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Improving the Operation of a Distribution Network by Optimal Siting and Sizing of Photovoltaic-Battery Energy Storage Systems

Nikola N. Krstic[1], Dragan S. Tasic[1], Dardan O. Klimenta[2,*], Milos J. Milovanovic[2]
[1]Department of Power Engineering, Faculty of Electronic Engineering, University of Nis, Aleksandra Medvedeva St. 4, RS-18000 Nis, Serbia
[2]Department of Power Engineering, Faculty of Technical Sciences, University of Pristina in Kosovska Mitrovica, Kneza Milosa St. 7, RS-38220 Kosovska Mitrovica, Serbia
*nikola.krstic@elfak.ni.ac.rs; dragan.tasic@elfak.ni.ac.rs; *dardan.klimenta@pr.ac.rs; milos.milovanovic@pr.ac.rs*

***Abstract*—This paper proposes an updated two-step approach to improve the operation of a distribution network (DN) through the optimal siting and sizing of one, two, or three systems, each consisting of a photovoltaic (PV) generator and a battery energy storage (BES) unit – the so-called "PV-BES system". The first step of the approach determines the optimal sites and optimal powers of the PV-BES systems, taking into account the DN load profile and the required improvement in DN operation. Parameters used to describe the quality of the DN operation include the average daily power losses and the voltage profile quality index of the DN. The optimal locations and optimal powers of the PV-BES systems are determined using metaheuristics of the particle swarm optimisation (PSO) and wild horse optimisation (WHO) methods considering various daily load profiles. Based on the optimal powers of the first step and the known daily variation of solar irradiation, the second step provides the individual maximum powers of the PV generators and BES units, as well as the storage capacities of the BES units required for the sizing of the PV-BES systems. The iterative method used for the sizing of the PV-BES systems in the second step of the proposed approach can be regarded as a novelty. Finally, all results were obtained using the IEEE 33-bus test radial DN topology, considering different numbers of PV-BES systems connected to the DN, different efficiencies of the BES units, and different priorities in the criterion function.**

***Index Terms*—Battery energy storage (BES) unit; Distribution network (DN); Wild horse optimisation (WHO); Particle swarm optimisation (PSO); Photovoltaic (PV) generator.**

I. INTRODUCTION

Improving the operation of distribution networks (DNs) has been attracting the attention of specialist researchers in recent decades, due to their great importance for the quality of electricity delivered to consumers and the overall operation of an electric power system. Moreover, due to increased environmental awareness, energy efficiency and the use of green technologies are among the priority requirements for the operation of DNs. One of the solutions to meet these requirements is the increased use of distributed renewable energy generation [1], [2].

By optimising the locations and sizes of these generators [3]–[6], the generators could have a positive impact on each DN and improve its operation in various ways [7]. These include increasing power supply reliability, reducing power losses [8], [9], improving the voltage profile [10], [11], and reducing and smoothing load peaks on the distribution lines [12].

The existing literature contains a very large number of research papers dealing with the same or similar topics. Some of these topics are, e.g., as follows. Voltage control in a DN with multiple photovoltaic (PV) generators and battery energy storage (BES) units was analysed in [13], and a control strategy for a grid-connected system consisting of a PV generator and a BES unit was considered in [14]. Furthermore, a control approach for a grid-connected system consisting of PV generators, a battery, and a supercapacitor was proposed in [15], and a mixed integer conic programming model was presented in [16] to find the optimal type, size, and location of BES units and various distributed generators in radial distribution systems.

The optimal sizing and placement of a PV generator and a BES unit in a real distribution system of a large chemical plant with an unbalanced load to improve the associated power losses, bus voltage profile, and voltage unbalance was investigated in [17], etc.

Various methods and approaches have been proposed in the literature for the optimal sizing and placement of PV-BES systems in DNs. There is literature in which only BES units are analysed [18]–[20], while there are also publications dealing only with PV generators [21]–[23]. In addition, there are papers in which the optimal sizing and placement of BES units in the presence of PV generators has been investigated [24]–[26]. The presence of a BES unit within the PV-BES system is necessary to achieve the power required to maximise the improvement of DN operation at a given time of the day [27]. This is because the generation of electricity from PV systems depends on solar radiation, which is not present throughout the day, cannot be controlled, and does not follow electricity consumption [14].

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In this paper, the improvement of the DN operation is achieved through the optimal placement and sizing of PV-BES systems in the DN. In the first step, the optimal locations and optimal powers of PV-BES systems are determined regarding the required improvement of DN operation. In the second step, the individual maximum powers of the PV generators and BES units and the storage capacities of the BES units needed for the sizing of the PV-BES systems are obtained. The proposed approach for PV-BES system siting and sizing differs from the publications reviewed here, as well as from numerous other review articles such as [27], [28], or [29], [30], and may be of interest to the research community, especially the second step. Specifically, such an approach is applied in this paper as follows.

The first step of the aforementioned determines the optimal locations and optimal powers of the PV-BES systems considering the configuration of the DN and its daily load profile. For this purpose, the metaheuristic optimisation methods, wild horse optimisation (WHO) [31]–[33] and particle swarm optimisation (PSO) [34], [35], are applied. These optimisation methods were chosen because WHO is a popular and relatively new optimisation method that has been used in recent years by many researchers, and PSO is one of the basic metaheuristics commonly used in the literature. In general, metaheuristic optimisation methods are widely used by researchers to solve complex nonlinear optimisation problems with many constraints, in which optimal sites and powers of PV-BES systems can also be included [24], [36], [37]. Furthermore, WHO and PSO are implemented to consider DN node sensitivity factors to reduce power losses and improve the voltage profile, when determining the optimal siting of PV-BES systems. The calculation of the power flow in the considered radial DN is solved using the backward/forward sweep iterative method according to [38].

The second step is used to size the units in each PV-BES system. In this step, the individual maximum powers of the PV generators and BES units together with the storage capacities of the BES units are determined based on the optimal powers of the PV-BES systems determined in the first step and the known diagram of daily solar irradiation (per unit). This is done using the proposed iterative method which can be regarded as a novelty. In each iteration of the proposed iterative method, the required maximum power of the PV generator is determined based on the periods of charging and discharging the BES unit obtained in the previous iteration using the value of the maximum power of the PV generator from the previous iteration. The results are generated for various daily load profiles and different numbers of PV-BES systems as in [39]. The effects of the efficiency and different modes of charging/discharging of the BES units, as well as different priorities in the criterion function on the sizing of the PV-BES systems, are also taken into account.

II. Optimisation Problem Formulation

Improving the voltage profile and reducing the power losses in the DN using PV-BES systems is a nonlinear optimisation problem with constraints. The nonlinearity arises from the nonlinear dependencies of the quality of the voltage profile and the power losses of the DN on the powers injected by the connected PV-BES systems. The control variables in this optimisation problem are the locations and the average hourly powers of the PV-BES systems, while the constraints are as follows:

$$i \in \{i_1, i_2, ..., i_n\}, \tag{1}$$

$$P(k) < P_{\max}(i), \tag{2}$$

where i is the index of a specific node in the DN to which the PV-BES system is to be connected, and $P(k)$ is the average hourly power injected in the DN by the PV-BES system in the k^{th} hour of the day.

The set of nodes (or their indexes) in which PV-BES systems can be connected is defined as $\{i_1, i_2, \dots i_n\}$, while $P_{\max}(i)$ is the maximum power of distributed generation that can be injected in the i^{th} node of the DN.

The dependent variables that appear in this optimisation problem are the individual powers of the PV generators and the BES units, the states of charge of the BES units, the currents flowing through the distribution lines, and the node voltages of the DN. Constraints on the maximum possible power of the PV generators (P_{PVmax}) and maximum charging (P_{BESmin}) and maximum discharging power (P_{BESmax}) of BES units (the power of the BES unit is positive in discharging and negative in the charging mode) can exist considering the cost of these elements and the available space for their implementation. Constraints for other dependent variables are set taking into account the maximum current and the permissible voltage range in the DN lines, as well as the maximum and minimum states of charge of the BES units. Constraints for the dependent variables are defined in the following manner:

$$P_{PV}(k) < P_{PV\max}, \tag{3}$$

$$P_{BESmin} < P_{BES}(k) < P_{BESmax}, \tag{4}$$

$$I < I_{\max}, \tag{5}$$

$$V_{\min} < V < V_{\max}, \tag{6}$$

$$SOC_{\min} < SOC < SOC_{\max}, \tag{7}$$

where I is the current flowing through a particular branch of the DN, V is the voltage at a particular node of the DN, and SOC is the state of charge of a particular BES unit. The powers $P_{PV}(k)$ and $P_{BES}(k)$ represent the average one-hour powers of the PV generator and the BES unit in the k^{th} hour. Their values, as well as the values of other variables, must be between the corresponding minimum and maximum values. The constraints on the powers of the PV generators and BES units, given in (3) and (4), are not taken into account in this paper. The reason for this is to achieve maximum improvement of DN operation, which requires sizing of the PV-BES system as determined in the second step of the proposed approach.

To improve the control of the BES units and maintain the desired state of charge for each of them at the end of the operating cycle, an additional constraint regarding the stored energy in the BES units is introduced. This additional constraint is as follows

$$W_{end} - W_{start} = \Delta W, \tag{8}$$

where W_{start} and W_{end} are the stored energies of a particular

BES unit at the beginning and end of the operating cycle, and ΔW is the desired increment in stored energy, which can have a positive or negative value.

Also, power generation must satisfy power demand and compensate for power losses in the DN at every moment. This makes two more constraints, one for active and the other for reactive power, that need to be fulfilled in the optimisation problem:

$$P_{DN} + P_{DG} = P_L + P_{Loss}, \quad (9)$$

$$Q_{DN} = Q_L + Q_{Loss}. \quad (10)$$

In (9) and (10), P_{DN} and Q_{DN} are the active and reactive power taken from the DN in the supply node, P_L and Q_L are the active and reactive load power, P_{Loss} and Q_{Loss} are the losses of active and reactive power in the DN, while P_{DG} is the active power injected into the DN by the PV-BES systems. In this paper, PV-BES systems operate with unit power factor, so the reactive power of PV-BES systems is not present in (10).

The main goal of applying optimisation to the DN using PV-BES systems is to improve the DN operation. For this reason, a two-parameter criterion function (C) of the following form

$$C = a \times P_{loss} + b \times VQI \quad (11)$$

is used. In the previous equation, P_{loss} represents the average daily power losses of the DN, VQI is the voltage quality index of the DN, while a and b are the weighting coefficients used for the determination of priorities. The value of the average daily power losses is calculated using

$$P_{loss} = \frac{1}{24}\sum_{k=1}^{24}\sum_{j=1}^{m} 3I_{k,j}^2 R_j, \quad (12)$$

while the value of the voltage quality index is determined by

$$VQI = \frac{1}{24}\sum_{k=1}^{24}\sum_{j=1}^{m}\left(V_{k,j} - V_{ref}\right)^2, \quad (13)$$

where $I_{k,j}$ is the root mean square (RMS) value of the load current flowing through the j^{th} path of the DN in the k^{th} hour, R_j is the resistance of the j^{th} path of the DN, m is the total number of the paths in the DN, $V_{k,j}$ is the node voltage at the end of the j^{th} path of the DN in the k^{th} hour, and V_{ref} is the reference voltage.

III. SOLVING THE OPTIMISATION PROBLEM USING WHO AND PSO

To determine the optimal locations and sizes of PV-BES systems, the optimisation problem formulated needs to be solved first. Solving such an optimisation problem involves finding the optimal sites and optimal powers of the PV-BES system to improve the voltage profile and minimise power losses in the DN, while respecting the given constraints (expressions (1)–(10)). These numerous constraints are the main reason why the authors decided to use metaheuristic optimisation methods instead of conventional methods for solving the optimisation problem. Other reasons can be found in the simplicity, easy implementation, and efficiency of metaheuristic optimisation methods on this type of optimisation problem, proven by numerous research papers in recent years.

The optimal locations and the optimal average hourly powers of the considered PV-BES systems during the day are determined by applying metaheuristics of PSO and WHO, using the daily load profile of the DN. PSO and WHO belong to population-based metaheuristic optimisation methods, where the population consists of a set of individuals, each of whom represents a vector of control variables and a potential solution to the optimisation problem.

When solving an optimisation problem with one PV-BES system, one element of the vector of control variables contains information on the site (the index of the node of the DN where the PV-BES system is connected), and the 24 remaining elements of this vector represent the average hourly powers of the system for each of the 24 hours during the day. In the case of connecting several PV-BES systems to the DN, the procedure is the same, only the vector of control variables has a larger number of elements, 25 for each PV-BES system. After each iteration, the elements of the vectors of control variables, representing the individuals, are changed to reduce the value of the criterion function. This procedure is repeated the required number of times (as long as it is unlikely that the criterion function of the best individual will change significantly, or until this change is negligible), and finally, the individual with the best criterion function will be singled out as the solution of the optimisation problem. As part of the solution of the optimisation problem, the optimal sites of the PV-BES systems are obtained directly, while the calculated optimal hourly powers are further used to determine the optimal size of each system.

To improve the efficiency and accuracy of the first step in the approach used, the number of nodes representing potential connection points of the PV-BES system is reduced, based on their values of the power loss sensitivity factor (*PLSF*) and the voltage quality sensitivity factor (*VQSF*). These sensitivity factors are determined as the ratio of the increase in power loss (ΔP_{Loss}) and the improvement in the voltage profile (ΔVQI) for the corresponding change in injected power in the observed node and the given increase in the injected power (ΔP), which for the ith node is obtained using (14) and (15):

$$PLSF(i) = \frac{\Delta P_{Loss}}{\Delta P(i)}, \quad (14)$$

$$VQSF(i) = \frac{\Delta VQI}{\Delta P(i)}. \quad (15)$$

The problem that arises when assessing the suitability of a node for the connection of distributed generation based on the sensitivity factors is that different increments of the injected power create different values for the sensitivity factors. Specifically, this can change the order of the nodes according to suitability. To solve this problem to a certain extent, this paper uses the mean value of the sensitivity factor determined by using twenty different values of the injected powers. Taking this into account, the node suitability index of the ith node (*NSI*(*i*)) for the connection of the PV-BES system is

$$NSI(i) = -\sum_{k=1}^{20} \left[\frac{1/20}{PLSF_{max}} \frac{\Delta P_{Loss}}{\frac{k}{20} P_{max}(i)} + \frac{1/20}{VQSF_{max}} \frac{\Delta VQI}{\frac{k}{20} P_{max}(i)} \right], \quad (16)$$

where P_{max} is the maximum power constraint of the PV-BES system used in (2), $PLSF_{max}$ and $VQSF_{max}$ are the maximum values of the power loss sensitivity factor and voltage quality sensitivity factor considering all nodes in the DN. This is done to equalise the priorities of power loss reduction and voltage profile improvement in the NSI value, while the minus sign is used so that the more suitable nodes have a higher NSI value. It is important to note that the value of P_{max} must be reduced according to the number of PV-BES systems connected on the DN to obtain the proper values for the NSI in the DN.

In this paper, only the nodes with the highest values of the suitability index (34 % of all nodes) are used as potential connection points for PV-BES systems when implementing metaheuristic optimisation methods. Also, it is important to note that the improvement achieved by the node selection according to the NSI values have a greater impact on the solution of the optimisation problem if the DN has a larger number of nodes.

A. Particle Swarm Optimisation

PSO is known to be a swarm-based metaheuristic algorithm inspired by the foraging behaviour of a flock of birds in nature [35]. Individuals within the population communicate with each other and move towards the individual who is in the place with the largest amount of food. In the optimisation method, the amount of food is correlated with the value of the criterion function (a greater amount of food means a lower value of the criterion function). To better search for the site where the optimal solution can be found, the direction of movement of the individual is not only affected by the site with the largest amount of food found so far (g_{best}), but also by the site with the largest amount of food that this individual has found so far ($p_{best,i}$). In this way, in each subsequent iteration, the individuals are getting closer to finding the site with the largest amount of food and thus the lowest value of the criterion function. This optimisation algorithm can be defined analytically as follows:

$$v_i(t+1) = wv_i(t) + C_1 r_1 \left(p_{best,i}(t) - x_i(t) \right) + \\ + C_2 r_2 \left(g_{best}(t) - x_i(t) \right), \quad (17)$$

$$x_i(t+1) = x_i(t) + v_i(t+1), \quad (18)$$

where t is the number of iterations, x_i is the site of the i^{th} individual (i^{th} vector of control variables), v_i is the displacement vector of the i^{th} individual, w is the inertia coefficient, C_1 and C_2 are the acceleration coefficients, and r_1 and r_2 are the random numbers in the interval [0, 1].

B. Wild Horse Optimisation

The WHO method is a swarm-based metaheuristic optimisation method inspired by the way wild horses live in nature. The population of wild horses lives in separate groups, each having one stallion (group leader) and several mares and foals that follow him and graze around him. The stallion has the right to mate and the task of leading the group to the appropriate area near the "water hole", for which he competes with the stallions of other groups. In addition, once in a while, the stallion must compete with the members of his group for the position of group leader. An interesting behaviour of wild horses is that in the mating season, to avoid mating between relatives and maintain genetic diversity, mares often part from their group and mate with stallions from other groups, while there is a possibility that when it grows up, the offspring (foals) will leave their group and join the other group.

The WHO method mimics and analytically describes the behaviour mentioned of wild horses, including grazing, mating, group leadership, and selection of the group leader to find the solution to the optimisation problem. Considering this, the WHO method can be divided into five main steps that are repeated in every iteration, excluding the first step:

1. *Creation of groups*. This is the initial step in the WHO method in which the total population of wild horses is randomly separated into groups, each having the same number of individuals and one stallion (group leader).
2. *Grazing behaviour*. In this step, the movement of the mares during grazing is defined. The mares move randomly around the area in whose center the stallion is located, which is analytically described by

$$\vec{X}_j' = A \times \cos\left(\vec{R}_j \times 180°\right) \times \left(\vec{S} - \vec{X}_j\right) + \vec{S}, \quad (19)$$

where $\vec{X}_j'$ and $\vec{X}_j$ are the new and the current location of the j^{th} individual in the group, respectively, $\vec{S}$ is the location of the stallion in the group, while $\vec{R}_j$ is the vector of random numbers from interval [0, 1] for the j^{th} individual in the group.

For more uniformly distributed exploitation of the search area around the stallion, in (19), the cosine function is used. Considering that the optimal solution is more likely to be near the position of the stallion, the attenuation coefficient A is used.

3. *Mating behaviour*. In this step, mares and stallions are selected for mating, and the crossing of their genes takes place creating a new individual. Each pair selected for mating is randomly chosen, but the mares and stallions in it must be from different groups. Arithmetic mean value crossing is used in this paper. The fact that individuals chosen for mating belong to different groups creates genetic diversity and represents the mechanism to escape the local optimum.
4. *Group leadership*. The movement of the stallion is generated in this step. The stallion tries to lead the group to the "water hole", but in doing so it is constantly competing with other stallions for a better place. This, as a result, creates the movement of the stallion around the "water hole", similar to that of the mares around him in the grazing period, in which the group with the most dominant stallion is located in the "water hole". Taking this into account, the "water hole" location ($\overrightarrow{WH}$) is found as the location with the lowest criterion function found so far. Using the location of the "water hole", the new location of the stallion in the group p ($\vec{S}_p'$) is defined using (20)

$$\vec{S}' = A \times \cos\left(\vec{R} \times 180°\right) \times \left(\overrightarrow{WH} - \vec{S}\right) + \overrightarrow{WH}. \quad (20)$$

5. *Selection of the group leader*. This final step selects the group leader based on the values of the criterion function of the group members. During the grazing period, group members change their locations, and after the mating new individuals are created. Each of these behaviours, in addition to the change in the location of the stallion determined in the previous step, creates new values for the criterion function of the group members. For this reason, again it is necessary to determine the fittest individual in each group (individual with the lowest value of criterion function in the group) to be the group leader (stallion).

IV. OPTIMAL SIZING OF THE PV-BES SYSTEM

In this paper, the optimal sizing of the PV-BES system that should be connected to a DN according to Fig. 1 corresponds to the minimum size of this system that can inject the required amount of power into the DN obtained by the optimisation method. In this way, with minimum size, the PV-BES system allows maximum possible improvement of the voltage profile and minimum power losses in the DN.

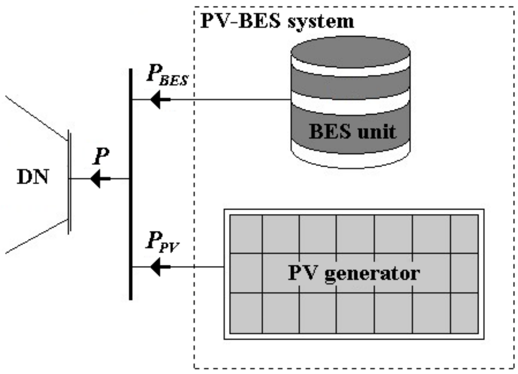


Fig. 1. Principal scheme of PV-BES system connected to the DN.

To determine the optimal size, the following data are necessary: (i) the optimal power previously determined that the PV-BES system should inject into the DN during the day to improve its operation and (ii) the daily diagram of solar irradiation. The first step in the proposed approach to determine the optimal size of the PV-BES system is to size the PV generator by determining its maximum required power $P_{PV\max}$. To do this, it is necessary to express the power of the PV generator for every hour of the day ($P_{PV}(k)$) in terms of its maximum required power ($P_{PV\max}$) and solar irradiation ($I_C(k)$) as

$$P_{PV}(k) = P_{PV\max}\frac{I_C(k)}{I_{C\max}}, \tag{21}$$

where $I_{C\max}$ is the maximum solar irradiation during the day.

For maximum utilisation of solar energy, PV generation follows the shape of the daily solar irradiation diagram, which is the main reason why the PV generator is often unable to generate the required optimal power. To overcome this issue, one BES unit should be added to the PV generator. Depending on needs, the BES unit can operate as a consumer of electricity (in charging mode) or a generator of electricity (in discharging mode), ensuring that the power injected into the DN is equal to the power required for optimal operation of the DN. Accordingly, the power of the BES unit is

$$P_{BES} = P_{opt} - P_{PV}, \tag{22}$$

where P_{opt} is the optimal power of the PV-BES system.

The charging periods of the BES unit take place when the optimal power P_{opt} is lower than the power of the PV generator P_{PV}, whereas the discharging appears when the optimal power is greater than the power of the PV generator. Taking into account that the average one-hour powers are used here, the energy stored in the BES unit at the end of the k^{th} hour, during charging and discharging, can be determined using

$$W_k = W_{k-1} - \eta \times P_{BES}(k) \tag{23}$$

and

$$W_k = W_{k-1} - \frac{1}{\eta} \times P_{BES}(k), \tag{24}$$

respectively, where W_k is the energy stored in the BES unit at the end of the k^{th} hour, W_{k-1} is the energy stored in the BES unit at the end of the $(k-1)^{th}$ hour, $P_{BES}(k)$ is the average one-hour power of the BES unit in the k^{th} hour (having a value lower than zero during the charging periods of the BES unit, or a value greater than zero during the discharging periods of the BES unit), and η is the efficiency of the charging and discharging process of the BES unit.

By substituting (21) into (22), and then substituting such a modified equation (22) into (23) and (24), the difference between the states of charge of the BES unit at the end and the beginning of the operating cycle becomes

$$\Delta W = \sum_i^n \left(P_{PV\max}\frac{I_C(i)}{I_{C\max}} - P_{opt}(i) \right)\eta - \\ - \sum_j^m \left(P_{opt}(j) - P_{PV\max}\frac{I_C(j)}{I_{C\max}} \right)\frac{1}{\eta}, \tag{25}$$

where i and j are the ordinal numbers of hours during the charging and discharging periods of the BES unit in the operating cycle, respectively, and n and m is the total number of hours of charging and discharging the BES unit during the operating cycle, respectively.

As the maximum power of the PV generator is not known in advance, the charging and discharging periods of the BES unit must be assumed considering the shape of the daily solar irradiation diagram and the optimal power of the PV-BES system. The assessment of the initial values for the charging and discharging periods of the BES unit is performed based on a comparison of the optimal power of the PV-BES system with the power of the PV generator, whose maximum required power corresponds to an ideal process of charging/discharging the BES unit, i.e.,

$$P_{PV\max} = \frac{\Delta W + \sum_i^T P_{opt}(i)}{\sum_i^T \frac{I_C(i)}{I_{C\max}}}, \tag{26}$$

where T is the total number of hours in the operating cycle, which is equal to the sum of the charging and discharging periods, i.e., $T = n + m$. Therefore, (26) is derived from (25) for the case of ideal efficiency of the BES unit, i.e., for $\eta = 1$.

Substituting the initial values of the charging and discharging periods (n and m), the actual value of the BES unit efficiency (η), and the desired increment in the stored energy of the BES unit (ΔW) into (25) yields the maximum power of the PV generator

$$P_{PV\max} = \frac{\Delta W + \sum_i^n P_{opt}(i)\eta + \sum_j^m P_{opt}(j)\frac{1}{\eta}}{\sum_i^n \frac{I_C(i)}{I_{C\max}} \times \eta + \sum_j^m \frac{I_C(j)}{I_{C\max}} \times \frac{1}{\eta}}. \quad (27)$$

If this maximum power of the PV generator is not equal to the one used to determine the latest values of the charging and discharging periods of the BES unit, the procedure will be repeated with the latest value of the maximum power of the PV generator. The iterative procedure and other steps in the proposed approach are illustrated in the form of a flow chart shown in Fig. 2.

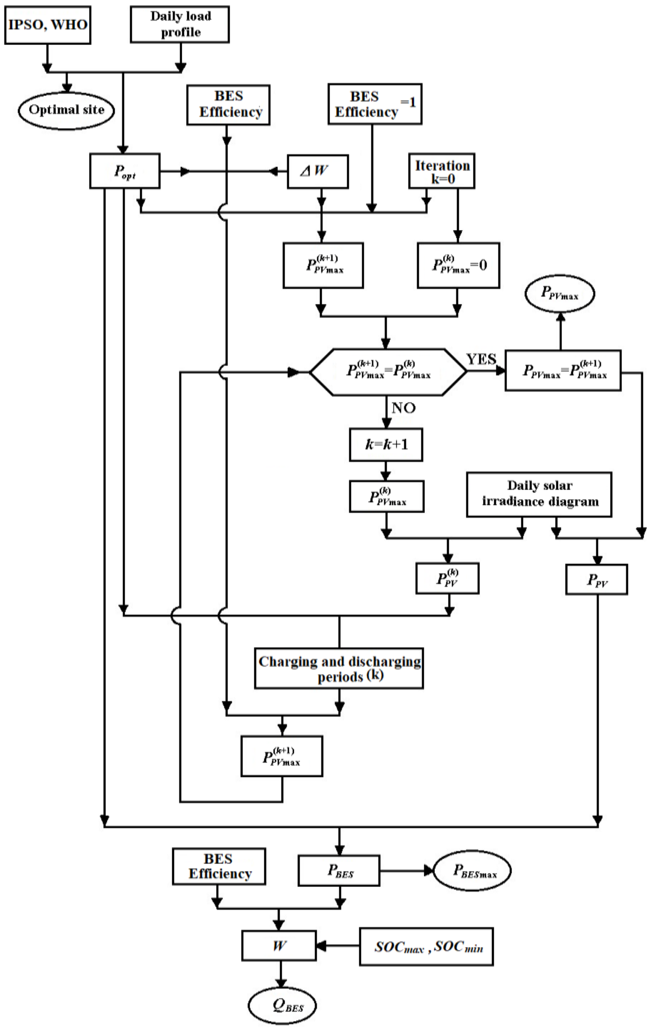


Fig. 2. Flow chart of the proposed approach.If the maximum power of the PV generator is known, it is possible to determine the power of the BES unit using (21) and (22) for each hour of the operating cycle. By comparing the absolute values for the power of the BES unit, obtained for each hour of the operating cycle, the maximum charge/discharge power required for sizing the BES unit can be determined using

It should be noted here that if the efficiency of the BES unit equals 1 (an ideal process of charging and discharging), the calculation is much simpler because in that case there is no need for an iterative procedure and the maximum power of the PV generator is calculated directly using (26).

$$P_{BES\max} = \max\left\{\left|P_{BES}(k)\right|\right\}, \quad k = 1, 2, \ldots T. \quad (28)$$

The stored energy of the BES unit at the end of each hour within the operating cycle can be determined using the power values of the BES unit and (23) and (24). Then, the required storage capacity of the BES unit (Q_{BES}), as an important parameter for its sizing, is determined based on the obtained minimum and maximum values for the stored energy, and the minimum and maximum values for the state of charge of the BES unit given in constraint (7)

$$Q_{BES} = \frac{W_{\max} - W_{\min}}{SOC_{\max} - SOC_{\min}}. \quad (29)$$

W_{max} and W_{min} are the maximum and minimum values of stored energy in the BES unit of the operating cycle.

V. Results and Discussion

All results of this study were obtained using the IEEE 33-bus test radial DN topology shown in Fig. 3. For simplicity and to draw general conclusions, it is assumed that the distance between two neighbouring nodes in the DN is 300 m. The voltage level of the DN is 10 kV, while the values of resistance and reactance are r = 0.414 Ω/km and x = 0.365 Ω/km, respectively.

Both optimisation methods (PSO and WHO) are implemented in such a way that the optimal solution is reached after 200 iterations with populations of 100, 200, or 300 individuals depending on whether one, two, or three PV-BES systems are connected to the DN. Optimisation methods are implemented in such a way that they provide the best possible results. With this in mind and using the results of some test simulations, the values for the inertia coefficient w and the acceleration coefficients C_1 and C_2 in PSO are w = 0.8, C_1 = 0.7, and C_2 = 0.8. In addition, groups of 20 individuals are used in WHO, using the uniform crossover strategy to determine the optimal site, and the *whole arithmetic recombination strategy* to determine the optimal power.

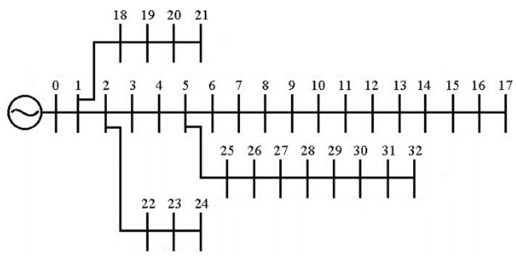
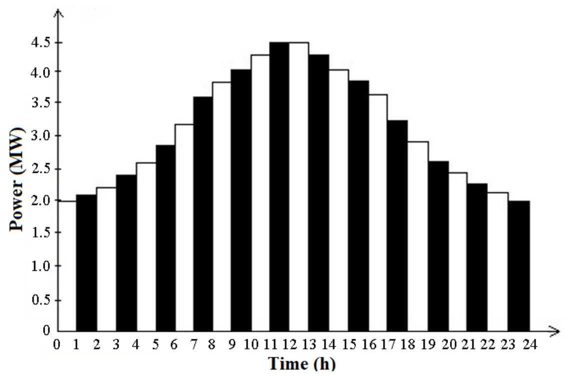


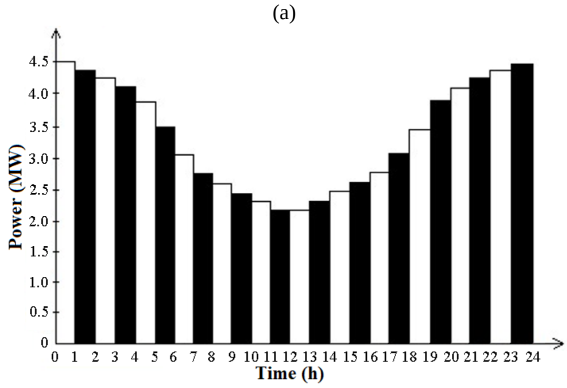
Fig. 3. IEEE 33-bus test radial DN.

Three different daily DN load profiles are considered. The load profiles (total load of DN during the day) are shown in Fig. 4. The shapes of the first two daily load profiles have a more theoretical scope and have been chosen as examples of load profiles that more or less match the power coming from the PV generator and the shape of the daily solar irradiation diagram. As can be seen in Figs. 4(a) and 4(b), the first and second load profiles have a different distribution of power over the day, but the same values of maximum power $P_{\max1.2} = 4.5$ MW and average power $P_{av1.2} = 3.311$ MW. The third daily load profile in Fig. 4(c) has the shape of a typical load profile of the DN with the same values for the maximum and average powers as in the first two cases, $P_{\max3} = 4.5$ MW, and $P_{av3} = 3.311$ MW.

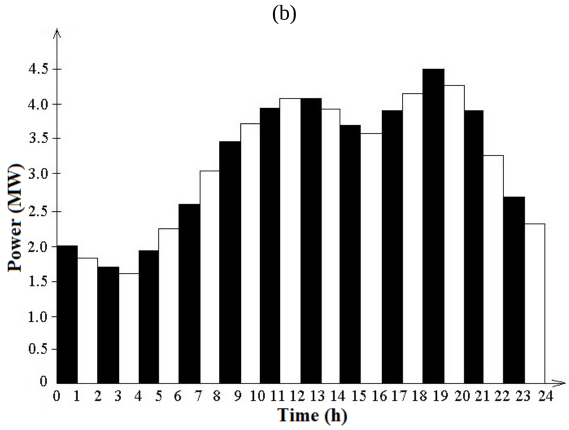
In all the cases considered, the load is evenly distributed among the nodes of the DN (each node has the same load). Each load profile consists of the same combination of electricity consumers, namely: 40 % industrial electricity consumers (constant power load type with power factor $cos\varphi = 0.87$) and 60 % resistive load (constant impedance load type with power factor $cos\varphi = 1$), whose summarised values for a voltage level of 10 kV (the rated voltage of the DN) are shown in Fig. 4.



(a)



(b)



(c)

Fig. 4. Various daily load profiles of the considered DN: (a) First daily load profile; (b) Second daily load profile; (c) Third daily load profile.

The daily solar irradiation diagram used to determine the power of the PV generator, expressed in percent (per unit), is shown in Fig. 5.

It is important to point out that when determining the storage capacity of the BES units, the minimum and maximum values of the state of charge of the BES units, in all considered cases, are: $SOC_{min} = 0.1$ and $SOC_{max} = 0.9$.

Table I shows the average daily power losses and the DN voltage quality index for the case before connecting the PV-BES system to the DN for all three daily load profiles (I, II, and III). The results of Table I can be considered as expected. Although the powers of the first and second daily load profiles are distributed differently by hour, they are the same, as are the values of average daily power losses and the voltage quality index. Compared to the corresponding data obtained for the third daily load profile, these parameters appear to be slightly higher.

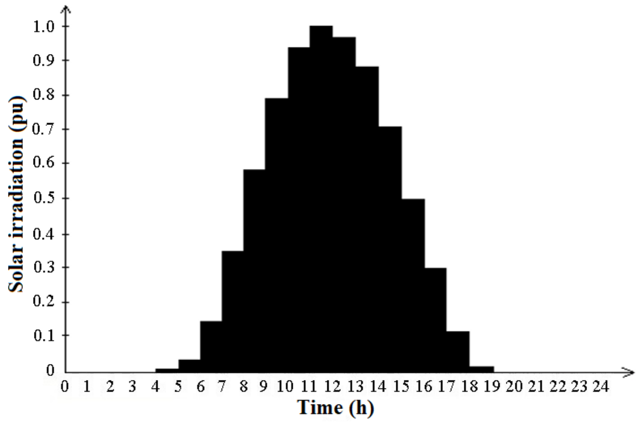


Fig. 5. Daily solar irradiation diagram.

TABLE I. AVERAGE DAILY POWER LOSSES AND VOLTAGE QUALITY INDEX OF THE DN FOR THE CASE BEFORE CONNECTING PV-BES SYSTEMS.

Daily load profile	I	II	III
P_{loss} (kW) VQI (10^3 V^2)	60.077 514.969	60.077 514.969	54.377 465.769

Table II lists the results obtained for the case after connecting one PV-BES system to the DN, considering the corresponding optimal sites and optimal powers previously determined. These results, in addition to the average daily power losses (P_{loss}) and the voltage quality index (VQI), include the optimal site (i.e., node index in the DN) in which the PV-BES system is connected, as well as the required maximum power of the PV generator ($P_{PV\max}$), required maximum power of the BES unit ($P_{BES\max}$), and the required storage capacity of the BES unit (Q_{BES}) obtained for different values of efficiency of the BES unit ($\eta_1 = 1$, $\eta_2 = 0.9$, and $\eta_3 = 0.8$) and increment in the stored energy of the BES unit ($\Delta W_1 = 10$ MWh and $\Delta W_2 = -10$ MWh).

It is important to point out that when the efficiency of the BES unit is changed, the increase in the stored energy of the BES unit is equal to zero. In addition, the efficiency is equal to one when different increments in the stored energy of the BES unit are considered. Taking into account the form of the criterion function used, the efficiency values and the desired increment in the stored energy of the BES unit do not affect the optimal site and optimal power of the PV-BES system, but only its sizing parameters (maximum power of the PV generator, maximum power of the BES unit, and storage capacity of the BES unit). The results tabulated in parentheses refer to cases where WHO is used for optimisation, while the remaining results (not in parentheses) are obtained using PSO.

The first thing that can be seen from Table II is that the results obtained using both optimisation methods have approximately the same values, which can be explained by the similar nature of the optimisation methods used. Specifically, the average daily power losses and the voltage quality index after connecting a PV-BES system to the DN have practically the same values for the first and second daily load profiles and slightly lower values for the third. Therefore, it is clear that the values of the average daily power losses and the voltage quality index depend on the load power and not on their hourly distributions, which is expected considering the presence of the BES unit. When comparing the results of Tables I and II, it is clear that connecting the PV-BES system to the DN can reduce its power losses and significantly improve its voltage profile.

TABLE II. AVERAGE DAILY POWER LOSSES AND VOLTAGE QUALITY INDEX OF THE DN FOR THE CASE AFTER CONNECTING ONE PV-BES SYSTEM TO THE DN, AND THE OPTIMAL SITE AND SIZING PARAMETERS OF THAT PV-BES SYSTEM.

Daily load profile	**I**	**II**	**III**
P_{loss} (kW)	21.437 (21.437)	21.437 (21.435)	19.390 (19.389)
VQI (10^3 V^2)	13.422 (13.422)	13.421 (13.425)	12.127 (12.131)
Optimal site	7 (7)	7 (7)	7 (7)
$P_{PV\max 1}$ (MW)	9.660 (9.660)	9.660 (9.660)	9.133 (9.133)
$P_{BES\max 1}$ (MW)	5.657 (5.657)	7.760 (7.761)	5.632 (5.632)
Q_{BES1} (MWh)	38.446 (38.446)	57.686 (57.686)	40.285 (40.285)
$P_{PV\max 0.9}$ (MW)	10.627 (10.627)	11.126 (11.126)	10.150 (10.149)
$P_{BES\max 0.9}$ (MW)	6.624 (6.624)	9.227 (9.227)	6.649 (6.648)
$Q_{BES0.9}$ (MWh)	41.847 (41.847)	63.463 (63.463)	43.997 (43.997)
$P_{PV\max 0.8}$ (MW)	11.921 (11.921)	13.128 (13.128)	11.508 (11.508)
$P_{BES\max 0.8}$ (MW)	7.918 (7.918)	11.229 (11.229)	8.007 (8.007)
$Q_{BES0.8}$ (MWh)	45.911 (45.911)	70.427 (70.427)	48.224 (48.224)
$P_{PV\max +10}$ (MW)	11.028 (11.028)	11.028 (11.028)	10.501 (10.501)
$P_{BES\max +10}$ (MW)	7.025 (7.025)	9.128 (9.128)	7.000 7.000
Q_{BES+10} (MWh)	49.861 (49.861)	69.656 (69.656)	51.835 (51.835)
$P_{PV\max -10}$ (MW)	8.292 (8.292)	8.292 (8.292)	7.765 (7.765)
$P_{BES\max -10}$ (MW)	4.289 (4.289)	6.392 (6.392)	4.264 (4.264)
Q_{BES-10} (MWh)	27.571 (27.571)	45.800 (45.800)	28.884 (28.884)

Furthermore, Table II shows that the optimal location of the PV-BES system does not depend on the shape of the daily load profile and that for the three profiles, it is node 7, which is located in the middle of the DN. Table II also shows that the maximum power of the PV generator is proportional to the average daily load power. This is expected because the PV generator has to inject the power into the DN power that is proportional to the load power to reduce power losses and improve the voltage profile. The results related to the sizing of the BES unit show that its maximum power and its required storage capacity directly depend on the match between the power generation profile of the PV generator (daily solar irradiance diagram) and the daily load profile of the DN. This is the reason why the maximum power and the required storage capacity of the BES unit have significantly higher values in the case of the second daily load profile.

Moreover, the results in Table II show that as the efficiency of the BES unit decreases, both the size of the BES unit (its maximum power and its required storage capacity) and the size of the PV generator (its maximum power) increase. A similar effect occurs when the increment in the stored energy of the BES unit is positive (the stored energy is higher at the end than at the beginning of the operating cycle). The explanation for this lies in the fact that for the same discharge power, the charging power of the BES unit must be increased. On the contrary, when the increment in the stored energy of the BES unit is negative, the charging power of the BES unit decreases and therefore the maximum power of the PV generator and the maximum power and storage capacity of the BES unit also decrease.

Tables III and IV show the average daily power losses and the voltage quality index of the DN for the cases after connecting two and three PV-BES systems to the DN, respectively. In addition, these tables contain the optimal sites and sizing parameters of those PV-BES systems.

The results in Table III or Table IV obtained by both optimisation methods are again similar to each other, but in this case, the differences are greater than in the case when one a PV-BES system is connected to the DN, which can be explained by the higher complexity of the optimisation problem. Also, considering the values of average daily power losses and the voltage quality index, it can be seen that WHO gave slightly better results, especially in the case when two PV-BES systems are connected on the DN.

TABLE III. AVERAGE DAILY POWER LOSSES AND VOLTAGE QUALITY INDEX OF THE DN FOR THE CASE AFTER CONNECTING TWO PV-BES SYSTEMS TO THE DN, AND THE OPTIMAL SITE AND SIZING PARAMETERS OF THOSE PV-BES SYSTEMS.

Daily load profile	**I**	**II**	**III**
P_{loss} (kW)	9.896 (9.860)	9.919 (9.777)	9.004 (8.860)
VQI (10^3 V^2)	4.678 (4.586)	4.783 (4.320)	3.951 (3.876)
Optimal site 1	12 (13)	12 (12)	11 (12)
$P_{PV1\max}$ (MW)	4.403 (4.168)	4.399 (4.352)	4.457 (4.134)
$P_{BES1\max}$ (MW)	2.634 (2.448)	3.441 (3.459)	2.836 (2.519)
Q_{BES1} (MWh)	17.317 (16.885)	25.852 (26.137)	19.749 (18.197)
Optimal site 2	27 (27)	27 (27)	27 (27)
$P_{PV2\max}$ (MW)	4.579 (4.731)	4.566 (4.667)	4.154 (4.387)
$P_{BES2\max}$ (MW)	2.924 (2.802)	3.799 (3.797)	2.460 (2.737)
Q_{BES2} (MWh)	18.903 (18.535)	28.009 (27.493)	18.415 (19.487)

Comparing the results in Table III or Table IV with those in Table II, it can be seen that the average daily power losses can be further reduced and that the voltage profile can be additionally improved with the increase in the number of PV-BES systems connected to the DN.

TABLE IV. AVERAGE DAILY POWER LOSSES AND VOLTAGE QUALITY INDEX OF THE DN FOR THE CASE AFTER CONNECTING THREE PV-BES SYSTEMS TO THE DN, AND THE OPTIMAL SITE AND SIZING PARAMETERS OF THOSE PV-BES SYSTEMS.

Daily load profile	I	II	III
P_{loss} (kW)	7.295 (7.277)	7.141 (7.236)	6.648 (6.750)
VQI (10^3 V^2)	2.624 (2.821)	2.661 (2.781)	2.524 (2.457)
Optimal site 1	4 (4)	5 (4)	5 (4)
$P_{PV1\max}$ (MW)	3.772 (3.479)	3.611 (3.618)	3.382 (3.643)
$P_{BES1\max}$ (MW)	2.310 (2.389)	2.873 (2.857)	2.129 (2.527)
Q_{BES1} (MWh)	15.039 (13.961)	21.410 (21.434)	15.687 (16.739)
Optimal site 2	13 (13)	13 (13)	13 (13)
$P_{PV2\max}$ (MW)	3.361 (3.703)	3.573 (3.626)	3.284 (3.427)
$P_{BES2\max}$ (MW)	2.135 (2.195)	2.882 (2.922)	2.170 (1.999)
Q_{BES2} (MWh)	14.591 (14.797)	21.291 (21.716)	14.494 (14.890)
Optimal site 3	29 (29)	29 (29)	28 (29)
$P_{PV3\max}$ (MW)	2.805 (2.880)	2.498 (2.893)	2.566 (2.621)
$P_{BES3\max}$ (MW)	1.716 (1.711)	2.107 (2.335)	1.732 (1.629)
Q_{BES3} (MWh)	11.158 (11.530)	15.232 (17.245)	10.883 (11.611)

It is important to emphasise here that the additional improvement mentioned of the DN performance, which is achieved by adding one or two more PV-BES systems to the DN, decreases with the increase in the number of PV-BES systems. This additional improvement is illustrated in Figs. 6 and 7. Therefore, adding more than three PV-BES systems to this type of DN would not make a noticeable difference and, for that reason, it was not considered. Tables II–IV show that the sum of the maximum powers of PV generators, the sum of the maximum powers of BES units, and the sum of the storage capacities of BES units are approximately the same regardless of the number of connected PV-BES systems. The optimal locations for the PV-BES systems in the case, when two or three are connected on the DN, are the nodes located along the two main branches, and in some cases, depending on the applied optimisation method, if they are not the same, then they are two adjacent nodes.

Figure 6 shows the voltage profiles of the DN for the hour of maximum load power, while Fig. 7 shows the average daily power losses in the DN paths. The results in Figs. 6 and 7 are generated for the DN without and with one, two, and three PV-BES systems.

In Fig. 6, it can be seen that the voltage along the DN nodes improves by connecting the PV-BES systems to the point that for three connected systems is approximately equal to the reference voltage (V_{ref} =1 pu).

Similarly, Fig. 7 shows how the average daily power losses in the paths of the DN decrease as the number of PV-BES systems connected to the DN increases. As indicated in Fig. 3, the path index is equal to the index of the node located at the end of that path. According to Figs. 6 and 7, in the case where only one PV-BES system is connected to the DN, in the vicinity of node 7 there are increases in voltage and average daily power losses, which are the result of high injected power into that node.

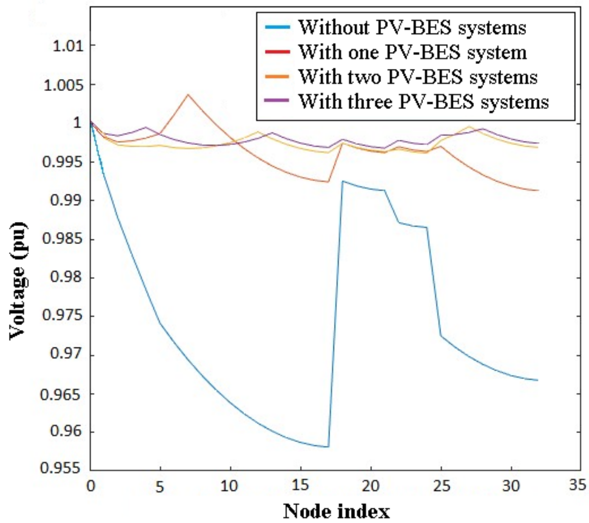


Fig. 6. Voltage profiles of the considered DN without and with one, two, and three PV-BES systems.

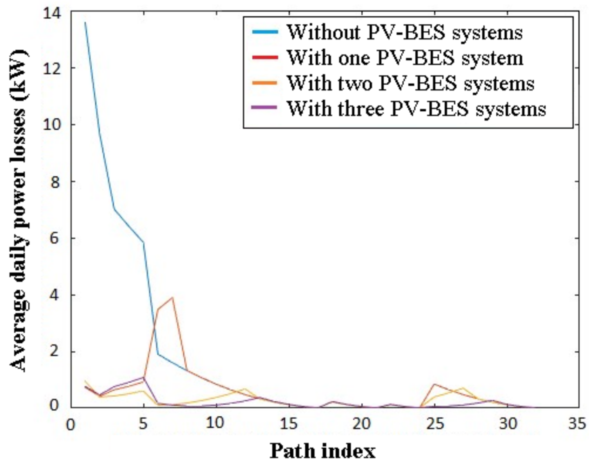


Fig. 7. Average daily power losses in DN paths without and with one, two, and three PV-BES systems.

The results shown in Figs. 6 and 7 are generated for the third daily load profile, which is considered to be the most representative.

Figure 8 shows the average one-hour powers of the PV-BES system (optimal power of the PV-BES system obtained using PSO or WHO to minimise the criterion function), the power of the PV generator, and the BES unit obtained for the first, second, and third daily load profiles. All results shown in Fig. 8 are obtained for the case where a PV-BES system is connected to the DN.

Based on Fig. 8, it is obvious that the optimal power of the PV-BES system follows the shape of the daily load profile, which corresponds to the criterion function used. In addition, the power of the PV generator follows the shape of the daily diagram of solar irradiation from Fig. 5, as stated earlier. The power of the BES unit is positive (the BES unit is discharging) in periods when there is no solar irradiation or it is low, or negative (the BES unit is charging) in periods of high solar irradiation.

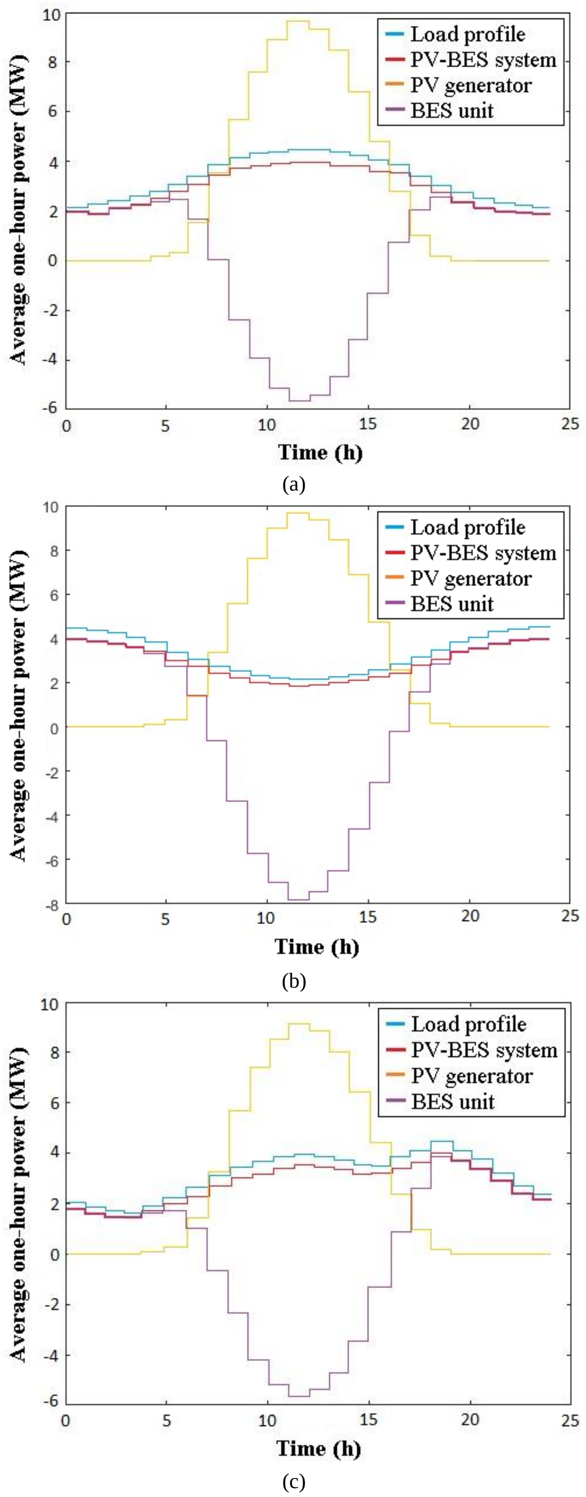


Fig. 8. Average one-hour powers of the PV-BES system (optimal power), PV generator, and BES unit obtained for various daily load profiles: (a) For the first daily load profile; (b) For the second daily load profile; (c) For the third daily load profile.

The results of Fig. 8 once again confirmed what was said based on Table II about the maximum powers of the PV generator and the BES unit.

Figures 9 and 10 show the state of charge of the BES unit during the day, in the case when one PV-BES system is connected to the DN (practically the same shape of the state of charge is present in the cases where two or three PV-BES systems are connected to the DN). Specifically, Fig. 9 shows the state of charge of the BES unit obtained for the first, second, and third load profiles, using the ideal efficiency ($\eta = 1$) and the zero increment in the stored energy ($\Delta W = 0$). Figure 10 shows the state of charge of the BES unit obtained for the third load profile in the cases with different efficiencies and increments in the stored energy of the BES unit.

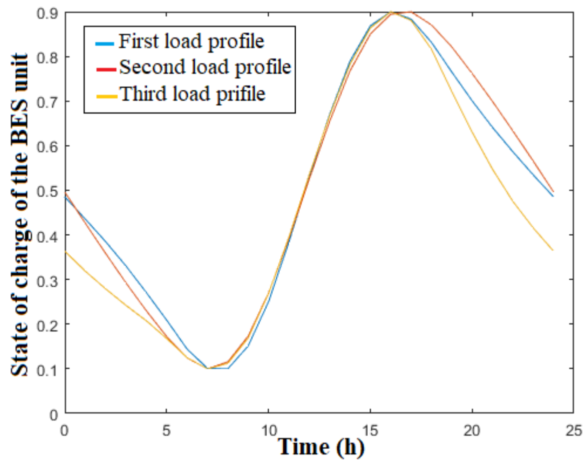


Fig. 9. State of charge of the BES unit with ideal efficiency and zero increment in stored energy, for various daily load profiles.

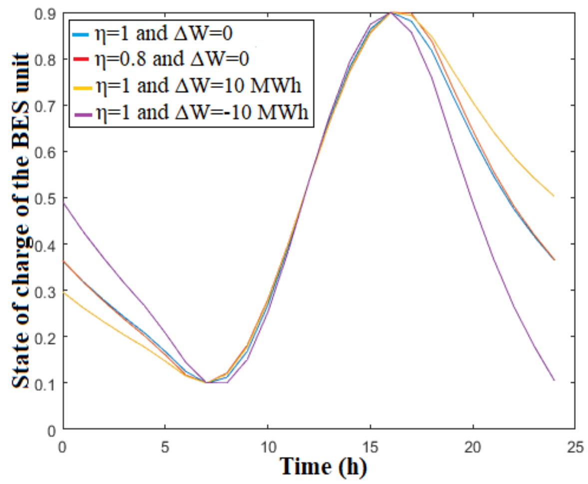


Fig. 10. State of charge of the BES unit for different efficiencies and increments in stored energy, for the third daily load profile.

In Figs. 9 and 10, it can be seen that the state of charge of the BES unit is between 0.1 and 0.9 for all the cases considered which are the limits used in (7). The state of charge at the beginning and end of the day depends on the load profile in the DN and the desired increment in the stored energy of the BES unit, whereas the efficiency of the charge/discharge process does has little effect on the shape of the state of charge of the BES unit. Figures 9 and 10 show the close correlation between stored energy and the state of charge of the BES unit, which can best be seen in the similarity of the stored energy increment and the difference between the state of charge at the end and the beginning of the day. Also, Figs. 9 and 10 show that the state of charge of the BES unit increases in the time of high solar irradiation when the BES unit is charging, and decreases in time of low solar irradiation when the BES unit is discharging.

All previously obtained results refer to the case of improving the voltage profile and reducing power losses with the same priority. This is achieved when both terms of the criterion function have approximately the same average values considering most iterations during the execution of PSO or WHO. Specifically, the values of the weighting coefficients that allow the same priority to improve the voltage profile and reduce the power losses are: $a = 1\frac{1}{\mathrm{W}}$ and $b = 0.4\frac{1}{\mathrm{V}^2}$.

Table V outlines the values of average daily power losses and voltage quality index for the case after connecting one PV-BES system, together with the corresponding optimal site and sizing parameters, obtained for various priorities in the criterion function for the third daily load profile.

TABLE V. AVERAGE DAILY POWER LOSSES AND VOLTAGE QUALITY INDEX OF THE DN FOR THE CASE AFTER CONNECTING ONE PV-BES SYSTEM TO THE DN, AND THE OPTIMAL SITE AND SIZING PARAMETERS OF THAT PV-BES SYSTEM OBTAINED FOR VARIOUS PRIORITIES IN THE CRITERION FUNCTION.

Priority case	I	II	III	IV	V
P_{loss} (kW)	14.694 (14.694)	15.849 (15.849)	19.390 (19.389)	22.083 (22.083)	25.322 (25.324)
VQI (10^3 V^2)	59.710 (59.715)	29.799 (29.798)	12.127 (12.131)	7.643 (7.643)	6.130 (6.130)
Optimal site	6 (6)	7 (7)	7 (7)	7 (7)	7 (7)
$P_{PV\max}$ (MW)	7.367 (7.366)	7.932 (7.932)	9.133 (9.133)	9.744 (9.743)	10.339 (10.340)
$P_{BES\max}$ (MW)	4.548 (4.548)	4.894 (4.895)	5.632 (5.632)	6.006 (6.007)	6.372 (6.372)
Q_{BES} (MWh)	32.578 (32.578)	35.067 (35.069)	40.285 (40.285)	43.046 (43.046)	45.668 (45.669)

Five cases of different priorities are considered, each of them having its pair of weighting coefficients. In the first case, the dominant priority is given to the reduction of power losses in the DN ($a = 1\frac{1}{\mathrm{W}}$, $b = 0.004\frac{1}{\mathrm{V}^2}$). In the second, the basic priority is given to the reduction of power losses ($a = 1\frac{1}{\mathrm{W}}$, $b = 0.1\frac{1}{\mathrm{V}^2}$). In the third case, the reduction of power losses and the improvement of the voltage profile have the same priorities ($a = 1\frac{1}{\mathrm{W}}$, $b = 0.4\frac{1}{\mathrm{V}^2}$). In the fourth, the basic priority is given to improving the voltage profile ($a = 0.4\frac{1}{\mathrm{W}}$, $b = 0.4\frac{1}{\mathrm{V}^2}$), and in the fifth case, the dominant priority is given to improving the voltage profile ($a = 0.01\frac{1}{\mathrm{W}}$, $b = 0.4\frac{1}{\mathrm{V}^2}$).

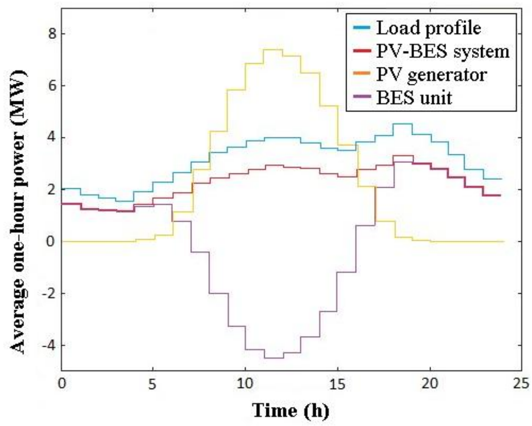
According to the results in Table V, the average daily power losses and the DN voltage quality index have lower values if they are given a higher priority. Also, since the voltage profile and power losses depend on the power flows in the DN, the changes in their values occur simultaneously. To some extent, these changes are beneficial to the improvement on both sides, as can be seen from the results in Cases I and V, where the values of voltage quality index (Case I) and power losses (Case V) are significantly improved compared to the corresponding values from Table I. After that, the improvement of the voltage profile and the reduction of power losses in the DN have opposing needs considering the amount of injected power from the PV-BES system, which is why the optimal values of the sizing parameters depend on the given priority.

Furthermore, from Table V, it can be seen that the maximum power required of the PV generator, the maximum power required of the BES unit, and the storage capacity required of the BES unit increase as the priority given to improving of the voltage profile increases. The explanation for this lies in the fact that improving the voltage profile requires the injection of a higher power from the connected PV-BES system than the reduction of power losses for the selected reference voltage (Fig. 11). The selected value of the reference voltage has a high effect on the results obtained. Specifically, in this paper the reference voltage is equal to 10 kV (or 1 pu), which is also the voltage of the power supply node. In the case when the reduction of power losses in the DN is given the dominant priority, the optimal location of the connected PV-BES system changes from node 7 to node 6.

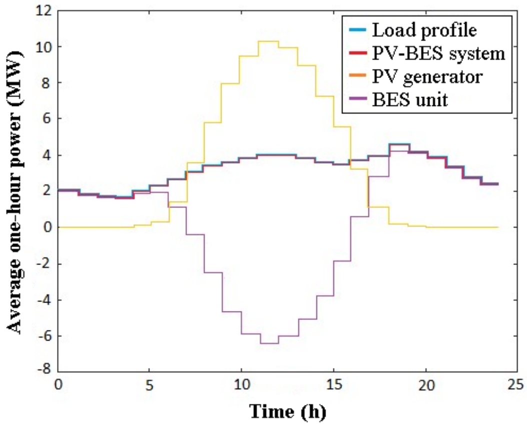
It is important to point out that, in addition to the PSO and WHO, the authors also used the genetic algorithm [6] as well to solve the given optimisation problem. The results generated using the genetic algorithm were very similar to those in Tables II–V.

Figure 11 shows the average one-hour powers of the PV-BES system (optimal power), power of the PV generator, and power of the BES unit obtained for the third daily load profile using the following two priority cases: (i) case where the dominant priority is given to the reduction/minimisation of power losses (Fig. 11(a)) and (ii) case where the dominant priority is given to the improvement of the voltage profile (Fig. 11(b)).

It can be seen from Fig. 11(a) that the optimal power of the PV-BES system is approximately two-thirds of the load power if the priority is to reduce power losses.



(a)



(b)

Fig. 11. Average one-hour powers of the PV-BES system (optimal power), the PV generator, and the BES unit obtained for the third daily load profile and two different priorities in the criterion function: (a) The case where the priority is given to reducing power losses; (b) The case where the priority is given to improving the voltage profile.

However, if the priority is to improve the voltage profile, according to Fig. 11(b), the optimal power of the PV-BES system is almost identical to the load power. This results in higher operating powers and sizing parameters for the PV generator and BES unit if the priority is to improve the voltage profile.

VI. CONCLUSIONS

This paper effectively presented the proposed two-step approach for optimal siting and sizing of one or more PV-BES systems in the DN, to reduce power losses and improve voltage profile. The results obtained showed that the connection of such PV-BES systems to the DN improves its overall performance regardless of the shape of the load profile and that the level of improvement increases with the increase in the number of connected PV-BES systems. Moreover, it was found that only the nodes located along the two main (longest) branches in the DN can be the optimal sites to connect the PV-BES systems to the DN and that the indexes of those nodes change depending on the number of connected PV-BES systems.

The iterative method used in the second step of the proposed approach is found to be efficient in sizing the elements of the PV-BES system. Furthermore, it was observed that the sizing of the PV generator (its maximum power) in the PV-BES system is most affected by the average load power and that the sizing of the BES unit (its maximum power and its storage capacity) depends mainly on the matching between the load diagram and the power generation diagram of the PV generator. Regarding this, for the same level of improvement in the operation of the DN, both the decrease in efficiency and the increase in the amount of energy stored in the BES unit during the operating cycle increase the sizes of the PV generator and the BES unit. Finally, this study showed that the required size of the PV-BES system is larger in the case where priority is given to the improvement of the voltage profile than in the case where the reduction of power losses was prioritised.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] P. D. P. Reddy, V. C. V. Reddy, and T. G. Manohar, "Optimal renewable resources placement in distribution networks by combined power loss index and whale optimization algorithms", *Journal of Electrical Systems and Information Technology*, vol. 5, no. 2, pp. 175–191, 2018. DOI: 10.1016/j.jesit.2017.05.006.

[2] S. Gutta, T. G. Manohar, and A. V. S. Reddy, "Voltage control and power loss reduction in distributed networks using distributed generation", *International Journal of Innovative Technology and Exploring Engineering*, vol. 8, no. 12, pp. 2863–2867, 2019. DOI: 10.35940/ijitee.L3047.1081219.

[3] E. E. Elattar and S. K. Elsayed, "Optimal location and sizing of distributed generators based on renewable energy sources using modified moth flame optimization technique", *IEEE Access*, vol. 8, pp. 109625–109638, 2020. DOI: 10.1109/ACCESS.2020.3001758.

[4] D. Lamsal, A. K. Mishra, and P. Gautam, "Optimal location and sizing of distributed generation: B-coefficient matrix approach", in *Proc of 12th IEEE International Conference on Control and Automation (ICCA)*, 2016, pp. 810–815. DOI: 10.1109/ICCA.2016.7505378.

[5] K. E. Adetunji, I. W. Hofsajer, A. M. Abu-Mahfouz, and L. Cheng, "A review of metaheuristic techniques for optimal integration of electrical units in distribution network", *IEEE Access*, vol. 9, pp. 5046–5068, 2021. DOI: 10.1109/ACCESS.2020.3048438.

[6] O. D. Montoya, W. Gil-Gonzalez, and C. Orozco-Henao, "Vortex search and Chu-Beasley genetic algorithms for optimal location and sizing of distributed generators in distribution networks: A novel hybrid approach", *Engineering Science and Technology, an International Journal*, vol. 23, no. 6, pp. 1351–1363, 2020. DOI: 10.1016/j.jestch.2020.08.002.

[7] S. N. Syed Nasir, A. F. Othman, R. Ayop, and J. J. Jamian, "Power loss mitigation and voltage profile improvement by optimizing distributed generation", *Journal of Physics: Conference Series*, vol. 2312, art. 012023, 2022. DOI: 10.1088/1742-6596/2312/1/012023.

[8] A. Alam, A. Gupta, P. Bindal, A. Siddiqui, and M. Zaid, "Power loss minimization in a radial distribution system with distributed generation", in *Proc. of 2018 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)*, 2018, pp. 21–25. DOI: 10.1109/ICPECTS.2018.8521619.

[9] S. Das, O. B. Fosso, and G. Marafioti, "Efficient distribution network loss minimization with optimal DG placement and operation", in *Proc. of 2021 IEEE 12th Energy Conversion Congress and Exposition – Asia (ECCE–Asia)*, 2021, pp. 1885–1890. DOI: 10.1109/ECCE-Asia49820.2021.9478980.

[10] B. B. Pokharel, A. Shrestha, S. Phuyal, and S. K. Jha, "Voltage profile improvement of distribution system via integration of distributed resources", *Journal of Renewable Energy Electrical and Computer Engineering*, vol. 1, no. 1, pp. 33–41, 2021. DOI: 10.29103/jreece.v1i1.3519.

[11] A Singh, A. Shrestha, S. Phuyal, B. Adhikary, and A. P. Papadakis, "Particle swarm optimization approach for distributed generation allocation planning for voltage profile improvement", in *Proc. of 11th International Conference on Deregulated Engineering Markets Issues in South Eastern Europe (DEMSEE 2018)*, 2018, pp. 1–9.

[12] R. Jin, J. Song, J. Liu, W. Li, and C. Lu, "Location and capacity optimization of distributed energy storage systems in peak-shaving", *Energies*, vol. 13, no. 3, p. 513, 2020. DOI: 10.3390/en13030513.

[13] J. Radosavljević, "Voltage regulation in LV distribution networks with PV generation and battery storage", *Journal of Electrical Engineering*, vol. 72, no. 6, pp. 356–365, 2021. DOI: 10.2478/jee-2021-0051.

[14] W. Hao, J. Xu, G. Tong, W. Zhang, Y. Liu, and N. Tong, "Research on control strategy of PV-energy storage system connected to low voltage distribution network", in *Conference Proceedings of 2021 International Joint Conference on Energy, Electrical and Power Engineering. Lecture Notes in Electrical Engineering*, vol. 899. Springer, Singapore, 2022, pp. 659–674. DOI: 10.1007/978-981-19-1922-0_55.

[15] H. Yi and X. Yang, "A metaheuristic algorithm based on simulated annealing for optimal sizing and techno-economic analysis of PV systems with multi-type of battery energy storage", *Sustainable Energy Technologies and Assessments*, vol. 53, part C, art. 102724, 2022. DOI: 10.1016/j.seta.2022.102724.

[16] J. M. Home-Ortiz, M. Pourakbari-Kasmaei, M. Lehtonen, and J. R. S Mantovani, "Optimal location-allocation of storage devices and renewable-based DG in distribution systems", *Electric Power Systems Research*, vol. 172, pp. 11–21, 2019. DOI: 10.1016/j.epsr.2019.02.013.

[17] M.-Y. Chiang, S.-C. Huang, T.-C. Hsiao, T.-S. Zhan, and J.-C. Hou, "Optimal sizing and location of photovoltaic generation and energy storage systems in an unbalanced distribution system", *Energies*, vol. 15, no. 18, p. 6682, 2022. DOI: 10.3390/en15186682.

[18] L. A. Wong, V. K. Ramachandaramurthy, S. L. Walker, and J. B. Ekanayake, "Optimal placement and sizing of battery energy storage system considering the duck curve phenomenon", *IEEE Access*, vol. 8, pp. 197236–197248, 2020. DOI: 10.1109/ACCESS.2020.3034349.

[19] C. K. Das, O. Bass, T. S. Mahmoud, G. Kothapalli, M. A. S. Masoum, and N. Mousavi, "An optimal allocation and sizing strategy of distributed energy storage systems to improve performance of distribution networks", *Journal of Energy Storage*, vol. 26, art. 100847, 2019. DOI: 10.1016/j.est.2019.100847.

[20] X. Tang, K. Deng, Q. Wu, and Y. Feng, "Optimal location and capacity of the distributed energy storage system in a distribution network", *IEEE Access*, vol. 8, pp. 15576–15585, 2020. DOI: 10.1109/ACCESS.2020.2967435.

[21] K. Zaareer, C. Z. El-Bayeh, and Q. Salem, "Grid-connected PV systems: Impact evaluation & optimal allocation and sizing for losses minimization and voltage improvement (Jordanian case study)", *Journal of Electrical and Electronics Engineering*, vol. 12, no. 2, pp. 17–22, 2019.

[22] M. Q. Duong, T. D. Pham, T. T. Nguyen, A. T. Doan, and H. V. Tran, "Determination of optimal location and sizing of solar photovoltaic distribution generation units in radial distribution systems", *Energies*, vol. 12, no. 1, p. 174, 2019. DOI: 10.3390/en12010174.

[23] S. R. Seyednouri, H. Ebrahimian, and A. Jalili, "Power loss reduction and voltage profile improvement by photovoltaic generation", *International Journal of Engineering Trends and Technology*, vol. 20, no. 4, pp. 192–196, 2015. DOI: 10.14445/22315381/IJETT-V20P236.

[24] L. A. Wong, H. Shareef, A. Mohamed, and A. A. Ibrahim, "Optimal placement and sizing of energy storage system in distributed network with photovoltaic based distributed generation using improved firefly algorithms", *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, vol. 11, no. 7, pp. 895–903, 2017. DOI: 10.5281/zenodo.1131635.

[25] H. Wang *et al.*, "The optimal allocation and operation of an energy storage system with high penetration grid-connected photovoltaic systems", *Sustainability*, vol. 12, no. 15, p. 6154, 2020. DOI: 10.3390/su12156154.

[26] E Rodriguez, N. Vázquez, J. Arau, R Osorio, F. Medina, and C. Hernández, "Central energy storage system to reduce the harmful effects of PV systems under a high penetration scenario", *Electronics*, vol. 10, no. 19, p. 2418, 2021. DOI: 10.3390/electronics10192418.

[27] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, "Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality", *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 1205–1230, 2018. DOI: 10.1016/j.rser.2018.03.068.

[28] M. Stecca, L. R. Elizondo, T. B. Soeiro, P. Bauer, and P. Palensky, "A comprehensive review of the integration of battery energy storage systems into distribution networks", *IEEE Open Journal of the Industrial Electronics Society*, vol. 1, pp. 46–65, 2020. DOI: 10.1109/OJIES.2020.2981832.

[29] M. M. Haque and P. Wolfs, "A review of high PV penetrations in LV distribution networks: Present status, impacts and mitigation measures", *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 1195–1208, 2016. DOI: 10.1016/j.rser.2016.04.025.

[30] N. Mansouri, A. Lashab, J. M. Guerrero, and A. Cherif, "Photovoltaic power plants in electrical distribution networks: A review on their impact and solutions", *IET Renewable Power Generation*, vol. 14, no. 12, pp. 2114–2125, 2020. DOI: 10.1049/iet-rpg.2019.1172.

[31] M. H. Ali, S. Kamel, M. H. Hassan, M. Tostado-Veliz, and H. Zawbaa, "An improved wild horse optimization algorithm for reliability based optimal DG planning of radial distribution networks", *Energy Reports*, vol. 8, pp. 582–604, 2022. DOI: 10.1016/j.egyr.2021.12.023.

[32] R. Zheng, A. G. Hussien, H.-M. Jia, L. Abualigah, S. Wang, and D. Wu, "An improved wild horse optimizer for solving optimization problems", *Mathematics*, vol. 10, no. 8, p. 1311, 2022. DOI: 10.3390/math10081311.

[33] A. Kumar, S. Pant, M. K. Singh, S. Chaube, M. Ram, and A Kumar, "Modified wild horse optimizer for constrained system reliability optimization", *Axioms*, vol. 12, no. 7, p. 693, 2023. DOI: 10.3390/axioms12070693.

[34] K. Mahesh, P. AL Nallagownden, and I. AL Elamvazuthi, "Optimal placement and sizing of DG in distribution system using accelerated PSO for power loss minimization", in *Proc. of 2015 IEEE Conference on Energy Conversion (CENCON)*, 2015, pp. 193–198. DOI: 10.1109/CENCON.2015.7409538.

[35] H. Huang, J. Qiu, and K. Riedl, "On the global convergence of particle swarm optimization methods", *Applied Mathematics and Optimization*, vol. 88, art. no. 30, 2023. DOI: 10.1007/s00245-023-09983-3.

[36] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, "Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm", *Applied Energy*, vol. 232, pp. 212–228, 2018. DOI: 10.1016/j.apenergy.2018.07.100.

[37] P. Goli, S. Yelem, K. Jasthi, S. R. Gampa, and D. Das, "Optimum placement of battery energy storage systems and solar PV units in distribution networks using gravitational search algorithm", in *Proc. of the International Conference on Artificial Intelligence Techniques for Electrical Engineering Systems (AITEES 2022)*, 2022, pp. 113–123. DOI: 10.2991/978-94-6463-074-9_11.

[38] J. A. M. Rupa and S. Ganesh, "Power flow analysis for radial distribution system using backward/forward sweep method", *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, vol. 8, no. 10, p. 1551, 2014.

[39] Y. G. Werkie and H. A. Kefale, "Optimal allocation of multiple distributed generation units in power distribution networks for voltage profile improvement and power losses minimization", *Cogent Engineering*, vol. 9, no. 1, art. 2091668, 2022. DOI: 10.1080/23311916.2022.2091668.