UDC: 621.383.51
621.316

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Method for determining the optimal location and configuration of the system consisting of photovoltaic and energy storage system considering the reduction of losses in the distribution network

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Category of article: Original scientific research article

Highlights

- This paper considers the reduction of losses in the distribution network by connecting the system consisting of photovoltaic (PV) and energy storage system (ESS).
- The optimal location and optimal power of the system consisting of PV system and ESS is determined, taking into account the minimization of losses in the distribution network.
- Sizing of the PV system and ESS is carried out.
- The influence of the discrepancy between the actual and expected values of load and solar irradiation on the increase of losses in the distribution network and the change in the state of charge of ESS

Abstract

In this paper two-step method for determining the optimal location and configuration of the system consisting of PV system and ESS, considering the reduction of losses in distribution network, is presented. First step takes into account the daily load diagram and uses the metaheuristic particle swarm optimization method (PSO) to determine the optimal location and optimal power during the day of the system consisting of PV system and ESS in order to minimize the losses in distribution network. In the second step of the procedure, the individual powers of PV system and ESS are obtained and their configuration (sizing) determined. This is done by iterative procedure using the optimal values of combined power of these two systems during the day, obtained in the first step, and the shape of daily solar irradiation diagram of the PV system for the clear day. The configuration procedure is explained in detail, determining the maximum power of PV system, maximum power of ESS and energy capacity of ESS. In addition, the impact of the difference between the actual and the expected load diagram and the influence of the reduction of solar irradiation during the day on the increase of losses in the distribution network and the change in the state of charge of the ESS are considered. The paper considers cases with different load diagrams and different levels of ESS efficiency. All results are obtained using IEEE radial distribution network with 33 nodes.

Keywords

Photovoltaic (PV) System, Energy Storage System (ESS),

Particle Swarm Optimization Method (PSO), Losses in the Distribution Network

Note:

This article represents an expanded, improved and additionally peer-reviewed version of the paper "*Optimal location and configuration of the system consisting of photovoltaic and energy storage system considering the reduction of losses in distribution network*", awarded by Expert Committee EC-4 *Distributed Generation and Efficient Use of Electricity* at the 13th CIRED Serbia Conference, Kopaonik, September 12-16, 2022

Received: April 5th, 2023 Reviewed: April 25th, 2023
Modified: April 28th, 2023 Accepted: May 4th, 2023
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1. INTRODUCTION

Increasing environmental awareness has caused efficiency improvements and the use of green technologies to become one of the basic requirements and priorities set when considering power system operation. In meeting these requirements, renewable energy sources play a significant role, with numerous attempts made to facilitate their power system integration and operational improvements [1]. One particularly important form of their application is connection to the distribution network [2] where they play the role of distributed generation. Through this, renewable energy sources bring generation closer to the consumption and reduce transmission losses [3]. However, due to their intermittent character, they are often unable to achieve the required power that would bring the desired network efficiency increase. One of the solutions to this problem, especially in cases where distributed generation and load are largely mismatched, is the use of ESS [4]-[5].

Specifically, this paper discusses the distribution network efficiency improvements, using loss reduction [6], by utilising a system consisting of a PV system and an ESS [7]. This combined system operates like a distributed generation with possible control of the output power to the distribution network [8]-[9]. This power facilitates load shedding of certain parts of the distribution network, especially the supply ones, reducing pertaining losses. Distribution network power flows and currents along its lines are determined by an iterative method for power flows calculation in radial distribution networks [10]. To minimize distribution network losses, in this case, it is necessary to correctly locate the mentioned system and ensure at all times an adequate value of its output power [8]. The optimal location and power that need to be injected into the distribution network by a system composed of a PV system and an ESS, to minimize pertaining losses, [3], [11], were determined using the PSO metaheuristic optimization method, [12]-[15], considering the expected daily load diagram. Based on the obtained optimal power of the system during the day and the daily solar irradiation diagram of the PV system in the case of a clear day, individual powers of the PV system and ESS have been determined, together with their optimal configuration, i.e. sizing [11], [16]. Here, the required maximum powers of the PV system and the ESS were determined, along with the required energy capacity of the ESS, for different diagrams and load types, using different ESS efficiency levels.

The procedure used to determine the configuration of a system consisting of a PV system and an ESS is of an iterative type, where the maximum power of the PV system is determined based on the assumed values for the ESS charging/discharging periods [17], on the basis of which the ESS charging/discharging periods are more accurately determined in the next iteration. Initial values of the ESS charging/discharging periods are determined based on the shape of the daily load diagram of the distribution network and the daily solar irradiation diagram of the PV system. The iterative procedure ends when the ESS charging/discharging periods have the same value in two adjacent iterations. The procedure applied to determine the optimal location and configuration of a system consisting of a PV system and an ESS requires knowledge of the distribution network daily load diagram and the PV system solar irradiation diagram. Due to their stochastic nature, these diagrams cannot be predicted with certainty [18], which is why the optimal system configuration is performed based on their most probable values, including the expected load diagram and solar irradiation diagram of the PV system on a clear day. For this reason, the influence of the discrepancy between actual and expected (predicted) load values, as well as the influence of the PV system solar irradiation reduction due to cloud cover during the day, on the network losses increase and the change of the ESS state of charge has also been examined. [19].

2. DEFINING THE OPTIMIZATION PROBLEM AND CRITERION FUNCTION

Reducing distribution network losses by using a system composed of a PV system and an ESS is a nonlinear optimization problem with constraints. The non-linearity arises from the non-linear dependence of the distribution network losses on the injection power of the combined system and non-linear constraints that need to be met.

Control variables in this optimization problem are the location and the mean hourly power of a system composed of a PV system and an ESS. Constraints of the control variables have been given by the following relations:

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

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

where i is the distribution network node index where the system consisting of a PV system and an ESS is connected, while $P(k)$ is the mean hourly power injected by this system into the distribution network in the k-th hour. The set of node indexes where it is possible to connect the mentioned system is given as $\{i_1, i_2, \dots i_n\}$, while $P_{min}(k)$ and $P_{max}(k)$ are its minimum and maximum power in the k-th hour, determined by the minimum and maximum power of the PV system and ESS ($P_{min}(k) = P_{PVmin}(k) + P_{ESSmin}(k)$, $P_{max}(k) = P_{PVmax}(k) + P_{ESSmax}(k)$).

The dependent variables appearing in this optimization problem are the power of the PV system, power of the ESS, the ESS state of charge, the current along the distribution network lines and the voltage in its nodes.

Constraints of the dependent variables are determined by the minimum and maximum powers of the PV system and the ESS, the maximum operating current and the allowed voltage range of the distribution lines, as well as the allowed range of the ESS state of charge, which is given by the relations (3)-(7):

$$P_{PVmin}(k) < P_{PV}(k) < P_{PVmax}(k) \tag{3}$$

$$P_{ESSmin}(k) < P_{ESS}(k) < P_{ESSmax}(k) \tag{4}$$

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

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

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

where I and V are the distribution network current and voltage, while SOC is the ESS state of charge.

Powers $P_{PV}(k)$ and $P_{ESS}(k)$ are the mean one-hour powers of the PV system and ESS in the k-th hour, which, similar to the other quantities, must be between their minimum ($P_{PVmin}(k)$, $P_{ESSmin}(k)$) and maximum values ($P_{PVmax}(k), P_{ESSmax}(k)$). In this paper, limiting values for ESS powers (maximum charging power and maximum discharging power) do not represent a limiting factor to obtain an optimal solution and have the same value throughout the day. In contrast, the upper limit value for the power of the PV system $P_{PVmax}(k)$ depends on the ordinal number of hours in day k, and follows the shape of the daily solar irradiation diagram of the PV system. Lower limit value for PV system power $P_{PVmin}(k)$ is equal to zero for every hour of the day.

For the obtained ESS operating modes to be sustainable in time, when determining the optimal system configuration, equal states of charge at the beginning (SOC_0) and the end (SOC_T) of the operating cycle (day) are used. For this purpose, an additional constraint related to the ESS state of charge is used:

$$SOC_T - SOC_0 = 0 \tag{8}$$

The optimization problem solution is necessary to enable the distribution network loss minimization. For this reason, a single-parameter criterion function equal to the mean daily power of distribution network losses was used, given by the relation (9):

$$C = \frac{1}{24} \cdot \sum_{k=1}^{24} \sum_{j=1}^{m} 3 I_{k,j}^2 R_j \tag{9}$$

where: $C -$ criterion function, whose minimization needs to be performed, $I_{k,j} -$ effective current value in the k-th hour along the j-th distribution network section, $R_j -$ active resistance of the j-th distribution network section, $m -$ total number of distribution network sections.

3. SOLVING THE OPTIMIZATION PROBLEM AND DETERMINING THE OPTIMUM SYSTEM CONFIGURATION

In order to obtain an optimal location and configuration of the system consisting of a PV system and an ESS, it is first necessary to solve the set optimization problem. Solving this optimization problem comes down to finding the optimal values for the location and power of the system consisting of a PV system and an ESS to achieve the distribution network loss minimization. The metaheuristic optimization method of PSO was used to obtain the optimal location and the optimal mean hourly power during the day of the combined system. The advantage of PSO and metaheuristic optimization methods in general is their flexibility and possible application to a wide range of different optimization problems.

3.1 Solving the optimization problem

As mentioned, PSO was used to solve the set optimization problem. PSO belongs to population metaheuristic optimization methods and is inspired by the foraging process of flocks of birds in nature. A population consists of a set of individuals, each of which represents a vector of control variables and a potential solution to an optimization problem. Individuals in the population communicate with each other and move towards the one in the place with the largest amount of food, i.e. that has the lowest criterion function value. To facilitate better space search where the optimal solution can be found, the individual movement direction is not influenced only by the location with the largest amount of food found until then (g_{best}), but also by the location with the largest amount of food that individual had found until then (p_{besti}). In this way, in each subsequent iteration, the individuals are closer to finding the place with the largest amount of food, and thus the smallest criterion function value. The individual that has the smallest criterion function value at the end of the optimization process is also the optimization problem solution. The above optimization method can be analytically described through relations (10) and (11):

$$v_i(t+1) = w \cdot v_i(t) + C_1 \cdot r_1 \cdot (p_{besti}(t) - x_i(t)) + C_2 \cdot r_2 \cdot (g_{best}(t) - x_i(t)) \tag{10}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{11}$$

where: t – iteration ordinal number, x_i– location of i-th individual, $v_i -$ movement of i-th individual, w – inertia coefficient, $C_1, C_2 -$ acceleration coefficients, $r_1, r_2 -$ random numbers from the interval $[0,1]$.

When solving the above optimization problem, the individual is represented by a vector of control variables with 25 coordinates, the first of which is the location (the distribution network node index where the system is connected), and the other 24 coordinates are the mean one-hour powers of the observed system during the day. After each iteration, coordinates of the individuals are changed in order to reduce the value of their criterion function, which after the appropriate number of iterations (when the change in the criterion function of the best solution is negligible) gives the solution to the optimization problem. As part of the solution to the optimization problem, the optimal location of the system consisting of a PV system and an ESS was directly obtained, while the obtained optimal powers were used to determine the optimal system configuration.

3.2 Determining the optimal configuration of a system consisting of a PV system and an ESS

This paper adopts a configuration ensuring distribution network loss minimization with minimal sizing of the PV system and ESS, for the optimal configuration of a system consisting of a PV system and an ESS, whose principle diagram is shown in Figure 1.

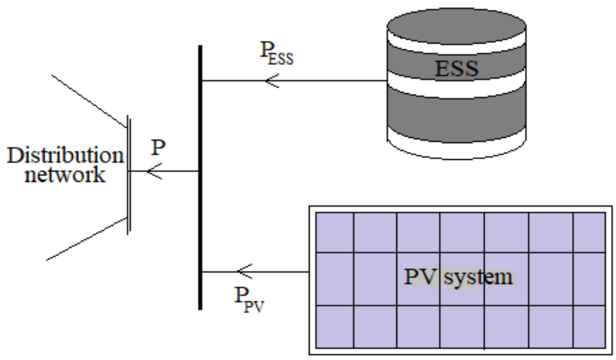

Figure 1. A principal diagram of a system consisting of a PV system and an ESS

To determine the optimal configuration, the obtained optimal power was used, which the mentioned system should inject into the distribution network during the day in order to minimize pertaining losses, as well as the daily solar irradiation diagram of the PV system. In the applied approach, the first step in determining the optimal configuration of a system consisting of a PV system and an ESS is sizing the PV system, i.e. determining its maximum power. To make this possible, it is necessary to express the PV system power for each hour of the day in terms of its maximum power (P_{PVmax}) and solar irradiation during the day:

$$P_{PV}(h) = P_{PVmax}\frac{I_C(h)}{I_{Cmax}} \tag{12}$$

where $P_{PV}(h)$ and $I_C(h)$ are power and solar irradiation of the PV system in the h-th hour, while I_{Cmax} is the maximum solar irradiation of the PV system during the day. The power of the PV system follows the daily solar irradiation diagram of its panels, which is the reason why this system is often unable to meet the required optimal power by itself. To solve this problem, an ESS was used, which, according to needs, can play the role of consumption (charging period) or generation (discharging period), and ensures that the power injected into the distribution network is equal to the optimal power (P_{opt}).

$$P_{ESS} = P_{opt} - P_{PV} \tag{13}$$

Considering that in this paper mean one-hour powers are used, the state of charge of the ESS at the end of the k-th hour, during charging and discharging can be determined from relations (14) and (15) respectively:

$$SOC_k = SOC_{k-1} - \frac{\eta}{Q_{ESS}}P_{ESS}(k) \tag{14}$$

$$SOC_k = SOC_{k-1} - \frac{1}{\eta \cdot Q_{ESS}}P_{ESS}(k) \tag{15}$$

where: SOC_k – ESS state of charge at the end of the k-th hour, SOC_{k-1} – ESS state of charge at the end of the k-1-th hour, $P_{ESS}(k)$ – mean one-hour power of the ESS in the k-th hour (with a value less than zero during the charging time and greater than zero during the discharge), Q_{ESS} – total, computational energy capacity of ESS, η – efficiency level of the ESS charging and discharging process.

By using the expression (12) in (13) and then expression (13) in (14) and (15), the difference between the ESS state of charge at the end and the beginning of the observed period (ΔSOC) can be determined as:

$$\Delta SOC = \sum_j^m \left(P_{PVmax}\frac{I_C(j)}{I_{Cmax}} - P_{opt}(j)\right)\frac{\eta}{Q_{ESS}} - \sum_i^n (P_{opt}(i) - P_{PVmax}\frac{I_C(i)}{I_{Cmax}})\frac{1}{\eta \cdot Q_{ESS}} \tag{16}$$

where i is the ordinal number of hours, while n is the total number of hours when the ESS is discharged, while j is the ordinal number of hours, with m being the total number of hours when the ESS is charged throughout the observed operating cycle.

The ESS charging periods occur when the required optimal power of the system composed of the PV system and ESS is lower, and the discharge periods when it is greater than the power of the PV system. Since the maximum power of the PV system is not known in advance, these periods must be assumed by looking at the shape of the optimal power and the solar irradiation diagrams. Using the assumed values for the charge and discharge periods, for a given efficiency level and zero difference between the state of charge of the ESS at the end and the beginning, the maximum power of the PV system based on expression (16) is:

$$P_{PVmax} = \frac{\sum_j^m P_{opt}(j)\eta + \sum_i^n P_{opt}(i)\frac{1}{\eta}}{\sum_j^m \frac{I_C(j)}{I_{Cmax}}\cdot\eta + \sum_i^n \frac{I_C(i)}{I_{Cmax}}\cdot\frac{1}{\eta}} \quad (17)$$

After determining the maximum power of the PV system using expression (17), it is necessary to check the accuracy of the assumption made about the ESS charging and discharging periods. This is done by comparing the optimal power of the system composed of the PV system and the ESS with the power of the PV system determined from its maximum power using expression (12). If it turns out that the assumption is not correct, the procedure needs to be repeated by using new, better estimated charging and discharging periods. It should be noted that if the ESS efficiency level is equal to one, the situation is much simpler because it is not necessary to assume charging and discharging periods, so the maximum power of the PV system is obtained directly.

When the maximum power of the PV system is known, by using the expressions (12) and (13) it is possible to determine the power of the ESS for each hour of the observed period. The highest one-hour power of the ESS by absolute value during the operation period (T) is the power according to which it is necessary to size the ESS:

$$P_{ESSmax} = \max\{|P_{ESS}(k)|\},\ k = \{1,2,\dots T\} \quad (18)$$

Subsequently, using expressions (14) and (15), the ESS states of charge are determined at the end of each hour inside the observed operation period. On the basis of the obtained values for the ESS states of charge, its sizing has been carried out, i.e. the required energy capacity determined. Minimum required energy capacity (ΔQ_{ESS}) which would enable the specified ESS operation is determined by using the expression (19):

$$\Delta Q_{ESS} = Q_{ESS} \cdot (SOC_{Max} - SOC_{Min}) \quad (19)$$

where SOC_{Max} and SOC_{Min} are maximum and minimum states of charge of the ESS within the observed operation cycle.

In addition to the required energy capacity of the ESS, in order to achieve the desired (optimal from the network loss reduction aspect) operating mode, it is necessary to determine the permissible range in which the initial ESS state of charge can be found, so that the state of charge during the day is within the permissible values. The maximum and minimum values of ESS state of charge during the operation can be expressed using the initial state of charge of ESS and the charge/discharge power (P'_{ESS}) as:

$$SOC_{Max} = SOC_0 - \frac{1}{Q_{ESS}}\sum_{k=1}^{kmax} P'_{ESS}(k) \quad (20)$$

$$SOC_{Min} = SOC_0 - \frac{1}{Q_{ESS}}\sum_{k=1}^{kmin} P'_{ESS}(k) \quad (21)$$

where k_{min} and k_{max} are ordinal number of hours in which the minimum and maximum ESS state of charge occurs, while in the charging time power P'_{ESS} is considered to be $P'_{ESS} = \eta P_{ESS}$, and during discharge time $P'_{ESS} = P_{ESS}/\eta$.

The minimum and maximum charge levels occurring in the ESS operation must be within the permissible limits ($SOC_{Max} \leq SOC_{max}$ i $SOC_{Min} \geq SOC_{min}$), so the allowed range in which the initial ESS state of charge can be found, is obtained using expression (22):

$$SOC_{min} + \frac{1}{Q_{ESS}}\sum_{k=1}^{kmin} P'_{ESS}(k) \leq SOC_0 \leq SOC_{max} + \frac{1}{Q_{ESS}}\sum_{k=1}^{kmax} P'_{ESS}(k) \quad (22)$$

4. DISCREPANCY BETWEEN ACTUAL AND EXPECTED VALUES OF LOAD AND SOLAR IRRADIATION

As can be seen in chapter 3, the presented method uses the expected load diagram of the distribution network to determine the optimal power that system consisting of a PV system and an ESS should inject into the network. Similarly, when determining the optimal system configuration, the method requires the knowledge of the shape of daily solar irradiation diagram of the PV system for the case of a clear day. Considering the above, it is clear that the system configuration optimality, and thus the distribution network loss reduction, largely depends on the forecast accuracy of the load diagram of the distribution network and solar irradiation diagram of the PV system. As can be assumed, three different cases are possible:

1. discrepancy between the actual and forecasted load diagram,
2. discrepancy between the actual and forecast solar irradiation diagram of the PV system,
3. discrepancy between actual and forecasted values of both considered diagrams.

In order to quantify the impact of the discrepancy between the actual and expected values of load and solar irradiation on the network loss increase, within each of the three examples, cases are considered where there is a change of the hourly characteristics compared to those predicted by the expected load diagram and the solar irradiation diagram of the PV system for the case of a clear day.

Depending on the method applied to solve the mentioned problem, two approaches were considered. In both approaches, in order to maximize the use of solar energy, it was assumed that the PV system operates with the maximum possible power at a given moment, which is directly proportional to the intensity of solar irradiation on its panels. On the other hand, the way to determine the ESS power depends on the approach used. Namely, in the first approach, the equality of the ESS state of charge at the beginning and at the end of the operating cycle must be preserved, while in the second approach this is not the case and only priority is network loss minimization. Therefore, the power of the ESS in the first approach (P_{ESS}^{I}) is equal to the ESS power obtained in the system configuration process (P_{ESS}), where the condition of equality of the ESS state of charge at the beginning and end of the operation cycle was satisfied.

$$P_{ESS}^{I} = P_{ESS} \tag{23}$$

Bearing in mind that the PV system power depends on the solar irradiation, which cannot be influenced, and that the ESS power is predetermined, the injected power of the system consisting of PV system and ESS in the first approach may greatly differ from the optimal value, which could result in a significant network loss increase. This can especially be pronounced in periods with higher cloud cover and higher load than expected, when the PV system power is only sufficient to provide an adequate supplement to the ESS.

Unlike the first, in the second approach, the load is measured and based on this information PSO determines the optimal power that system should inject into the network at a given moment in order to minimize losses. The power of the ESS in second approach (P_{ESS}^{II}) is adjusted so that at all times, regardless of the current PV system power (P_{PV}), in the network is injected optimal power needed for the loss minimization perspective (P_{opt}).

$$P_{ESS}^{II} = P_{opt} - P_{PV} \tag{24}$$

It is clear that this approach successfully minimizes the network losses, but can also lead to a large difference between the ESS state of charge at the end and at the beginning of the operating period, which is the reason why the use of this approach is limited to special situations. It should be noted that regardless of the used approach, the constraints in the form of required maximum power (P_{ESSmax}) and the required ESS energy capacity (ΔQ_{ESS}), obtained in the system configuration process, must be satisfied. These constraints for the k-th hour are given by expressions (25) and (26), respectively:

$$P_{ESS}^{I,II}(k) < P_{ESSmax} \tag{25}$$

$$P_{ESS}^{I,II}(k) < \Delta Q_{ESS} - \sum_{i}^{k-1} P_{ESS}^{I,II}(i) \tag{26}$$

5. PRESENTATION AND ANALYSIS OF THE RESULTS

All the results obtained in this paper refer to the IEEE radial distribution network with 33 nodes, shown in Figure 2. The same distance between every two adjacent nodes has been adopted and it is 250 m. This was done for the sake of simplicity in drawing general conclusions. The distribution network voltage level is 10 kV, while the values of longitudinal active resistance and reactance are r =0.414 Ω/km and x =0.365 Ω/km.

The PSO was implemented to obtaine the optimal solution after 100 iterations using a population of 200 individuals. Based on a large number of performed simulations, the values of inertia coefficient and the acceleration coefficients that gave the best results are adopted, and they are: $w = 0.85$, $C_1 = 0.5$ i $C_2 = 0.6$.

Three different distribution network load diagrams are considered, shown in Figures 3, 4 and 5. The shapes of the first two load diagrams have a more theoretical character and are chosen as examples of loads that more or less matches the daily solar irradiation diagram of the PV system. As can be seen from Figures 3 and 4, the first and second distribution network load diagrams have different distributions of load power in time, but the same maximum ($P_{max1,2} = 4.462MW$) and mean power ($P_{av1,2} = 3.285MW$). Unlike them, the shape of the third load diagram, shown in Figure 5, better describes the load that can be found in practice and has a slightly higher maximum ($P_{max3} = 4.75MW$) and mean power ($P_{sr3} = 3.398MW$). In all considered cases, a uniform load distribution was used across the distribution network nodes. Also, for each load diagram, two different types of load are considered, the constant power load type (industrial load), and the constant impedance load type (resistive load), where for the indicated distribution network voltage (10 kV) active powers of both load types are the same and equal to those on the load diagram.

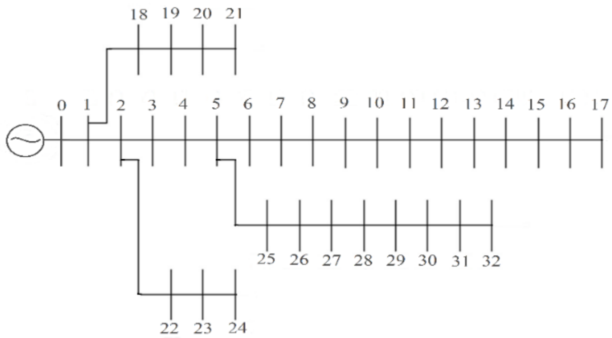

Figure 2. IEEE 33 distribution network

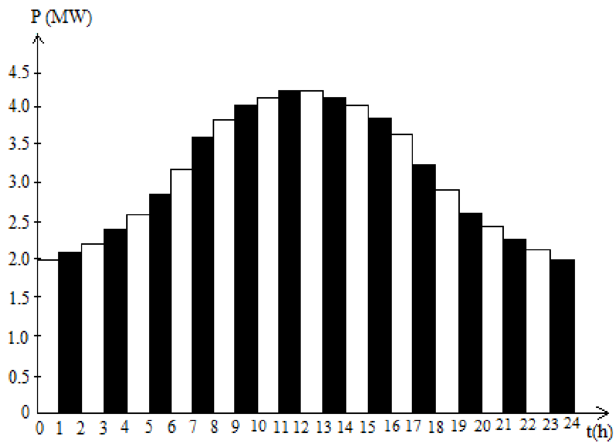

Figure 3. The first distribution network load diagram

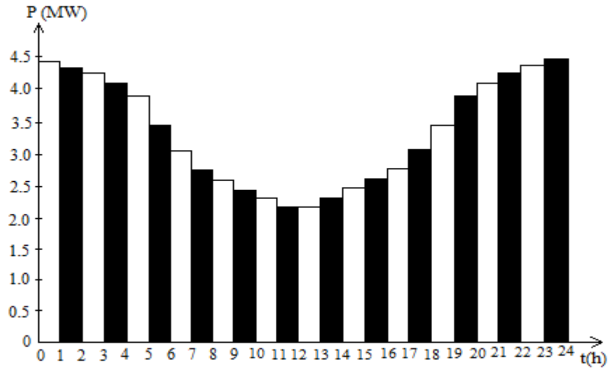

Figure 4. The second distribution network load diagram

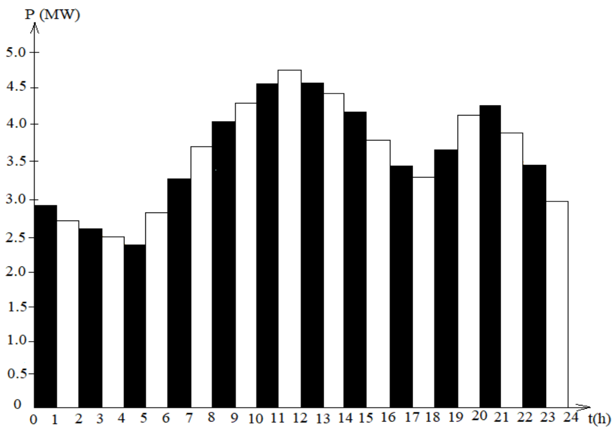

Figure 5. The third distribution network load diagram

It is important to note that in each considered case the time distribution of the load of each node is the same and follows the used load diagram of the distribution network. Likewise, the load power factor is the same throughout the day and uniform along the entire distribution network, while its value is $cos\varphi = 1$ and $cos\varphi = 0.89$ for resistive and industrial type loads, respectively.

The daily solar irradiation diagram of the PV system, used in determining the PV system power, expressed per unit, is given in Figure 6.

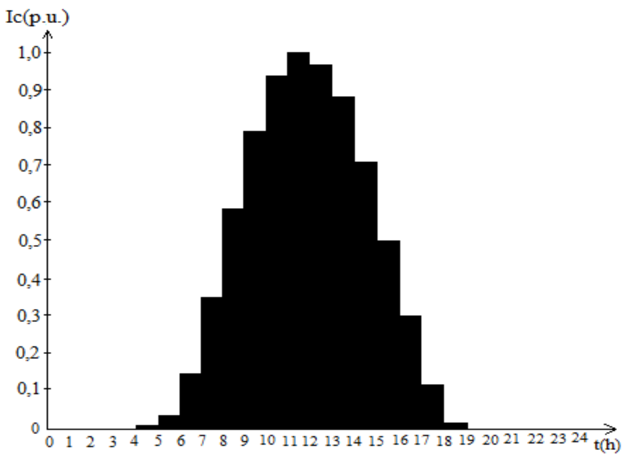

Figure 6. Daily PV system solar irradiation diagram

Table I shows the values of the mean daily power of losses in the distribution network before the system consisting of the PV system and the ESS has been connected, for all three load diagrams, where the values in brackets refer to the constant impedance load type, and the values without brackets to the constant power load type.

Table I. Mean daily power of losses before the system consisting of PV system and ESS has been connected

Load diagram	I	II	III
$P_{loss}[kW]$	63.037 (46.001)	63.037 (46.001)	68.097 (49.498)

Results in Table I are expected, given that the powers of the first and second load diagrams, although distributed differently in time, are the same in terms of values and slightly less than in the case of the third load diagram. Furthermore, the fact that the network nodes voltages are slightly lower than indicated, as well as the existence of reactive power flows in the network in the case of a constant power load, results in higher losses for such load type.

Considering the obtained optimal locations and power of the system consisting of PV system and ESS, Table II contains the results after it was connected to the distribution network. These results, in addition to the mean daily power of losses (P_{loss}), contain the optimal location (distribution network node index) where the system is connected (i), as well as the required maximum power of the PV system (P_{PVmax}), required maximum power of the ESS (P_{ESS}) and the required energy capacity of the ESS (ΔQ_{ESS}) for different levels of ESS efficiency (η=1, η=0.9 i η=0.8). It should be noted that in the presented procedure, the ESS efficiency level does not affect the location and power of the system consisting of PV system and ESS, only its configuration (maximum power of the PV system, maximum power and energy capacity of the ESS).

Based on the results in Table II, it can be concluded that by connecting a system consisting of PV system and ESS, distribution network losses can be significantly reduced. As the mean power of losses after connection is the same for the first and second load diagram, and slightly higher in the third, it may be ascertained that the level of losses after connection is affected by the load power value, rather than its distribution in time. Moreover, Table 2 shows that the optimal location of the system consisting of the PV system and the ESS does not depend on the load diagram, and that for all three load diagrams, regardless of the load type, it is node 5. In addition, Table 2 shows that the maximum power of the PV system increases with the increase of the mean daily power of load, while the influence of the shape of the load diagram is greater if the

ESS efficiency is lower (it does not exist for unit efficiency). For the energy capacity and maximum power of the ESS, the matching between the load diagram and the power generation diagram of the PV system is of the greatest importance, which is shown by a much higher energy capacity and maximum power of the ESS in the case of the second than in the case of the first load diagram. Also, the maximum power of the PV system and the required energy capacity and the maximum power of the ESS increase while the ESS efficiency decreases. This results from the fact that for the same injected power, more ESS discharge power is needed, and that for the same ESS charging power, more power coming from the PV system is needed, if a reduction in ESS efficiency occurs. The above observations are valid for both load types, whereby the slightly higher values of the maximum power of the PV system and ESS, as well as the energy capacity of the ESS, in the case of a constant power load type is the result of a slightly higher load in that case.

Table II. Mean daily power of losses after system consisting of PV system and ESS has been connected, connection location and system configuration parameters for different levels of ESS efficiency

Load diagram	I	II	III
$P_{loss}[kW]$	24.047 (11.257)	24.047 (11.257)	25.970 (12.125)
i	5 (5)	5 (5)	5 (5)
$P_{PVmax1}[MW]$	8.530 (8.354)	8.529 (8.354)	8.830 (8.640)
$P_{ESS1}[MW]$	4.988 (4.905)	6.855 (6.702)	5.056 (4.972)
$\Delta Q_{ESS1}[MWh]$	27.115 (26.680)	40.783 (39.827)	29.219 (28.701)
$P_{PVmax0,9}[MW]$	9.382 (9.192)	9.825 (9.619)	9.758 (9.551)
$P_{ESS0,9}[MW]$	5.841 (5.744)	8.154 (7.968)	5.984 (5.884)
$\Delta Q_{ESS0,9}[MWh]$	29.508 (29.045)	44.861 (43.817)	32.131 (31.554)
$P_{PVmax0,8}[MW]$	10.522 (10.316)	11.594 (11.347)	11.026 (10.796)
$P_{ESS0,8}[MW]$	6.981 (6.867)	9.923 (9.695)	7.252 (7.128)
$\Delta Q_{ESS0,8}[MWh]$	32.370 (31.872)	49.784 (48.624)	35.657 (35.017)

Figures 7 and 8 show the mean daily power of losses along the distribution network sections before and after the connection of the system consisting of PV system and ESS, for both considered load types that follow the third load diagram. The indexes (ordinal numbers) of the sections are equal to the node indexes at their ends.

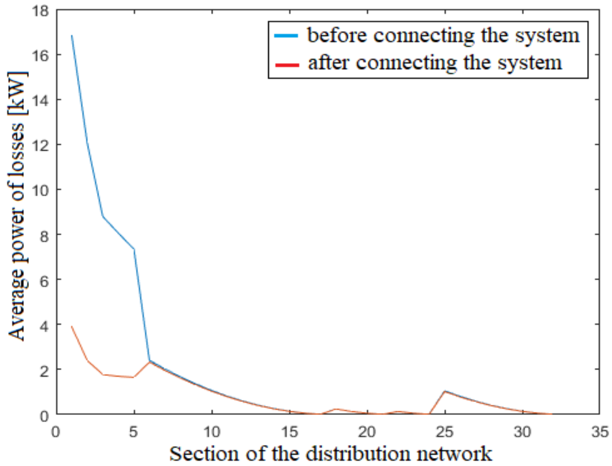

Figure 7. Mean daily power of losses along the distribution network sections for constant power load

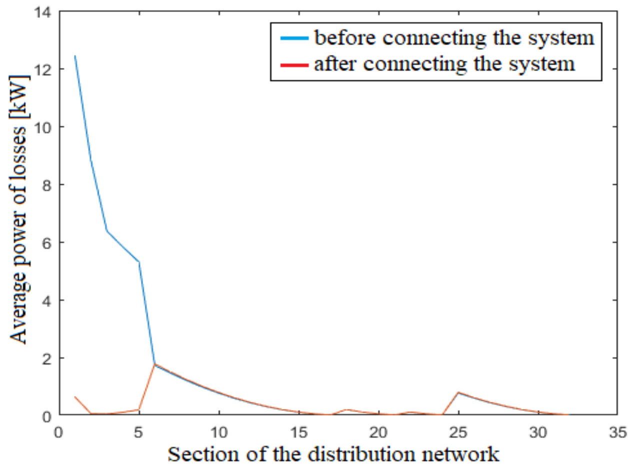

Figure 8. Mean daily power of losses along the distribution network sections for constant impedance load

Figures 7 and 8 show that by connecting a single system consisting of PV system and ESS, the greatest reduction in losses is achieved in the supply sections of the distribution network where several of its branches branch off. Also, it can be observed that due to the existence of reactive power flows that could not be significantly influenced by connected system, the supply sections losses are higher in the case of a constant power load type.

Figures 9 and 10 show the active load power of the distribution network, the optimal (operating) power of the system consisting of PV system and ESS, as well as the power of PV system and ESS individually, for the ideal efficiency of the ESS and the third load diagram.

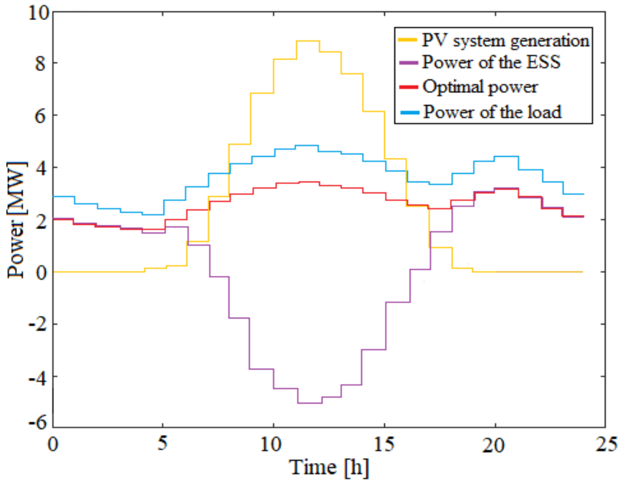

Figure 9. Active load power, optimal (operating) power of the system consisting of PV system and ESS, power of the PV system and power of the ESS, for constant power load type

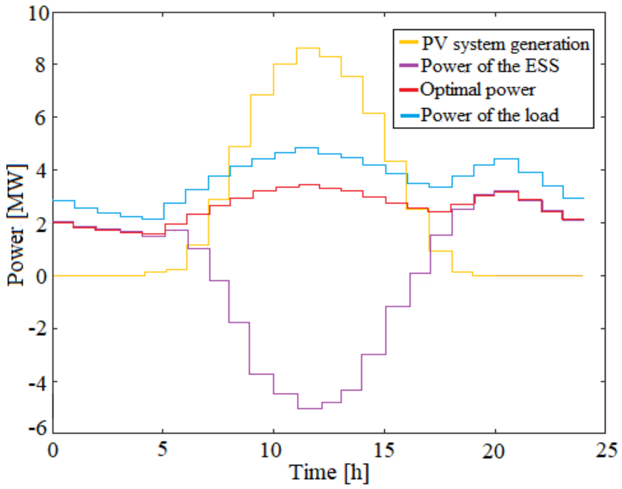

Figure 10. Active load power, optimal (operating) power of the system consisting of PV system and ESS, power of the PV system and power of the ESS, for constant impedance load type

Figures 9 and 10 show that the optimal (operating) power of the system consisting of PV system and ESS follows the shape of the load power, while in periods of high solar irradiation it is provided by the PV system, whereas at night and in periods with low solar irradiation it is generated by the ESS. As expected, in periods of high solar irradiation the ESS is charging, while in periods with low solar radiation it is discharging.

Table III shows the minimum mean daily power of losses, the mean daily power of losses obtained by the first and second approaches and the change in the ESS energy level obtained at the end of the operating cycle compared to that at the beginning using the second approach, for different discrepancies between the actual and expected values of load power and solar irradiation. It is important to note that the used load power deviation (ΔP) is the same percentage-wise for every hour during the day, which also applies to the solar irradiation deviation (ΔI_c). The minimum mean daily power of losses is obtained for the case when the system consisting of PV system and ESS injects optimal power every hour from the aspect of losses reduction, considering the real load value inside the network, and ignoring the constraints determined by the system configuration. This power of losses has a theoretical character and serves as a reference to evaluate the effectiveness of the first and second approach. The two mentioned approaches are explained in detail in the fourth chapter.

Table III. Minimum mean daily power of losses, mean daily power of losses in the first and second approach and the change in the ESS energy level obtained in the second approach, for different discrepancies between the actual and expected values for load power and solar irradiation.

$\Delta P(\%)$, $\Delta I_c(\%)$	$P_{loss,min}[kW]$	$P_{loss}^{I}[kW]$	$P_{loss}^{II}[kW]$	$\Delta W_{ESS}^{II}[MWh]$
30, 0	44,339 (20,414)	48,202 (23,564)	44,340 (20,414)	-19,365 (-18,949)
20, 0	37,651 (17,416)	39,355 (18,823)	37,652 (17,416)	-12,910 (-12,632)
10, 0	31,530 (14,653)	31,953 (15,006)	31,530 (14,653)	-6,454 (-6,316)
−10, 0	20,951 (9,837)	21,367 (10,190)	21,839 (10,625)	3,207 (3,154)
−20, 0	16,501 (7,780)	18,152 (9,214)	18,885 (9,904)	6,401 (6,290)
−30, 0	12,593 (5,963)	16,282 (9,206)	17,402 (10,284)	9,596 (9,426)
0, −10	25,970 (12,125)	26,921 (12,963)	25,970 (12,125)	-6,455 (-6,316)
0, −20	25,970 (12,125)	29,807 (15,505)	25,970 (12,125)	-12,910 (-12,632)
0, −30	25,970 (12,125)	34,674 (19,790)	25,970 (12,125)	-19,365 (-18,948)
30, −30	44,339 (20,414)	66,161 (38,681)	51,240 (26,270)	-29,219 (-28,701)
20, −30	37,651 (17,416)	54,174 (31,468)	39,322 (18,903)	-29,219 (-28,701)
10, −30	31,530 (14,653)	43,689 (25,167)	31,530 (14,653)	-25,819 (-25,264)
−30, −20	12,593 (5,963)	14,349 (7,565)	12,593 (5,963)	6,454 (6,316)
−30, −10	12,593 (5,963)	14,385 (7,545)	13,657 (6,911)	9,324 (9,159)
−20, −20	16,501 (7,780)	18,110 (9,255)	16,501 (7,780)	0 (0)

Based on the results in the Table III, it can be concluded that in most cases the losses obtained in the second approach are significantly lower than those obtained using the first approach. The difference between the losses obtained by the second approach and the minimum losses is a result of the constraints related to the maximum power and energy capacity of the ESS determined by the system configuration. Moreover, the results in Table 3 show that using the second approach ESS is recharged at the end of the day ($\Delta W_{ESS} > 0$) in the case when the load reduction is more significant than the solar irradiation reduction, while otherwise the energy of the ESS is lower at the end compared to the beginning of the day ($\Delta W_{ESS} < 0$). ESS discharge after the operating cycle is particularly pronounced when there is a load increase and a solar irradiation decrease compared to their expected values during the day.

By comparing the value of minimum average daily power of losses and the power of losses obtained using the first approach, it may be concluded that neglecting the deviations of the actual from the expected values of load and solar irradiation when determining the power of the PV system and the ESS leads to a network loss increase. On the other hand, large ESS discharges in the second approach indicate that consideration of the deviation and adjustment of the injection power into the network should not only be done at the expense of the ESS power, but also by increasing the powet of the PV system in the configuration phase.

6. CONCLUSION

This paper presents a methodology for determining the optimal location and configuration of a system consisting of PV system and ESS to reduce the distribution network losses. Obtained results showed that by connecting such a system, distribution network losses can be significantly reduced, regardless of the shape of the load diagram and its type, and that the optimal connection location is a node near the network centre (load). Furthermore, based on the results, it may be concluded that the greatest influence on the sizing of the PV system and its maximum power, has the mean daily load power, while the maximum power and energy capacity of the ESS mostly depend on the matching between the load diagram and the solar irradiation diagram of the PV system. By comparing the results for different levels of ESS efficiency, it is clear that the reduction of ESS efficiency leads to an increase in the maximum power of the PV system and the maximum power and energy capacity of ESS, for the same level of network losses reduction. Finally, it should be pointed out that the discrepancy between the actual and expected load power and the reduction of solar irradiation below the expected value can lead to an increase in network losses or to a great extent change the state of charge of the ESS.

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BIOGRAPHIES

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UDK: 621.383.51
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Metoda za određivanje optimalne lokacije i konfiguracije sistema sačinjenog od fotonaponskog i sistema za skladištenje energije uzimajući u obzir smanjenje gubitaka u distributivnoj mreži

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Kategorija rada: originalni naučno-istraživački članak

Ključne poruke

- Ovaj rad razmatra smanjenja gubitaka u distributivnoj mreži priključenjem sistema sačinjenog od fotonaponskog (PV) i sistema za skladištenje energije (ESS).
- Određena je optimalna lokacija i optimalna snaga sistema sačinjenog od PV sistema i ESS uvažavajući minimizaciju gubitaka.
- Izvršeno je dimenzionisanje PV sistema i ESS.
- Sagledan je uticaj nepoklapanja stvarnih i očekivanih vrednosti opterećenja i sunčeve iradijacije na povećanje gubitaka u mreži i promenu nivoa napunjenosti ESS.

Kratak sadržaj

U ovom radu je predstavljena dvostepena metoda za određivanje optimalne lokacije i konfiguracije sistema sačinjenog od PV sistema i ESS uzimajući u obzir smanjenje gubitaka u distributivnoj mreži. U prvom koraku je uvažavajući očekivani dnevni dijagram opterećenja distributivne mreže, a korišćenjem metaheurističke optimizacione metode roja čestica (PSO), određena optimalna lokacija i optimalna snaga u toku dana sistema sačinjenog od PV sistema i ESS kako bi se minimizovali gubici u distributivnoj mreži. U drugom koraku procedure, određene su pojedinačne snage PV sistema i ESS i izvršena je njihova konfiguracija (dimenzionisanje). Ovo je urađeno iterativnim postupkom koristeći vrednosti optimalne zbirne snage ova dva sistema u toku dana dobijene u prvom koraku i oblika dnevnog dijagrama sunčeve iradiajacije PV sistema u slučaju vedrog dana. Postupak konfiguracije je detaljno objašnjen, a u okviru njega je određena potrebna maksimalna snaga PV sistema, maksimalna snaga ESS kao i energetski kapacitet ESS. Takođe, sagledan je uticaj odstupanja stvarnog od očekivanog dijagrama opterećenja kao i smanjenje sunčeve iradijacije u toku dana na povećanje gubitaka u distributivnoj mreži i promenu nivoa napunjenosti ESS. U radu su razmatrani slučaji sa različitim dijagramima opterećenja i različitim stepenima efikasnosti ESS. Svi rezultati su dobijeni korišćenjem IEEE radijalne distributivne mreže sa 33 čvora.

Ključne reči

Fotonaponski (PV) sistem, sistem za skladištenje energije (ESS), optimizaciona metoda roja čestica (PSO), gubici u distributivnoj mreži

Napomena:

Članak predstavlja proširenu, unapređenu i dodatno recenziranu verziju rada „*Optimalna lokacija i konfiguracija sistema sačinjenog od fotonaponskog i sistema za skladištenje energije uzimajući u obzir smanjenje gubitaka u distributivnoj mreži*“, nagrađenog u Stručnoj komisiji STK-4 *Distribuirana proizvodnja i efikasno korišćenje električne energije*, na 13. Savetovanju CIRED Srbija, Kopaonik, 12-16. septembra

Primljeno: 5. april 2023. Recenzirano: 25. april 2023.
Izmenjeno: 28. april 2023. Odobreno: 4. maj 2023.

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