male mayflies, nature, the female mayflies do to form in a swarm and rather they move individually to male mayflies for breeding. Let's $f_{id}(k)$ is the current position of an *i*th female mayfly in the search space dimension *d*, $f_{i,min} \leq \forall f_i \leq f_{i,max}$, its position is updated by velocity factor to the current and is given by,

$$f_i(k+1) = v_i(k+1) + f_i(k) \tag{19}$$

Here, the attraction is modelled deterministic instead of random by assuming the mating process between 1st best male and 1st female mayflies, 2nd best male and 2nd female mayflies and so on as their fitness function in the current iteration. For this mating, the velocities of female mayflies are updated by,

$$\begin{aligned} & if\ F\big(f_i(k)\big) > F\big(m_i(k)\big), \\ & \qquad v_{ij}(k+1) = v_{ij}(k) + \\ & \qquad c_3 \times exp\big(-\vartheta D_{xf}^2\big)[m_i(k) - f_i(k)] \\ & else\ F\big(f_i(k)\big) \leq F\big(m_i(k)\big) \\ & \qquad v_{ij}(k+1) = v_{ij}(k) + fl \times r_j \end{aligned} \tag{20}$$

where $v_{ij}(k)$ is the velocity of *i*th female mayfly in dimension *j = 1:D* at present current iteration *k*; $f_{ij}(k)$ is the current position of *i*th female mayfly in dimension j ; c_3 is the positive attraction coefficient, ϑ reduces mayfly visibility in relation to one another, and Cartesian distance between male and female mayflies which can be determined by Eq. (15), fl and r_j are the random walk for the female mayflies which are attracted by male mayflies, and a random variable between [-1, 1], respectively.

4.3 Characterization of mating process

The mating process of male and female mayflies is simplified by using crossover operator of genetic algorithm (GA) as per their position in the swarm w.r.t. their fitness function. The results of the crossover are two offspring as generated by,

$$\begin{aligned} OS_1 &= R * M_p + (1-R) * F_p\ \& \\ OS_2 &= R * F_p + (1-R) * M_p \end{aligned} \tag{21}$$

where R is a random number between specified range, M_p and F_p are the male and female parents, respectively; and OS are the two offspring by initial values are zero.

5. Results and discussion

The simulations are performed on a core i7 2.6 GHz 16GB RAM PC with MATLAB 2021b environment. The proposed meta-heuristic MOA is implemented on standard radial IEEE 33-bus distribution system [25]. Initially, the total load and distribution losses are assumed to be supplied by grid alone. The analysis of network performance under these conditions is considered as Case 1. In order to minimize the grid-dependency of the whole system, the optimal location and sizes of solar photovoltaic system are determined and this scenario is treated as Case 2. The obtained results of MOA are compared with literature works. Later, in Case 3, the system assumed under islanding mode due to faulty conditions at upstream network, the required capacity of BESS and D-STATCOM at optimal location are determined. In Case 4, for different islanding time periods, the required BESS capacities are determined.

5.1 Case 1

The test system consists of 33 buses and inter-connected by 32 branches. The total real and reactive power loads are 3715 kW and 2300 kVAr. In this case, the system is considered as grid-connected mode without considering PV, BESS and D-STATCOM in systems. Thus, the total load and losses are served by upstream network. By performing Radial Distribution Power Flow (RDPF) [26], the total real and reactive power losses are determined as 210.998 kW and 143.033 kVAr. The minimum voltage

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Table 1. Comparison of MOA with literature

Method	bus #	Size (kW)	P_{loss} (kW)
Base	-	-	210.548
GABC [7]	30	1543	125.15
MRFO [21]	6	2590.2	111.021
CTLBO [11]	8	3609.8	192.72
HGWO [9]	6	2590	111.018
WOA [13]	6	2589.6	111
SKHA [8]	6	2590.215	111.018
KHA [8]	6	2590.216	111.018
PFA [19]	6	2590.264	111.03
MOA	**6**	**2590.264**	**111.03**

magnitude of 0.9038 p.u. is sensed at bus-18. Including losses, the grid-power imported is 3925.998 kW + j 2443.033 kVAr and the system grid-dependency is 100%.

5.2 Case 2

In this case, the grid-dependency of the system is proposed to minimize by integrating a PV system optimally. Considering real power loss minimization as an objective function, the proposed MOA is implemented. The search spaces for location and sizes are considered as [bus-2, bus-33] and [0, 3715 kW], respectively. The size of 2590.264 kW is obtained at bus-6 and results for real and reactive power losses of 111.03 kW and 81.684 kVAr, respectively. Also, the minimum voltage at bus-18 is raised to 0.9424 p.u. This optimal PV system caused to reduce the grid-dependency to 32.3%. The results of proposed FPA are compared with and presented in Table 1. From this comparative study, it can be observed MOA is superior in terms of global optima than GABC [7], MROF [21], CTLBO [11]. However, it has shown its competitiveness for HGWO [9], WOA [13], SKHA, KHA [8] and PFA [19].

5.3 Case 3

Considering islanding mode, the network performance is re-evaluated by treating bus-6 as slack bus. Under this condition, including losses, the deficit power of 1221.886 kW and 2376.011 kVAr are the required and optimal sizes of BESS and D-STATCOM, respectively. By performing Radial Distribution Power Flow (RDPF), the total real and reactive power losses are reduced to 97.15 kW and 76.011 kVAr. The minimum voltage magnitude is raised to 0.9568 p.u. at bus-18. Since the whole system is serving by its own energy sources, the grid-dependency is now 0%. In comparison to Case 1 and Case 2, the system performance is observed better even under islanding conditions. For three cases, the real and reactive power losses and voltage profiles are given in Fig. 2 and 3, respectively. In comparison to Case 1 and Case 2, the voltage profile is significantly improved in Case 3, even though the network is islanded from the main grid and serving the total load without load reduction.

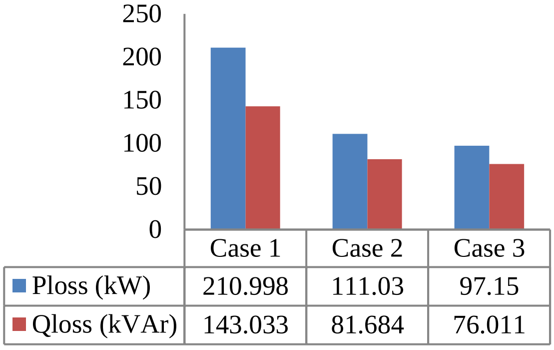

Figure. 2 Comparison of losses for all cases

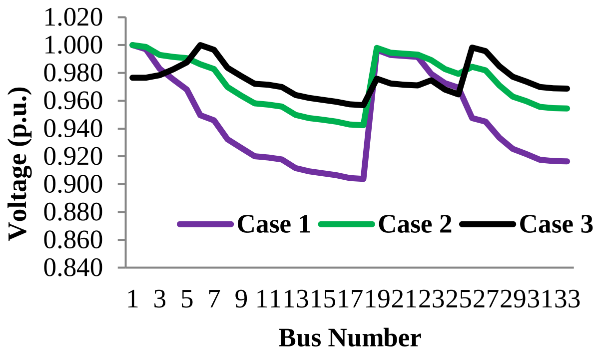

Figure. 3 Comparison of voltage profile for all cases

Initially, the energy yield by the PV system (2590.264 kW) is evaluated using PVWatts [27] considering metrological data of Bangalore (Lat, Lon: 12.95^0, 77.55^0), Karnataka. The AC energy output from PV system is evaluated using design parameters as follows: array tilt = 20^0, array azimuth = 180^0, system losses = 14.08%, invert efficiency = 96%, DC to AC Size ratio: 1.2. From the results of PVWatts, the average daily power generation is determined as 469.30 kWh. Using the data given in [25], the average hourly demand is determined for the network as 2850.61 kWh. From these values, the deficit power is computed as 2381.31 kWh. The parameters in BESS design are chosen as follows: $D_d = 0.8$, $\rho_a = 0.85$, $V_b = 48$ V and $\tau_b = 0.964$ [28]. Finally, the required BESS capacity is 75.68 kAh.

6. Conclusion

In this paper, a recent and efficient meta-heuristic mayfly optimization algorithm (MOA) is presented for solving the optimal allocation of photovoltaic (PV) distributed generation (DG) in the electrical distribution network (EDN), considering grid connected mode. Later, to sustain under islanding mode, optimal design and allocation of hybrid energy systems considering PV, battery energy storage (BESS), and distribution-static synchronous compensator (D-STATCOM) The simulations were performed on the IEEE 33-bus EDN. In comparison to the base case, the network performance is improved significantly in terms of reduced losses and improved voltage profile by having an optimal PV system in the network. And, the proposed hybrid energy system is well capable of meeting the entire network load. Thus, the requirement for autonomous and sustainable microgrids towards continuously increasing electricity demand. On the other hand, MOA is seen as superior to some heuristic approaches used in the literature and is also very competitive with various approaches.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

M.S. Giridhar: Conceptualization and writing-original draft preparation. K. Radha Rani: Writing-original draft preparation and formal analysis. P Sobha Rani: Writing-review and editing. Varaprasad Janamala: Conceptualization, methodology, software simulation and results validation.

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