OPTIMAL PLACEMENT OF PHOTOVOLTAIC SYSTEMS FROM THE ASPECT OF MINIMAL POWER LOSSES IN DISTRIBUTION NETWORK BASED ON GENETIC ALGORITHM

by

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In this paper, an optimal placement of photovoltaic systems as a source of active power in radial distribution network is considered. The objective of this optimization problem is minimizing system losses and improving voltage profiles based on optimal placement and sizing of photovoltaic systems. The maximal installed capacity of photovoltaic systems in distribution network is predefined and must not be exceeded. The simulation is done for three different cases from the aspect of input data (characteristic days for each month, Monte Carlo simulation, and whole year data). In this way, both consumption behavior and solar potential are considered in order to find optimal solution. Genetic algorithm is implemented for the calculation of optimal solution.

Key words: *photovoltaic systems, optimal placement and sizing, power loss reduction, voltage profile, genetic algorithm*

Introduction

The advent of RES and distributed energy sources has led to significant changes in the distribution systems operation and planning. With distributed energy sources, electricity is produced and consumed locally. Local production reduces the active power flows in the distribution network (DN) which provides many positive effects of which the most significant are reduction of active power losses and the achievement of better voltage profiles. Sometimes, big production from distributed energy sources can increase active power losses when the power flowing from a RES to the power supply station is greater than the load. On the other hand, a large ratio of R/X in DN leads to a more significant increase in voltage values due to the generation of active power compared to the transmission networks. Therefore, it may happen that the consumer node voltages exceed the maximum allowed values [1].

Photovoltaic (PV) systems are the RES that can be integrated into the DN with the highest dispersed level. The reason for this is their low dimensionality, which practically enables installation of a PV system on the roof of each home or facility. In addition, another major advantage of PV systems is that their production is highest during the day when the consumption reaches its peak value. This is the reason why the analysis of PV systems impact on the DN is conducted most often [2, 3].

In order to reduce power losses and improve system voltages, appropriate planning of the power system with the presence of RES is required. Several things need to be considered

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such as the number and the capacity of the PV units, the optimal PV location, and the type of network connection. The installation of PV units at non-optimal locations and with non-optimal size may cause higher power loss, voltage fluctuation problems, system instability, and increase of the operational cost [4]. The first group of papers deal with the optimal allocation of distributed energy sources in order to improve voltage profiles in the DN. Optimal allocation of distributed generation (DG) in radial distribution systems based on new voltage stability index under load growth is presented in [5]. Comparison of single- and multiple-DG concepts in terms of power loss, voltage profile and line flows under uncertain scenarios is presented in [6]. Long term scheduling for optimal allocation and sizing of DG units considering load variation is presented in [7]. Optimal multi-objective allocation and sizing of DG and shunt capacitor banks considering load uncertainty via MOPSO approach is presented in [8]. A new approach for optimum DG placement and sizing based on voltage stability maximization and minimization of power losses is presented in [9]. The second group of papers deals with the reduction of power system losses with optimal allocation of DG. A multi-objective optimization approach for optimal allocation of DG is presented in [10], where total imposed costs with total network losses are opposed. Optimal placement of different type of DG in DN is presented in [11]. A MINLP technique for optimal placement of multiple DG units in distribution system is presented in [12]. An approach for reducing the searching space for the optimal allocation and sizing of DG is implemented in [13]. Some papers deal with optimal allocation of DG in order to improve reliability of the system. Some of them are presented in [14, 15]. The number of optimization techniques for finding the optimal solution of the defined optimization problem are numerous. In the first group of papers, classic optimization algorithms such as linear programming and non-linear programming are presented in [16, 17]. The second group of papers used metaheuristic-based approaches for finding the optimal solution. Improved multi-objective particle swarm optimization with preference strategy for optimal DG integration into the distribution system is presented in [18]. A combination of genetic algorithm (GA) and particle swarm optimization for optimal DG allocation and sizing in distribution systems is presented in [19]. A combination of GA and particle swarm optimization has been expanded with fuzzy optimal theory in [20]. Optimal multiple DG output through rank evolutionary particle swarm optimization is presented in [21]. Multi-objective evolutionary particle swarm optimization is presented in [22]. Multi-distributed generation planning using hybrid particle swarm optimization-gravitational search algorithm including voltage rise issue is presented in [23]. A new evolutionary solution method for dynamic expansion planning of DG-integrated primary DN is presented in [24]. Finally, an overview of all techniques and methods for optimal allocation and sizing of DG is presented in [25].

In this paper, the methodology for determining the optimal positions and sizes of PV systems is presented. In order to determine the optimal positions, analyzes were done for three different cases. For each of the three analyzed cases, time intervals with hourly resolution were analyzed. In the first case, period of whole year is analyzed. In second case, Monte Carlo simulation is done for getting the probability of irradiation and consumption in each hour of the day. Finally, in the third case, analysis is done for each characteristic day of the month. In contrast to previous papers, in this paper, which has the task of determining an optimal solution that will reduce the power systems losses and improve voltage profiles, it is assumed that solar potential is not the same in all the buses of the DN. In this way, presented analysis can include the DN that covers a broader geographic area. Besides that, in this paper various methods that can consider the variable potential of solar radiation during the year to determine the optimal solution have been analyzed. Analyzes were conducted on the case of

IEEE 33-bus test system. The results obtained from this example confirm the advantages of the proposed methodology.

Mathematical model

Mathematical model is defined as a standard optimization problem with a criterion function (CF) and equality and inequality constraints. The aim of CF is to find optimal values and positions for the PV systems for which, through calculation of LF (LF), minimum values of active power losses and best voltage profiles of the considered DN would be achieved.

Production of PV system

Based on the known values of the solar irradiation and ambient temperature, the production of PV system can be calculated using:

$$P_{\mathrm{PV}} = P_n \frac{I_{\mathrm{cell}}}{1000} \eta_{\mathrm{PV}} \left[1 - \frac{\Delta p}{100} (t_{\mathrm{cell}} - 25) \right] \tag{1}$$

$$t_{\mathrm{cell}} = t_{\mathrm{amb}} + \frac{NOCT - 20}{800} I_{\mathrm{cell}} \tag{2}$$

where P_n [kW] is the installed capacity of PV system, I_{cell} [Wm^{-2}] – the irradiation on the surface of the cell, Δp [%] – the temperature reduction of PV system efficiency, t_{cell} [°C] – the cell temperature, t_{amb} [°C] – the ambient temperature, *NOCT* [°C] – the temperature of PV system under normal conditions, and η_{PV} – the efficiency of conversion.

Load flow – backward-forward method

The *Backward-forward* method, well-known as *Shirmohammadi's* algorithm, is an iterative calculation of LF in radial DN. The algorithm starts with the initialization of procedure which consists of loading data concerning DN, numeration of branches and nodes by layers, and setting up an index of iteration to the initial value (h = 1). Iterative procedure comes after initialization, and each iteration has three following steps [26]:

– Calculation of the injected currents (starting from the nodes in the first layer) is:

$$\hat{i}_i^{(h)} = \left[\frac{\hat{S}_{p,i}}{\hat{v}_i^{(h-1)}} \right]^* + \hat{y}_{0,i} \cdot \hat{v}_i^{(h-1)} :, i = 1, \dots, n_{\mathrm{nodes}} \tag{3}$$

where $\hat{i}_i^{(h)}$ is the current of injection in the node i, iteration h, $\hat{S}_{p,i}$ – the specified load in the bus i; $\hat{v}_i^{(h-1)}$ – the voltage in the bus i, iteration h–1, $\hat{y}_{0,i}$ – the sum of admittances of shunt elements in the bus i, and n_{nodes} – number of buses.

– The calculation of branch currents (starting branches in the last layer) accordingly to the following definition:

$$\hat{j}_i^{(h)} = \hat{i}_i^{(h)} + \sum_{j \in i} \hat{j}_i^{(h)} \quad , i = n_{\mathrm{lines}}, \dots, 1 \tag{4}$$

where $\hat{j}_i^{(h)}$ is the current in branch (i) in iteration (h), $\sum_{j \in i} \hat{j}_i^{(h)}$ – the sum of all currents which direction is from bus (i) in iteration (h), and n_{lines} – the number of branches.

– Calculation of voltages in buses (starting from bus in the first layer):

$$\hat{v}_i^{(h)} = \hat{v}_{i-1}^{(h)} - \hat{z}_i \, \hat{j}_i^{(h)} \quad , i = 1, \dots, n_{\mathrm{nodes}} \tag{5}$$

where $\hat{z}_i$ is the impedance of branch (i).

At the end of each iteration the condition of convergence is questioned (are the powers of imbalance lesser than the predefined value), if condition is met iterative procedure ends, otherwise it moves to the next iteration.

Power losses

The total losses in distribution system can be calculated:

$$P_{\text{loss}} = \sum_{t=1}^{T} \sum_{i=1}^{n_{\text{lines}}} I_{it}^2 R_i \tag{6}$$

where I_{it}^2 [p. u.] is the effective value of the current in the branch i at time t, R_i [p. u.] – the resistance of the branch i, P_{loss} [p. u.] – the power losses for period of interest in the DN, and T – the analyzed time interval.

Voltage profile

The voltage profile can be calculated:

$$V_{\text{profile}} = \sum_{t=1}^{T} \sum_{i=1}^{n_{\text{nodes}}} \frac{(V_{it} - V_{\text{nom}})^2}{V_{\text{nom}} T n_{\text{nodes}}} \tag{7}$$

where V_{nom} is the nominal voltage of the DN (equal to 1 [p. u.]), V_{it} [p. u.] – the effective value of voltage of the i^{th} bus at time t, and V_{profile} [p. u.] – the sum of total voltage deviations from nominal voltage for period of interest for all the buses in the DN.

Criterion function

The value of CF can be calculated:

$$CF = w_1 P_{\text{loss}} + w_2 V_{\text{profile}} \tag{8}$$

$$w_1 + w_2 = 1 \tag{9}$$

where w_1 and w_2 are the weighting factors based which value is between 0 and 1 on which is defined priority of power losses and voltage profile.

Constraints

The following constrains are considered in the model, eqs. (10)-(13):

$$P_{\text{PV min}} \le P_{\text{PV}} \le P_{\text{PV max}} \tag{10}$$

$$Q_{\text{PV}} = 0 \tag{11}$$

$$V_{\min} \le V_i \le V_{\max}, \quad i = 1, \ldots, n_{\text{nodes}} \tag{12}$$

$$P_j \le V_{j\max}, \quad j = 1, \ldots, n_{\text{lines}} \tag{13}$$

$$\sum_{k=1}^{n_{\text{PV}}} P_{\text{PV},k} \le 0.4 P_{\text{load}} \tag{14}$$

where $P_{\text{PV min}}$ and $P_{\text{PV max}}$ are the minimal and maximal active power generated from PV, P_{PV} and Q_{PV} – the active and reactive power generated from PV in each hour, $V_{\min}$ and $V_{\max}$ – the minimal and maximal value for effective value of the voltages in each bus and hour, $P_{j\max}$ – the maximal active power that can flow through branch j, $P_{\mathrm{PV},k}$ – the installed capacity of PV system, η_{PV} – the number of buses with installed PV systems, and P_{load} – the total value of the load in the DN.

According to [4], the maximum penetration level of distributive generation, without violating the transient stability limit is 40% of the total connected load, so this value is adopted in this paper eq. (14).

Genetic algorithm

The GA belongs to the group of heuristic methods of optimization which is based on simulation of natural evolution mechanism with the aim of studying adaptive behavior. This method was introduced and published in 1970s by Holland [27]. That simple GA, with minor modifications (regenerating possible solution in case of not permitted combination) is also used in this paper. The GA uses binary representation, simple genetic operators (selection, mutation, cross-over). By its application the natural process of evolution is simulated, for which can conclude following (also for GA) [27]:
- there is population of individuals,
- some individuals are better-adopted to environment,
- stronger individuals have better chance to survive and reproduce,
- characteristics of the individuals are written down in a genetic code,
- children inherit the characteristics of their parents, and
- individuals can mutate.

For GA, individual represents current approximation of solution for the ongoing problem. Each individual is coded, and certain amount of quality is added to each individual – fitness, which is determined based on CF. During initialization, the starting population is generated, and it is commonly generated by randomly chosen solutions from domain (it is allowed that the starting solution obtained by some other optimization method be added to the initial population). Then comes the process that is repeated until the convergence criterion is met. That process comprises executing genetic operators (elitism, selection, cross-over, and mutation). Besides the quality assessment of individual which must be conducted, all GA operations are carried out on encrypted individuals. It is common that with multiple application of operator selection worse units die and the better ones remain and cross-over in the next step. With cross-over characteristics of parents are being transferred to their children. Mutation changes the characteristics of the individuals by a random gene change. Based on this kind of procedure the average quality of population rises from generation to generation.

This process is repeated until the exact CF is met or until the iterative process achieves the predefined number of generations (as is the case in this paper).

Used algorithm

In this part, algorithm that is used in the program is shown step by step. First part is defining and loading all input parameters needed for the calculation.
- Load basic information about network (number of buses, number of branches, base voltage, base power, convergence criterion…).
- Load all parameters needed for calculation of network state (line parameters, daily load characteristics, PV generation, solar potential, voltage and line limits…).

– Define parameters needed for GA (number of generations, number of chromosomes in the population, rates for cross-over, elitism and mutation, weighting coefficients needed for calculation of the individual's fitness…).
– Define range within solutions are looked for (min. and max. values of installed PV power), discrete step of search (smallest difference between two values of installed power in PV) and total amount of allowed power that can be installed in the network.

Second part is calculation itself.

– The LF calculation for DN without PV ⇨ total active power losses and voltage profile ⇨ starting point of the search.
– Generating initial population randomly making sure that total amount of installed power is not exceeded and performing LF for calculation of power flow losses and voltage profile.
– Entering the loop where is three basic steps performed (ranking individuals accordingly to fitness value, applying GA operators (elitism, selection, cross-over and mutation) to generate new population and performing LF for calculation of CF).
– When the termination condition met (predefined number of generations) calculation is stopped and the best solution is obtained.

Algorithm verification

Verification of the presented algorithm is done on a simple, meshed DN which is taken from [28] and shown in fig. 1. All the data and parameters for DN can be found in [28].

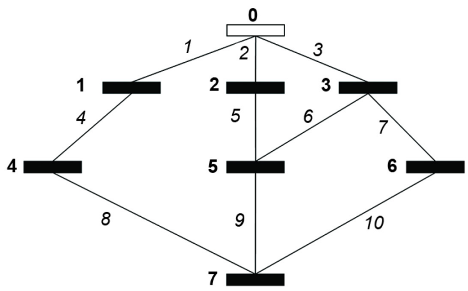

Figure 1. Simple DN – 8 nodes [28]

In order for the model to be verified it is necessary to check whether the way of calculating the criterial function returns good results (LF calculation – active power losses and voltage profile) as well as if GA returns accurate results as a tool which can be used to solve optimal problem described in this paper.

For the calculation of the LF – Shirmohammadi's algorithm is used for radial network, *i. e.* compensational algorithm for weakly meshed network. Program for calculation of LF is verified by comparing results from the program with results from [28].

The GA is verified by comparing results obtained by GA with the results obtained by full search with the same step, 0.05 kW. Calculation is done for one characteristic day arbitrarily selected. Results of the verification are presented in tab. 1, where are compared results for the base case (there is no PV systems in the DN), results from the full search and the results got from the algorithm used in this paper. From the results in tab. 1 it can be seen that used algorithm gave optimal solution, as the results from used algorithm are the same as the results got from full search.

Input data

The proposed solution method was applied on an IEEE 33 bus test system, shown in fig. 2. Base network state, as well as all parameters that are important for the calculation, are given in [29]. The proposed methodology was tested for three cases.

Table 1. Comparison of the results

	Base state	Full search	Used algorithm	Base load	
Active power losses [kWh]	594.26	546.98	546.98		
$V_{profile}$ [p. u.]	0.002	0.0019	0.0019		
V_{min} [p. u.]	0.9953	0.9961	0.9961		
V_{max} [p. u.]	1	1	1		
	Installed power of PV [kW]			P [kW]	Q [kvar]
Bus 0 (root of the DN)	0	0	0	0	0
Bus 1	0	442.05	442.05	1262.5	25.62
Bus 2	0	44.65	44.65	2416.58	49.05
Bus 3	0	80.4	80.4	612.74	124.36
Bus 4	0	35.7	35.7	435.1	88.3
Bus 5	0	1643.15	1643.15	2295.8	465.1
Bus 6	0	450.95	450.95	575.4	116.8
Bus 7	0	1772.6	1772.6	3564.5	723.5

In the first case, for the calculation of optimal allocation and installed power values of PV systems, annual data of the mean hourly irradiation as well as the normalized average hourly load values were used. Data of solar irradiation were taken from the National Renewable Energy Laboratory, Golden, Cal., USA website for the location of Belgrade, while the annual load data were taken for one of the distributive stations in city of Belgrade. Those data are shown in fig. 3.

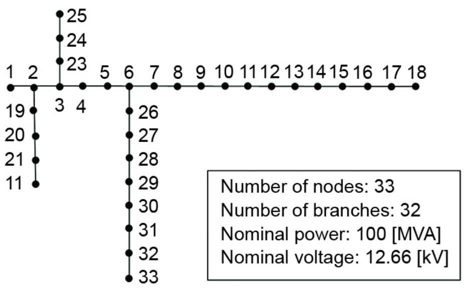

Figure 2. The IEEE DN – 33 nodes [29]

Mean hourly load values for the each node were obtained by multiplying the normalized consumption graph shown in fig. 3 with the maximum power consumption of the IEEE 33 bus test system shown in tab. 2.

In the second case, the calculation of optimal allocation and installed power values of the PV systems is determined using the characteristic load diagrams and solar irradiation diagrams for each month, shown in fig. 4. Those data are determined based on the data from the first case. In this way, instead of 8760, the calculation is reduced to 12 × 24 = 288 data. The characteristic diagrams are determined as follows. For each month, the average hourly load values and solar irradiation is first determined, after which the real data of the day for which the sum of the square of the deviation is minimal in relation to the average day. As in the previous case, mean hourly load values for each node were obtained by multiplying the normalized characteristic consumption diagrams shown in fig. 4 with the maximum power consumption of the IEEE 33 bus test system shown in tab. 2.

In the third case, based on the annual normalized data of the load values and solar irradiation, the diagrams of the probability density are formed for each hour. These diagrams are shown in figs. 5 and 6. For each hour, the calculations were done on a sample of 50 data using Monte Carlo simulation, simulating different scenarios. In this way, the calculation is done on a sample of 24 × 50 = 1200 data.

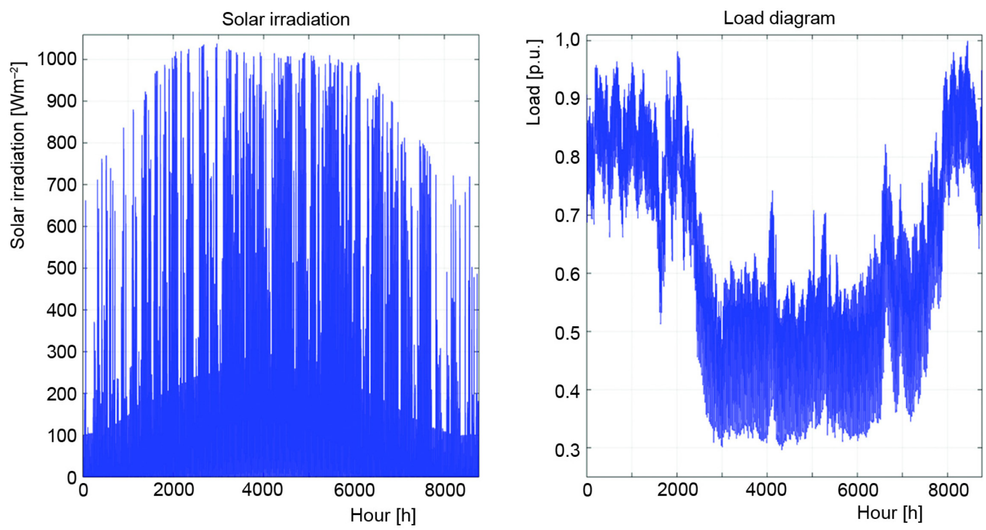

Figure 3. Annual average hour solar irradiation and normalized load diagram

Table 2. The IEEE DN – 33 nodes, base load

Bus	*P* [kW]	*Q* [kvar]	Bus	*P* [kW]	*Q* [kvar]	Bus	*P* [kW]	*Q* [kvar]
1	0	0	12	60	35	23	90	50
2	100	60	13	60	35	24	420	200
3	90	40	14	120	80	25	420	200
4	120	80	15	60	10	26	60	25
5	60	30	16	60	20	27	60	25
6	60	20	17	60	20	28	60	20
7	200	100	18	90	40	29	120	70
8	200	100	19	90	40	30	200	600
9	60	20	20	90	40	31	150	70
10	60	20	21	90	40	32	210	100
11	45	30	22	90	40	33	60	40

For each of the mentioned cases, two calculations are performed, the first assuming that solar irradiation is the same in each node and the other assuming that it is different. Solar potential is introduced as factor between 0.95 and 1 which PV output is multiplied with in each hour. It is considered that same solar potential have all nodes on one part of feeder, which is given in tab. 3.

Table 3. Coefficients that describes solar potential for the different parts of feeder

	Main trunk of feeder	Lateral 1	Lateral 2	Lateral 3
Buses	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	19, 20, 21, 22	23, 24, 25	26, 27, 28, 29, 30, 31, 32, 33
Solar potential	0.95	1	0.98	0.96

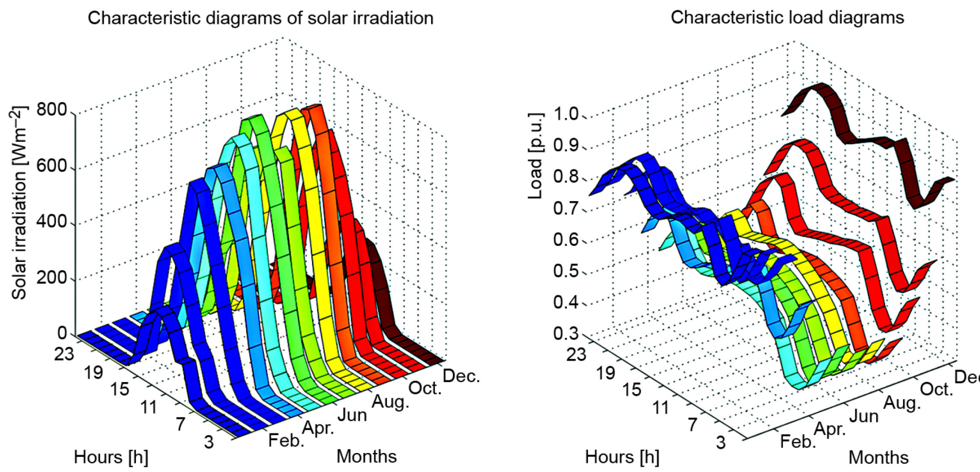

Figure 4. Characteristic diagrams of solar irradiation and characteristic load diagrams
(*for color image see journal web site*)

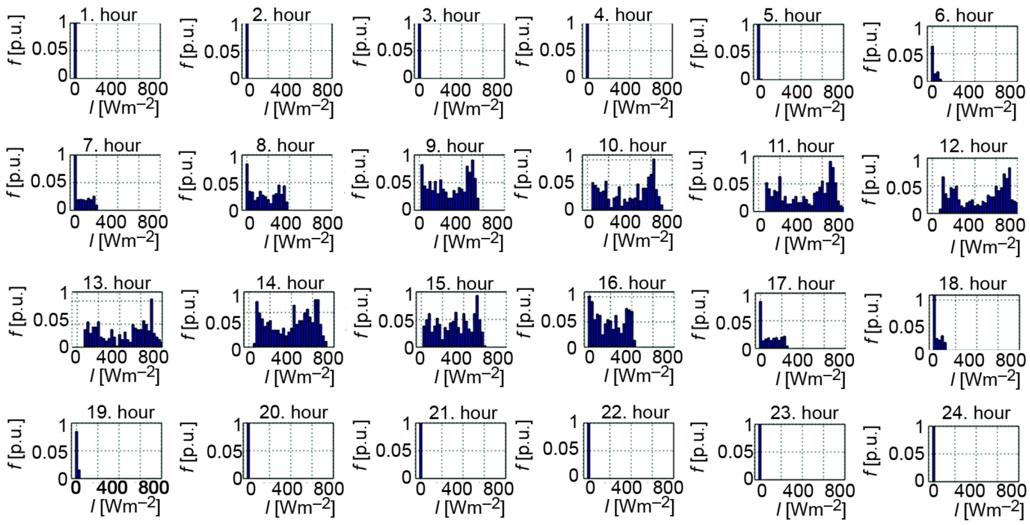

Figure 5. Probabilistic diagrams of solar irradiation for each hour

Results

In this chapter, the results of proposed analyzes are shown. Analyzes are conducted on radial IEEE 33 bus system described in chapter *Input data*. In all cases first it is considered that solar potential is the same in all buses, while in second case solar potential vary on four parts of feeder from 0.95 to 1, given in tab. 3. While searching for optimal locations and sizes of PV systems, there was only one limitation, besides limitations mentioned in 2.5, that total amount of installed power of PV system does not overcome 40% of total load in DN. The PV systems can be put in all buses, except in network root (bus 1), however, it can also happen that in optimal state some buses do not contain PV system. Weighting factors for calculation of the CF are 0.7 and 0.3, respectively. Factors are chosen in that way so slight advantage is given toward minimization of power losses.

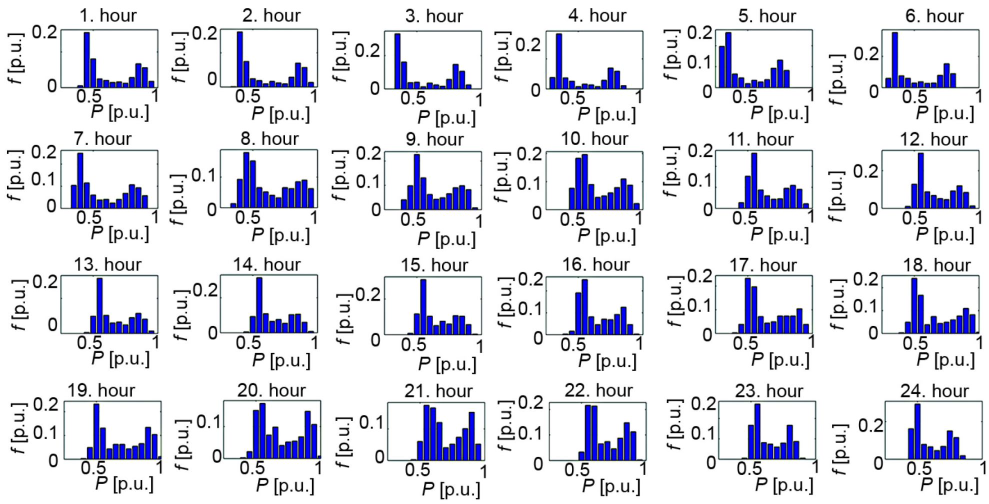

Figure 6. Probabilistic diagrams of normalized load values for each hour

Figures 7 and 8 show diagrams of averaged power losses per hour in [p. u.] for 24 hours period for all three cases and the base case (when there is no PV systems installed). Base values for normalizing power losses and rest of the parameters are given in the fig. 1. From fig. 7 it can be seen that best solution is obtained in Case 1 when the period of whole year is being analyzed. That was expected, but interesting part is that in Case 2 are obtained better results (almost as good as in the Case 1) then in the Case 3. From fig. 8, when solar potential is not same in all the buses, it can be seen that in all three cases are obtained almost similar results from the aspect of power losses.

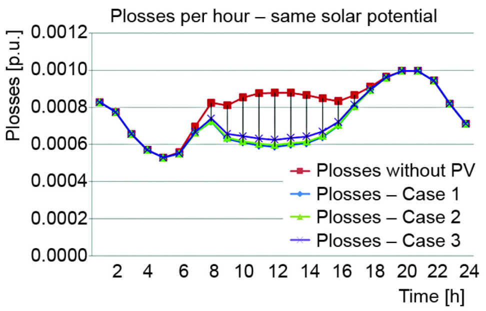

Figure 7. Averaged power losses in for each hour for all three cases when solar potential is equal in each bus

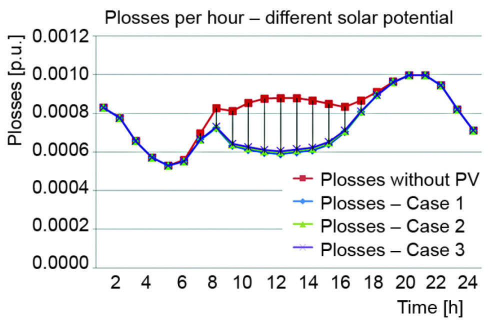

Figure 8. Averaged power losses in each hour for all three cases when solar potential is not equal in each bus

In figs. 9 and 10 are given diagrams of voltage profile (minimum voltage in [p. u.] at each hour for whole feeder) for all three cases and the base case (when there is no PV systems installed). From fig. 8 same situation as for power losses can be seen. The highest minimum voltage values are obtained in Case 1 when the period of whole year is being analyzed. Also, Case 2 (Monte Carlo simulation for getting probability of irradiation and consumption) gave better results than Case 3 (analyzed period were characteristic day for each month). In fig. 10, it can be seen that all of three methods have similar solution. As it can be seen from the results (figs. 7-10) PV systems have big influence on DN state and with optimal sizes and values can significantly reduce power losses and improve voltage profile in hours when there is irradiation.

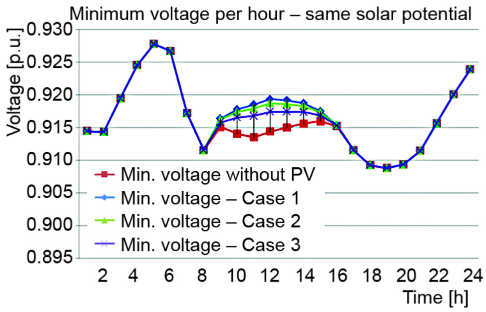

Figure 9. Minimum voltage in each hour for all three cases when solar potential is equal in each bus

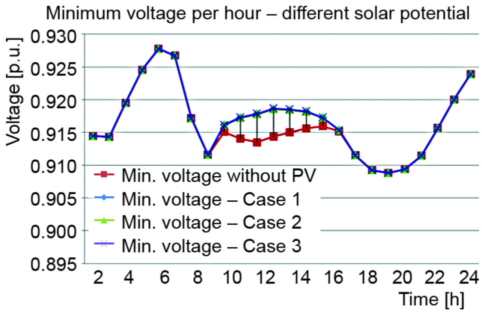

Figure 10. Minimum voltage in each hour for all three cases when solar potential is not equal in each bus

Table 4 shows given optimal values for each PV system installed in each bus (for the case where PV system should not be installed zero value is placed for the installed power) for all three cases and for both subcases, when solar potential is the same in all buses (subcase A) and when it is not (subcase B).

Table 5 shows calculation results for all cases. As it is said before, best CF is obtained in Case 1 when the average hourly values for the whole year were analyzed (8760 data). It is also very important to mention that as it can be seen from the results from tabs. 4 and 5, solar potential has influence on the optimal positions and sizes of the PV system and according with that it has impact on optimal DN state.

The PV systems generate power in hours when load is the highest (worst state of DN), while on the other hand when load is at the lowest point PV systems do not generate power. With installed power of PV systems of maximum 40% of total installed load, power losses are reduced for more than 10% (this is roughly estimate that depends on DN, installed equipment, and load characteristics, ...). All of this speaks in favor of PV systems and the significance of sizing and optimal placement for future PV systems. Also, it can be seen (tabs. 4 and 5) that solar potential has influence on sizes of PV systems and on state of DN, so it could not be neglected in the analysis of optimal places and sizes of PV system.

Conclusion

In this paper, analysis for optimal allocation and size of PV systems is conducted on radial IEEE 33 DN. The objective function is combination of active power losses and voltage profile. The GA, as high speed tool for this optimization, is used. This analysis is executed on three different scenarios with two subcases. In first scenario, period of whole year was analyzed. In second case, Monte Carlo simulation is done in order to get probability for values of irradiation and consumption. Finally, in the third case, characteristic day for each month was period of interest. In all three cases, first solar potential was equal on whole feeder while in the second subcase, solar potential was different along the feeder.

By comparing the results, before and after installation of the PV systems, it could be seen that voltage profile is better than in original case, while active power losses reduced significantly. Also, comparing results in first and second scenario it can be noticed that solar potential has big influence on the allocation of PV systems in DN.

Table 4. Optimal values of installed PV systems in each node for all cases when solar potential is the same (subcase A) and when it is not (subcase B)

	Scenario 1		Scenario 2		Scenario 3	
PV Output [W]	A	B	A	B	A	B
Bus 1	0	0	0	0	0	0
Bus 2	35650	1426	2852	1426	1426	0
Bus 3	14260	24242	8556	24242	2852	14260
Bus 4	5704	82708	0	18538	101246	64170
Bus 5	12834	38502	5704	29946	18538	61318
Bus 6	31372	65596	82708	95542	37076	38502
Bus 7	52762	2852	1426	11408	9982	11408
Bus 8	39928	42780	48484	21390	29946	22816
Bus 9	19964	9982	51336	24242	2852	75578
Bus 10	12834	34224	172546	12834	67022	101246
Bus 11	42780	29946	37076	34224	44206	25668
Bus 12	4278	25668	27094	28520	27094	72726
Bus 13	71300	35650	25668	0	5704	31372
Bus 14	24242	22816	94116	8556	19964	15686
Bus 15	94116	168268	8556	268088	4278	62744
Bus 16	19964	54188	34224	17112	52762	48484
Bus 17	221030	17112	42780	11408	4278	57040
Bus 18	45632	19964	62744	88412	85560	151156
Bus 19	9982	1426	34224	32798	42780	2852
Bus 20	9982	18538	32798	25668	5704	24242
Bus 21	11408	77004	5704	31372	11408	44206
Bus 22	9982	1426	7130	4278	2852	0
Bus 23	14260	7130	51336	47058	4278	32798
Bus 24	25668	11408	0	29946	25668	5704
Bus 25	7130	4278	14260	29946	7130	37076
Bus 26	0	29946	75578	52762	19964	69874
Bus 27	5704	55614	221030	22816	72726	18538
Bus 28	11408	18538	7130	61318	119784	141174
Bus 29	185380	47058	64170	145452	181102	7130
Bus 30	44206	268088	1426	5704	112654	5704
Bus 31	19964	55614	176824	169694	68448	21390
Bus 32	158286	39928	17112	34224	48484	142600
Bus 33	162564	112654	8556	34224	189658	17112

Table 5. Calculation results for all three cases when solar potential is the same (subcase A) and when it is not (subcase B)

	Scenario 1		Scenario 2		Scenario 3		Base Case
	A	B	A	B	A	B	
CF	4.415	4.473	4.4487	4.4735	4.4494	4.4833	
Losses [kWh]	629455.5973	637715.531	634258.3954	637787.7721	634344.4586	639181.4862	711304.125
V_{profile} [p. u.]	0.0295	0.0299	0.0297	0.03	0.0298	0.03	0.0325
$V_{\min}$ [p. u.]	0.9088	0.9088	0.9088	0.9088	0.9088	0.9088	0.9088
$V_{\max}$ [p. u.]	1	1	1	1	1	1	1

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