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Optimal sizing and location of SVC devices for improvement of voltage profile in distribution network with dispersed photovoltaic and wind power plants

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HIGHLIGHTS

- Significant voltage variations in a distribution network with dispersed generation.
- The use of SVC devices to improve the voltage profiles are an effective solution.
- Number, size and location of SVC devices are optimized using genetic algorithm.
- The methodology is presented on an example of a real distribution system in Serbia.

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ABSTRACT

Intermittent power generation of wind turbines and photovoltaic plants creates voltage disturbances in power distribution networks which may not be acceptable to the consumers. To control the deviations of the nodal voltages, it is necessary to use fast dynamic control of the reactive power in the distribution network. Implementation of the power electronic devices, such as Static Var Compensator (SVC), enables effective dynamic state as well as a static state of the nodal voltage control in the distribution network. This paper analyzed optimal sizing and location of SVC devices by using genetic algorithm, to improve nodal voltages profile in a distribution network with dispersed photovoltaic and wind power plants. Practical application of the developed methodology was tested on an example of a real distribution network.

1. Introduction

Historically, development of the distribution networks followed the traditional centralized concept where the power generation was centralized and distribution network was passive with radial topology. Power flow in a traditional distribution network was unidirectional and determined by the load profile. Voltage drops were compensated by voltage regulated transformers and traditional capacitor banks for power factor improvement. However, the power system is changing; a large number of dispersed generation (DG) units, such as wind turbines (WT) and photovoltaic (PV) plants are commonly connected to a distribution network [1–3]. Modern distribution network is active with bidirectional power flows defined by the load profile and power generation of the DG units. By connecting the DG units to a distribution network, the power losses and node voltages are changing [4,5]. Major repercussions on the voltage profile are the consequence of the intermittent WT and PV plants generation. Power generation of the WT depends on the wind speed, while the power generation of the PV is dependent on the insolation. Variations of the wind speed and insolation over the time are causing intermittent power generation of WT and PV sources, and as a consequence, creating voltage disturbances in all power distribution network nodes [5,6].

To maintain the voltage profile within the acceptable limits, it is necessary to control the reactive power in the distribution network. When power demand in the distribution network is increased, while the power generation of the DG sources is low, it is necessary to generate the reactive power to compensate the voltage drops due to the consumed power flow. With favorable wind conditions and solar radiation, WT and PV plants generate active power, causing the nodal voltage increase. With large generation of the DG sources, and low demand in the distribution network, overvoltages in some nodes of the distribution network

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may occur. Under such conditions, it is necessary to absorb the reactive power to reduce the nodal voltages.

Since generation of the WT and PV plants can be highly intermittent, e.g. during unstable wind or partially cloudy weather, unacceptable voltage deviations can occur leading to a cut off of some distributed sources such as WT. To control the deviations of the nodal voltages, it is necessary to use fast dynamic control of the reactive power in the distribution network. The use of Flexible AC Transmission Systems (FACTS) devices, such as SVC, to improve the nodal voltage profiles is an effective solution [7–12]. When large generation units are connected to the distribution network, FACTS devices are usually installed at the power plant connection point to the distribution network [9]. With dispersed power generation, with large number of units (PV and WT) with rated power of a few kW to a few MW connected to different nodes of the distribution network, the concept of installing FACTS devices at the connection point of each DG unit cannot be technically and economically justified. Under such conditions, it is necessary to optimize the system for the reactive power control. By using multi-criteria optimization in this paper, optimization was done for the number and location of SVC devices in a weak distribution network with large number of dispersed WT and PV plants. The goal is to improve voltage profile for various possible operating conditions. With adequate selection of criteria functions, a compromise is achieved between the standard deviation of voltage in the network and total installed power of SVC devices. Such approach in solving the problem of voltage profile in a weak distribution network with large number of dispersed WT and PV plants has not been considered in the published literature. Optimization for the location and parameters of SVC devices was done by direct implementation of optimization procedure. Optimization for the number of SVC devices was done by comparison of the results of various scenarios considering different numbers of SVC devices. The methodology is presented on an example of a real distribution system in the Banat region in Serbia.

2. System description

This paper analyzes an actual medium voltage (35 kV, 20 kV and 10 kV) distribution network that supplies several villages in the Banat region in Serbia. The network is shown on a geographical map in Fig. 1. Distribution network is radial, supplied from a 110/35 kV Substation in node 1. Single line diagram of analyzed network is presented in Fig. 2. Network parameters are given in Table 1. Except the branch between nodes 7 and 8, all transmission lines are overhead lines with standard Aluminum Conductor Steel Reinforced (ACSR) of various sizes.

Analyzed Banat region has technically usable wind and solar resources [13,14]. Available resources and existing regulatory law for subsidized electrical power production from the renewable sources in Serbia, provides economical justification for the development of PV and WT projects in the analyzed region. The paper presents a scenario of a widespread use of the roof mounted PV systems connected to the low voltage network and numerous PV systems of small rated power connected to the nodes of the medium voltage network. In addition to the dispersed PV plants, it is assumed that two WT plants are connected to the network in the nodes 13 and 27. Table 2 provides a summary of injected power in all network nodes, as well as the maximum and the minimum consumed active power.

Presented scenario of development of distributed PV and WT projects is based on the actual Wind Power Plant projects, as well as on the available ground spaces and rooftop PV array in the analyzed region. Present national regulations for connecting distributed sources to the power distribution network are based only on compliance with the technical criteria for the allowable unit power rating determined by the short circuit power at the connection point [15]. In that regard, proposed scenario is satisfying the national regulations. On the national level, there is no strategy for optimal distributed generation mix and unit power rating of distributed sources. Implementation of one of the DG planning methodologies, presented in reference [16], as well as optimal planning of rooftop PV panels [17], can significantly increase the acceptable level of the total installed capacity of the distributed renewable sources, and also reduce their negative impact on the distribution system. With that in mind, research presented in this paper may be useful in the future analyses of optimal multi-criteria planning of distributed sources in a particular region.

3. Demand and dispersed units production time profiles

Node voltages of the distribution network depend on active and reactive power flows of the connected transmission lines. Active power flows are determined by the time diagrams of power demand and power generation. Injected active powers are directly dependant on the power of the primary energy source (wind speed and solar irradiation) and virtually independent of the voltage conditions in the network. Consumed power can depend, to a certain extent, on the voltages in the consumer nodes contingent upon the load characteristics. For the purpose of this analysis, it is assumed that the consumed power is independent of the voltage. Active demand power and DG units' generation are variable over the time, and therefore the node voltages are also variable. Wind speed and solar irradiation fluctuations occur on different time scales: seconds, minutes, hours, days, months, seasons and years. In this paper only 10-min voltage variations were analyzed.

3.1. Wind turbine production time profile

Electric power production time profile of a wind turbine is defined by its wind speed profile and power curve. The major wind turbine manufacturers provide the actual power curve of their WT in the technical note. The curve is usually given for a fixed air density (standard is $\rho_0 = 1.225\ \text{kg/m}^3$). In order to determine production power of a wind turbine for a ten minute interval, it is necessary to know the actual air density and wind speed at the hub height of the selected wind turbine. If measured height is different from the height of the wind turbine, it is necessary to extrapolate the measurement data at the hub height [18,19]. Then, calculation of the corresponding effective wind speed is calculated according to the following equation [20]:

$$V_{eff_t} = V_t \left(\frac{\rho_t}{\rho_0}\right)^{\frac{1}{3}}, \tag{1}$$

where ρ_t is the actual air density at the hub height. The electrical power of wind turbine for each ten minute interval t is estimated according to the following equation:

$$P_t = P_{power\ curve}(V_{eff_t}), \tag{2}$$

where $P_{power\ curve}(V_{eff_t})$ is the standard power curve of the wind turbine for the fixed air density $\rho_0 = 1.225\ \text{kg/m}^3$.

It should be mentioned that the previous approach to estimation of the production power is acceptable for a pitch-controlled wind turbine. For a stall-controlled wind turbine the power output predicted by a given power curve for the estimated wind speed V_t is calculated first, and then the power output is adjusted according to the following equation [20]:

$$P_t = P_{power\ curve}(V_t)\frac{\rho_t}{\rho_0}. \tag{3}$$

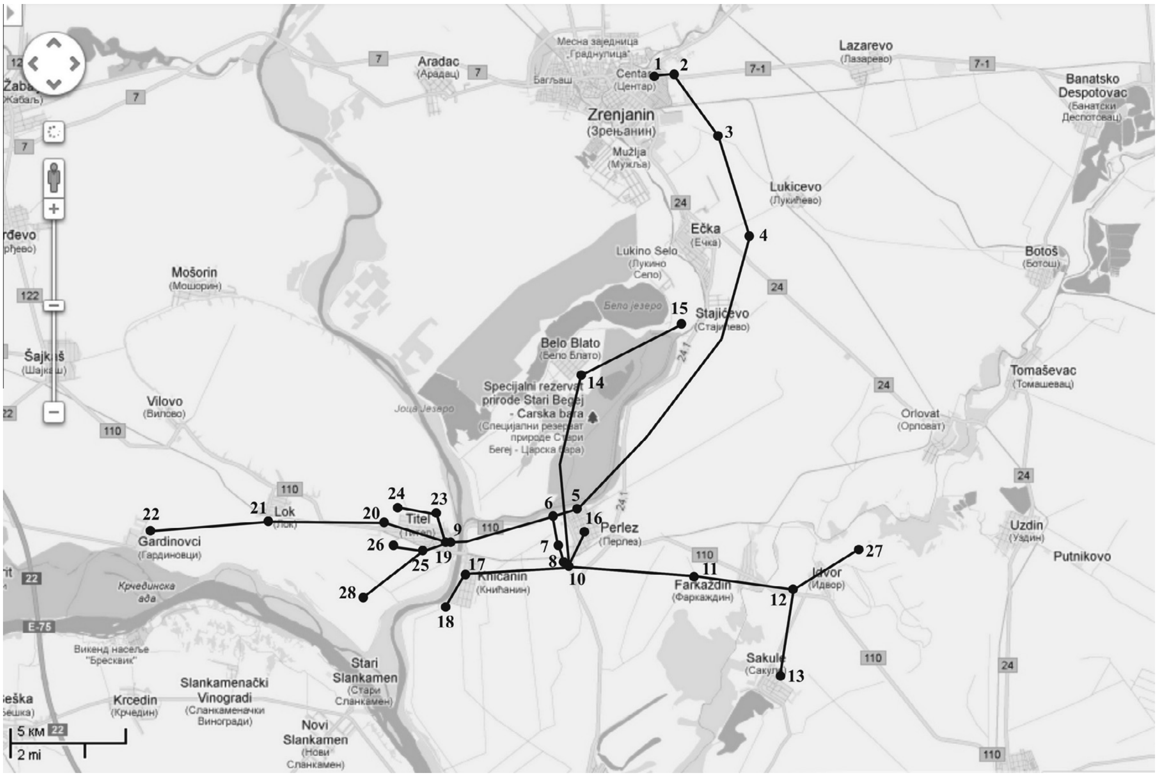

Fig. 1. Analyzed distribution network with dispersed PV and WT plants in the Banat region, Serbia.

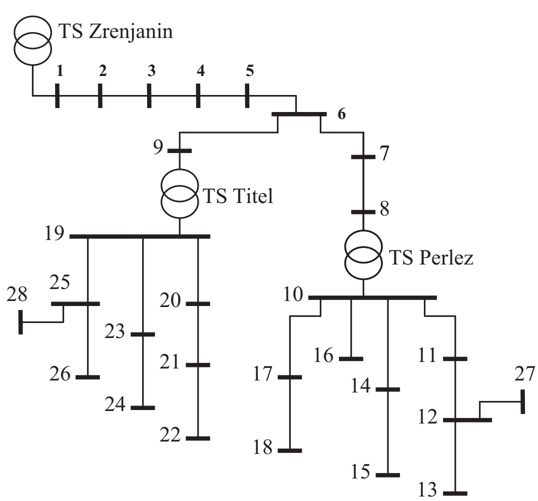

Fig. 2. Single line diagram of analyzed network.

In this analysis, the wind speed measurement data were obtained in the target region in the vicinity of the wind generator over a period of one year. The characteristic day is selected based on the statistical analysis of the measurement data. Based on the Eqs. (1) and (2) and the standard power curve of the wind generator Vestas V112, 3 MW, the time production diagram of the wind turbine is estimated and presented in Fig. 2.

Modern wind turbines can control the power factor and they can work in both inductive and capacitive mode. For the analysis presented in this paper, it is assumed that the wind turbines are operating with unity power factor, so there is no reactive power exchange with the distribution network. This assumption is introduced for two reasons: first, national technical regulations do not require using distributed sources in voltage regulation; second, wind turbine owners want to minimize losses on interconnecting power lines between the wind turbines and the distribution network by operating the wind turbines with unity power factor.

3.2. Photovoltaic array production time profile

Assessment of the time generation diagram of photovoltaic panels was done based on solar irradiation and ambient temperature measurements. It was assumed that all photovoltaic panels were oriented towards the south under a fixed angle. It was also assumed that the panels were clean and equipped with MPPT systems. Injected power of a PV panel into the distribution network (P_{PVt}) for each ten minute interval t is estimated according to the following equation [21]:

$$P_{PVt} = \eta_{inv} P_{PVSTC} \frac{I_{PVt}}{I_{STC}} \cdot (1 + \alpha_{TPV}(T_{PVt} - T_{STC})) = \eta_{inv} P_{PVSTC} \frac{I_{PVeqt}}{I_{STC}}, \tag{4}$$

where P_{PVSTC} is the declared power of a PV panel under the standard test conditions (STC); I_{PVt} is solar irradiation on the surface of a PV panel in a ten minute interval t; I_{STC} = 1000 W/m^2 is the solar irradiation that corresponds to STC; η_{inv} is the efficiency of the inverter; α_{TPV} is the temperature coefficient of the power change of the PV panel, typically equal to $-0.5\%/°C$; T_{STC} = 25 °C is the temperature of the panel STC and T_{PVt} is the temperature of the panel during a ten minute interval t, which is estimated according to the following equation [21]:

$$T_{PVt} = T_{amb\ t} + \left(\frac{\text{NOCT} - 20}{800}\right) \cdot I_{PVt}, \tag{5}$$

where $T_{amb\ t}$ is the measured ambient temperature during the ten minute interval t and NOCT (Normal Operation Cell Temperature) is the cell temperature in a module when the ambient temperature is 20 °C, solar irradiation is 0.8 kW/m^2 and the wind speed is 1 m/s.

Table 1
Network parameters presented in Fig. 1.

Nodes connection line	Voltage level (kV)	Length of line (km)	Conductor cross-section size (mm^2)	Resistance (Ω)	Reactance (Ω)
1–2	35	0.7	3 × 50	0.4	0.24
2–3	35	4.1	3 × 70	1.7	1.44
3–4	35	5.4	3 × 240	0.64	1.9
4–5	35	13.4	3 × 70	5.5	4.7
5–6	35	1.9	3 × 50	1.2	0.7
6–7	35	2.0	3 × 95	0.6	0.7
6–9	35	5.0	3 × 50	3	1.77
7–8	35	0.4	3 × 150	0.1	0.07
10–11	20	1	3 × 70	0.43	0.37
11–12	20	2.5	3 × 70	1.08	0.92
12–13	20	2	3 × 70	0.87	0.73
10–14	20	2	3 × 70	0.87	0.73
14–15	20	1.5	3 × 50	0.91	0.57
10–16	20	1.5	3 × 70	0.65	0.55
10–17	20	1.5	3 × 70	0.65	0.55
17–18	20	1.5	3 × 50	0.91	0.57
19–20	10	1	3 × 70	0.43	0.37
20–21	10	2	3 × 70	0.87	0.73
21–22	10	1.5	3 × 50	0.91	0.57
19–23	10	1	3 × 70	0.43	0.37
23–24	10	2	3 × 50	1.21	0.75
19–25	10	1.5	3 × 50	0.91	0.57
25–26	10	2	3 × 50	1.21	0.75
12–27	20	3	3 × 95	0.96	1.1
25–28	10	2	3 × 70	0.87	0.73

Table 2
Maximum (P_{DEMmax}) and minimum (P_{DEMmin}) consumed active power and rated power of the DG's connected to the nodes of the distribution network shown in Fig. 1.

Node	P_{PVmax} (MW)	P_{WTmax} (MW)	P_{DEMmax} (MW)	P_{DEMmin} (MW)
1	–	–	–	–
2	–	–	–	–
3	–	–	–	–
4	–	–	–	–
5	0.5	–	–	–
6	–	–	–	–
7	–	–	–	–
8	–	–	–	–
9	0.8	–	–	–
10	–	–	–	–
11	0.6	–	0.87	0.60
12	–	–	0.80	0.55
13	1.0	3	1.00	0.69
14	0.8	–	0.67	0.46
15	0.8	–	0.67	0.46
16	1.5	–	1.34	0.92
17	1.0	–	0.80	0.55
18	0.8	–	0.53	0.37
19	1.5	–	–	–
20	1.2	–	1.09	0.75
21	0.6	–	0.55	0.38
22	1.0	–	0.55	0.38
23	0.8	–	0.82	0.56
24	–	–	0.82	0.56
25	–	–	1.09	0.75
26	1.0	–	0.55	0.38
27	–	3	–	–
28	3	–	–	–

This parameter is typically obtained from the manufacturers of the PV modules.

In this analysis, the ambient temperature and horizontal irradiation measurement data were obtained in the target region over a period of one year. Solar irradiation on the surface of a PV panel (I_{PVt}) calculation was done based on the measured horizontal solar irradiation for each ten minute interval t. These calculations can be found in the literature related to the solar resources, such as the Ref. [21].

The characteristic day is selected based on the statistical analysis of the measurement data. Fig. 3 shows the time diagram of the equivalent solar irradiation (I_{PVeqt}) for a characteristic day in the analyzed target region.

When PV panel of small installed capacity is connected to distribution network, the Distributive System Operator (DSO) does not require that these sources are used in voltage regulation, and therefore, they usually operate with PF $\geqslant$ 0.95 [15]. In addition, current IEEE 1547 standard only allows PV generation at unity power factor [22]. Taking into consideration national and international recommendations, it is assumed in this analysis that all PV plants operate with unity power factor, without reactive power exchange with the distribution network. This is in accordance with the fact that, in the past period, only the grid-connected inverters with topologies designed to supply only active power to the grid were available on the market [23]. New inverter technologies, such as [24,25], are capable to control the power factor. Advantages of modern inverters of the new generation may be used in the future PV plants, so the PV plants may participate in voltage control and can be better integrated in the distribution system.

3.3. Demand time profiles

To obtain power demand profile, ten minute interval measurements of active power were taken in node 1 (see Fig. 1) where supply substation 110/35 kV/kV is located. Based on the statistical analysis of the measured demand profiles, the characteristic day in the year was selected. Approximately 90% of the power demand in the analyzed network, is from the residential consumers, and therefore, it is assumed that the relative power demand profiles in all consumer nodes are the same. Fig. 4 shows a normalized active power demand time diagram characteristic to the analyzed consumers in Fig. 1. Normalization is done for the base power of 1 MW. Based on the measured data, the selected demand power factor is 0.95. Demand time diagrams in a randomly selected consumer node i were obtained by normalization of the diagram in Fig. 4 according to the ratio of the installed consumed power in the node i and the total installed consumed power in the analyzed network.

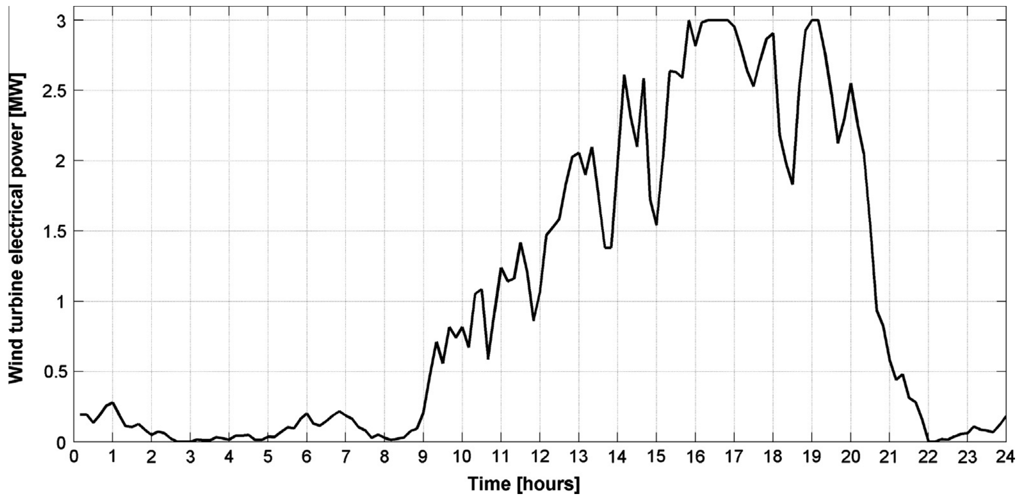

Fig. 3. Time production diagram of the test wind turbine for a characteristic day.

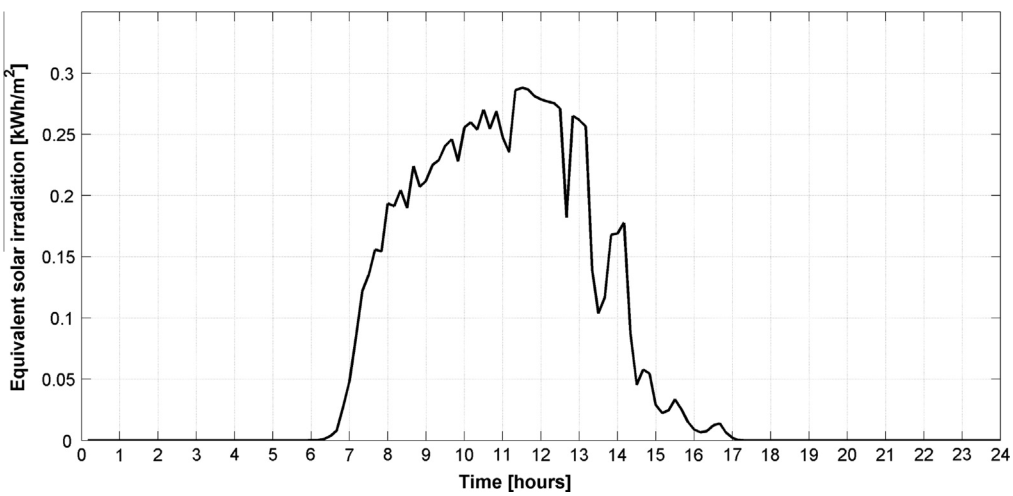

Fig. 4. Time diagram of the equivalent solar irradiation for a characteristic day in the analyzed region.

4. Static Var Compensator (SVC)

A Static Var Compensator (SVC) is defined as a device whose output is adjusted to exchange capacitive or inductive current in order to maintain or to control specific parameters of the electrical power system [26]. In this paper, the considered SVC corresponds to a TCR (Thyristor Controlled Reactor) as shown in Fig. 5.

The reactive power Q_{SVC} injected by the SVC is controlled by firing delay angle α according to the following equation:

$$Q_{SVC} = \frac{U^2}{X_c} - U^2 B_{SVC}(\alpha), \tag{6}$$

where U voltage at SVC connection point is the voltage being controlled, X_L total inductance, X_c capacitor reactance. According to the Fourier analysis, the variable susceptance, B_{SVC} can be expressed as:

$$B_{SVC} = \frac{2\pi - \alpha + \sin 2\alpha}{\pi X_L}. \tag{7}$$

Maximum inductive and capacitive injected power Q_{SVC} is defined by the reactances X_L and X_c:

$$\frac{U^2}{X_C} - \frac{U^2}{X_L} \le Q_{SVC} \le \frac{U^2}{X_C}. \tag{8}$$

For the load flow calculation done in this paper, the node where SVC device is installed is modeled as the PU node, where generated active power is equal to zero, and voltage is equal to the target value for that node. That can be the nominal voltage or any other voltage within the acceptable voltage tolerances.

5. Optimal SVC integration in distribution network

Distributed sources are causing voltage variations as a consequence of the intermittent generation of the DG units due to the changes of the solar irradiation and the wind speed. Voltage control in a distribution network can be achieved by controlling the reactive power flow [27,28]. By injecting (or absorbing) the reactive power in a suitable node in the system, the system node voltages can be directly influenced. In general, such influence is weaker as the injection point is further away. Node voltage variations can be compensated to a certain extent by controlling the time profile of the injected reactive power in the distribution network. SVC device, described in Section 4, proved to be an effective system for dynamic control of the reactive power injection into a given node. The base question, the optimization task addressed in this paper is: in which node (or nodes) of a complex distribution network with DG, SVC devices should be installed and what is the rated power of such system.

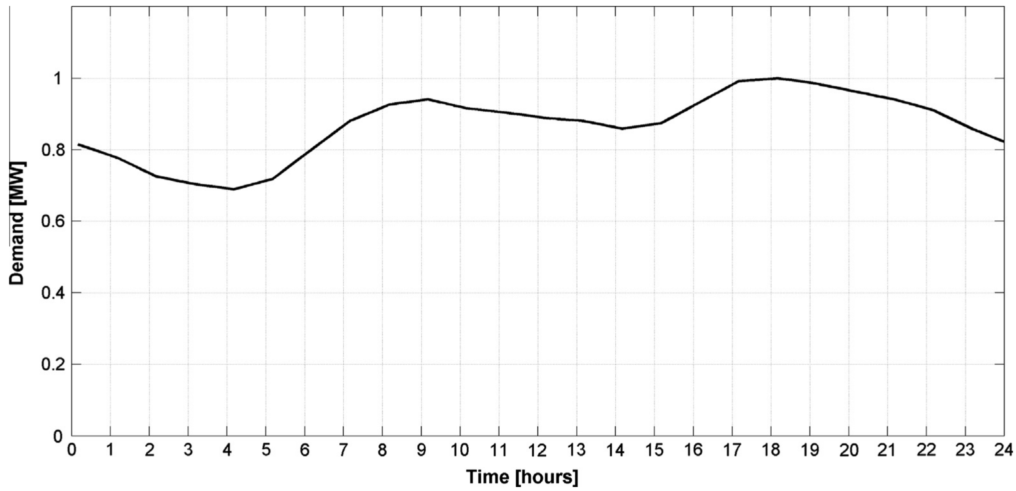

Fig. 5. Normalized demand time profile.

5.1. Optimization task

The problem of optimal location and parameter settings of SVC devices is specified as the two criteria optimization problem in this paper. The first criterion function (f_1) is the maximum standard voltage deviation in the network:

$$f_1 = \max_i \sigma_i, \tag{9}$$

where σ_i is the standard voltage deviation at node i, defined by the following equation:

$$\sigma_i = \sqrt{\frac{1}{T-1}\sum_{t=1}^{T}(U_i^t - U_{iref})^2}, \quad (i = 1, \ldots, N), \tag{10}$$

where U_i^t is voltage at node i at time interval t; U_{iref} is reference voltage at node i; T is number of time intervals (total time); N is number of nodes in the network.

In this analysis, selected time interval t is t = 10 min, which represents the sampling rate of measured parameters: wind speed and solar irradiation. Total sampling time is T = 144 ten minutes intervals (1 day). Reference voltages U_{iref}, (i = 1,…, N) can be set to the nominal values or can be assigned for each node within acceptable tolerances from the nominal values.

It should be noted that voltage deviation is the percentage voltage difference from the nominal value, and standard voltage deviation is a statistical parameter given by Eq. (10).

The second criterion function (f_2) is the sum of SVC devices rated power:

$$f_2 = \sum_{k=1}^{M} Q_{svc}^k, \tag{11}$$

where: Q_{svc}^k is rated power of SVC device installed in node k; M is number of SVC devices.

According to defined criterion functions, optimization problem could be described by the following equation:

$$\min(f_1, f_2), \tag{12}$$

Subject to constraints:

– Active and reactive power balance at all system buses.
– Upper and lower limits of voltages at all network buses.
– Internal operating limits of SVC devices.

The approach of simultaneous minimization of these two criteria is used for the solution of the defined optimization problem. This approach is selected because these criteria could be in conflict, so their possible aggregation to a unique optimization criterion is not adequate. Thus, optimal procedure tends to simultaneously minimize maximum standard voltage deviation and rated power of SVC devices. Instead of a single criterion optimization, as the final result of the two criteria optimization, the set of optimal solutions, known in the literature as Pareto optimal solutions, or Pareto front [29] is obtained.

5.2. Optimization method

There are several methods for solving optimization problem defined by Eq. (12). They are mainly of evolutive type. As opposed to the classical ones, these methods are well suitable for the mixed criteria functions, as well as in case of different types of variables (real, integer, continuous, discrete, logic, etc.). They are based on the evolution concept in the nature. In this paper, genetic algorithm, known in the literature as "Non-dominated Sorted Genetic Algorithm II", or NSGA-II [29] is used for the search of optimal solutions. NSGA-II algorithm is selected because it presents one of the standard procedures for solving the multi-criteria optimization problems. Main characteristic of this algorithm is that the algorithm is using elitism principle and provides the mechanism of even distribution of the solutions on the Pareto front. The superiority of NSGA-II lies in the way multiple objectives are reduced to a single fitness measure by the creation of number of fronts, sorted according to non-domination. Detailed description of NSGA-II algorithm is given in [29].

NSGA-II method is based on population consisting of chromosomes i.e. possible solutions. For that reason, it is not possible to include the number of SVC devices in the optimization process. Chromosomes used to code solutions with one SVC device would not have the same length and structure as the chromosomes used to code solutions with two or more SVC devices. If a population contains chromosomes of different length and structure, it would not be possible to apply genetic operators. Without applying genetic operators, it would not be possible to do the optimization. This is the property of any other method based on population (PSO, Ant Colony,…). Optimization for the number of SVC devices was done based on calculations for different scenarios by comparison of the results.

Binary coding of potential location and rated power of SVC devices is made as the requirement of the applied NSGA-II algorithm, to ensure the corresponding chromosome form and to enable the use of optimization method. Then, the population of desired dimensions is made of chromosomes coded this way. It should be emphasized that the computation process is organized, giving all solutions as feasible, i.e. they do not violate any specified limits.

6. The results and discussion

For the subject network (Fig. 1 and Table 1), defined characteristic power demand diagrams (Fig. 4 and Table 2), and characteristic time diagrams of power generation of the DG units (Figs. 2 and 3 and Table 2), the load flow calculation was performed in all network branches for each analyzed ten minute interval. Voltage variations in all network nodes were determined as the result of calculations, as well as the corresponding standard voltage deviations according to the Eq. (10). In addition to the calculation of standard voltage deviations, voltage deviations were calculated for the two extreme but viable scenarios:

1. Injected power of DG are $P_{PV}(i) = 0$, $P_{WT}(i) = 0$, $P_{DEM}(i) = P_{DEMmax}(i)$.
2. Injected power of DG are $P_{PV}(i) = P_{PVmax}(i)$, $P_{WT}(i) = P_{WTmax}(i)$, $P_{DEM}(i) = P_{DEMmin}(i)$.

The first scenario has the minimum node voltages so the lower acceptable voltage limits may be violated, whereas in the second scenario, the voltage may be increased above the acceptable upper limits. Acceptable voltage limits used in this paper are ±10% of nominal voltage value.

Voltage variation analysis and calculation results for the case when SVC devices are not used (base calculation) are given in Section 6.1.

According to the methodology and optimization criteria described in Section 5, calculation of the optimal location and power output of the SVC devices was done for the following cases:

1. With one SVC device.
2. With two SVC devices.

Table 3
Standard voltage deviations in network nodes for a characteristic day and maximum voltage deviations in network nodes when SVC devices are not used.

Node	Voltage deviation (%)	Minimal voltage (%)	Maximal voltage (%)
1	0	105.00	105.00
2	0.09	104.42	105.01
3	0.48	101.73	104.96
4	0.67	100.00	104.62
5	1.91	91.35	104.48
6	2.17	89.63	104.52
7	2.26	89.07	104.58
8	2.28	88.99	104.59
9	2.39	87.67	104.13
10	2.48	90.06	108.61
11	2.62	89.64	109.00
12	3.00	88.94	110.14
13	3.16	88.62	110.61
14	2.51	89.65	108.46
15	2.52	89.44	108.40
16	2.50	89.75	108.50
17	2.50	89.75	108.51
18	2.52	89.59	108.46
19	2.53	89.26	108.24
20	2.66	87.86	107.79
21	2.80	86.44	107.38
22	2.89	85.74	107.24
23	2.58	88.22	107.75
24	2.62	86.83	106.97
25	2.85	87.18	108.06
26	2.97	86.25	107.87
27	3.17	88.94	110.79
28	3.05	87.18	108.75

Calculation results and voltage variation analysis for different rated power of the SVC devices in cases when one and two optimally located SVC devices are used are given in Sections 6.2 and 6.3 respectively.

6.1. Voltage analysis for the base calculation

Standard deviation of the node voltages for the network shown in Fig. 1, based on the average ten minute load flow calculations for the characteristic day, is given in Table 3. The largest standard voltage deviation occurs in node 27 and it is equal to 3.17%, followed by node 13 where standard voltage deviation is equal to 3.16%. Such results are expected, because wind generators of relatively significant rated power are connected to these nodes. Besides, these nodes are relatively far away from the medium voltage 110 kV network, so the short circuit impedances in them are relatively high.

In addition to the voltage variations, under the maximum power demand conditions, if there is no injected power from the DG, voltage sags may occur in remote nodes and lower acceptable voltage limits may be violated. Furthermore, with minimum demand, and maximum power generation, voltages in all network nodes are above the nominal values. Results of voltage calculations for the two extreme conditions when SVC devices are not used (base case), are given in the last two columns of Table 3. The

Table 4
Solutions from Fig. 8 with one SVC device.

Solution	Node of SVC integration	Rated power of SVC (Mvar)	Maximal voltage deviation (%)	Minimal voltage (%)	Maximal voltage (%)
1	11	3.42	1.69	90.05	105.67
2	11	3.28	1.72	89.40	105.82
3	17	2.45	1.76	88.59	106.63
4	17	2.48	1.78	88.57	106.65
5	17	2.43	1.80	88.52	106.71
6	17	2.41	1.86	88.50	106.73
7	17	2.35	1.88	88.43	106.80
8	14	2.15	1.90	88.23	106.99
9	17	2.06	1.91	88.13	107.13
10	14	2.06	1.94	88.12	107.10
11	17	1.96	1.98	88.02	107.26
12	14	1.83	2.00	87.88	107.52
13	14	1.80	2.01	87.85	107.60
14	14	1.75	2.05	87.80	107.73
15	14	1.69	2.07	87.72	107.90
16	14	1.66	2.11	87.69	107.98
17	14	1.65	2.13	87.68	108.01
18	14	1.55	2.16	87.58	108.25
19	14	1.51	2.19	87.54	108.36
20	16	1.46	2.23	87.49	108.36
21	14	1.44	2.28	87.45	108.56
22	15	1.39	2.31	87.42	108.45
23	15	1.31	2.32	87.34	108.65
24	15	1.26	2.34	87.25	108.72
25	23	1.25	2.74	89.15	109.89
26	23	1.22	2.75	89.03	109.91
27	23	1.15	2.76	88.90	109.98
28	23	1.13	2.76	88.80	110.01
29	23	1.06	2.79	88.62	110.08
30	23	0.98	2.81	88.47	110.17
31	23	0.94	2.82	88.30	110.21
32	23	0.84	2.84	88.06	110.32
33	25	0.80	2.86	87.94	110.41
34	21	0.80	2.94	88.43	110.25
35	21	0.72	2.96	88.24	110.33
36	21	0.62	2.97	87.97	110.45
37	21	0.58	2.99	87.89	110.49
38	21	0.43	3.01	87.46	110.66
39	22	0.40	3.06	87.36	110.62
40	22	0.31	3.08	87.13	110.71

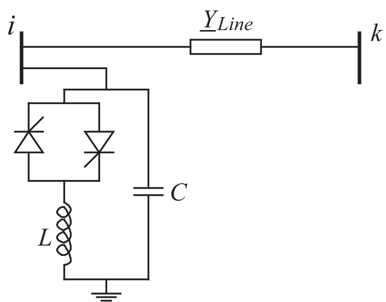

Fig. 6. Static Var Compensator.

highest voltage occurs in node 27 when DG production is maximum and power demand is minimum, and the lowest voltage occurs in node 22 when DG's do not inject power while the power demand is maximum. Due to intermittent nature of the DG production, it is not technically acceptable to use voltage regulated transformers to maintain the voltage within the acceptable limits, due to the need to change the tap changer position frequently.

The above analysis shows that voltage variations in distribution networks with DG can be large, and that generally, when the networks are weak and generation of the DG units is significant, it is necessary to install the reactive power control devices in the network.

6.2. Voltage analysis in case when one SVC device is installed

Two criteria optimization method described in Section 5 is used in the case when one SVC device is installed. Calculation was done on a population of 40 members, and it lasted for 100 generations. The result of optimization is a set of optimal solutions. For each optimal solution, voltage deviation was calculated in all network nodes, and the most critical node with the largest voltage deviation was selected. Table 4 provides complete data of all solutions for the case of installation of one SVC device, i.e. optimum location and SVC device rated power as well as the maximum standard voltage deviation in the analyzed network. In addition, the minimum and the maximum voltages in the most critical node in the network for the extreme conditions of power generation and power demand are given in the last two columns of Table 4, for all 40 solutions.

The choice of the final solution from the set of optimal solutions can be made based on the target (required) value of standard voltage deviation. If the criterion is that standard voltage deviation in all nodes shall be less than 3%, it is sufficient that the rated power of SVC device is 0.58 Mvar, and that the SVC device is installed in node 21. If the criterion is that standard voltage deviation in all nodes shall not be greater than 2%, then according to Table 4, the SVC device shall have the rated power of minimum 1.96 Mvar and it shall be installed in node 17. For this case, Fig. 6 shows how the average ten minute injected active power of DG and reactive power of SVC device are changing during the characteristic day. Fig. 6 also presents the total active power consumption. However, if the extreme conditions of power generation and power demand are also taken into consideration to select the final solution, Table 4 shows that only the first solution satisfies with respect to the allowable maximum voltage deviations of ±10%. Therefore, the final choice would be the first solution. By installing the SVC device of rated power 3.42 Mvar, voltage in all analyzed network nodes under all cases of power generation and power demand would stay within a deviation range of ±10% and at the same time, standard voltage deviation for a characteristic day in all nodes would be less than 1.7%.

6.3. Voltage analysis in case when two SVC devices are installed

When two SVC devices are installed, the same optimization method is used as in the case when one SVC device is installed. The result of optimization is a set of optimal solutions presented graphically in Fig. 8, together with the results of calculations with one SVC device. Fig. 8 shows how maximum standard voltage deviation in the most critical nodes depends on rated power of the optimal located SVC devices. Based on the results for both cases presented in Fig. 8, it can be clearly observed that by increasing the SVC device rated power, the maximum standard voltage deviation in the network is decreasing. Table 5 provides complete data of all solutions in case of installation of two SVC devices. The last two columns of Table 5 are the minimum and the maximum voltages for the extreme conditions of power generation and power demand.

The choice of the final solution from the set of optimal solutions can be made based on the target value of standard voltage deviation, as in the previous case with one SVC device. If, for example, the criterion is that standard voltage deviation in any node shall not be greater than 1%, then, according to Table 5, it is necessary to install two SVC devices, one in node 13 (SVC device with rated power of 1.90 Mvar) and the other one in node 28 (SVC device with

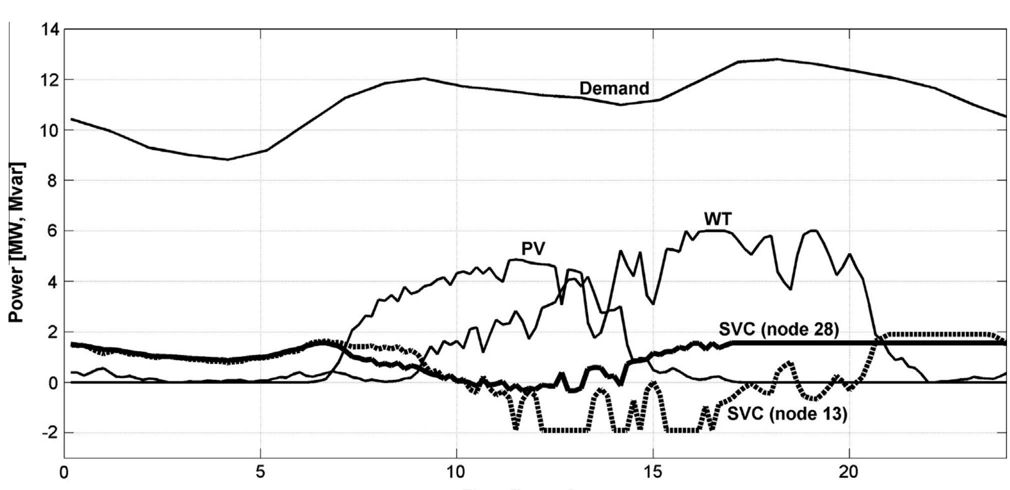

Fig. 7. Average ten minute injected active power of DG and reactive power output of SVC devices installed in nodes 13 and 28 during the characteristic day.

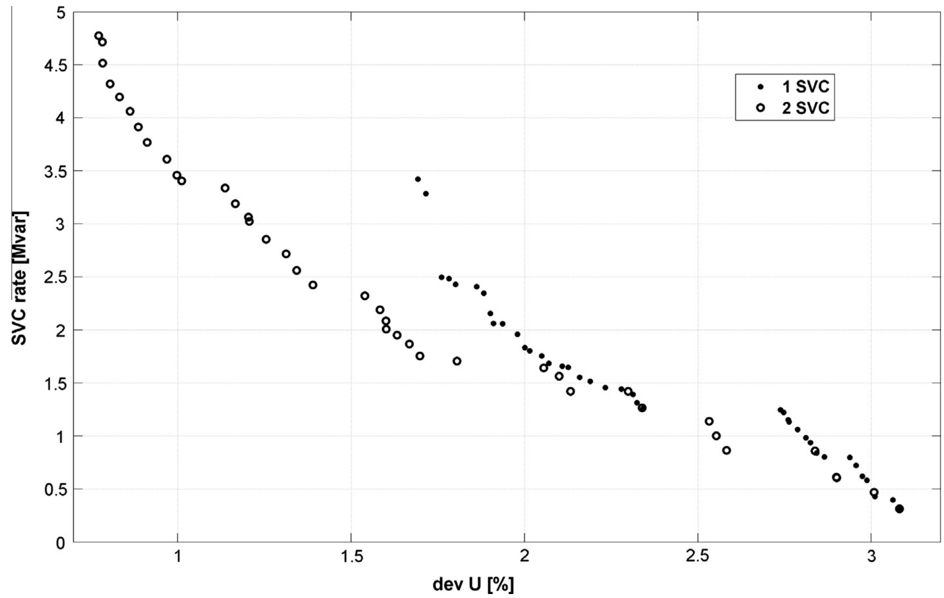

Fig. 8. Set of optimal solutions for the case of one SVC device and two SVC devices.

Table 5
Solutions from Fig. 8 with two SVC devices.

Solution	Node of SVC 1	Node of SVC 2	Rated power of SVC 1 (Mvar)	Rated power of SVC 2 (Mvar)	Maximal voltage deviation (%)	Minimal voltage (%)	Maximal voltage (%)
1	19	27	2.77	2.00	0.77	92.69	106.34
2	19	27	2.77	1.94	0.78	92.64	106.48
3	19	27	2.57	1.94	0.78	92.45	106.48
4	19	27	2.40	1.92	0.80	92.25	106.10
5	19	27	2.28	1.92	0.83	92.13	106.10
6	13	19	2.05	2.01	0.86	91.98	105.91
7	19	27	2.00	1.92	0.89	91.84	106.10
8	13	19	1.89	1.88	0.91	91.70	106.38
9	19	27	1.70	1.92	0.97	91.52	106.10
10	13	28	1.90	1.56	1.00	91.30	106.70
11	13	28	1.90	1.51	1.01	91.28	106.71
12	13	19	1.89	1.45	1.14	91.24	106.38
13	13	28	1.90	1.29	1.17	92.81	106.70
14	28	16	1.55	1.51	1.20	90.95	107.89
15	25	16	1.51	1.51	1.21	93.44	108.12
16	28	16	1.18	1.68	1.26	92.73	107.55
17	28	16	1.20	1.52	1.31	92.64	107.88
18	28	16	1.20	1.36	1.34	92.55	108.18
19	28	16	1.09	1.33	1.39	92.57	108.28
20	28	16	0.54	1.78	1.54	89.28	107.13
21	28	16	0.53	1.66	1.58	89.10	107.44
22	28	16	0.57	1.51	1.60	89.07	107.74
23	25	16	0.54	1.47	1.60	88.94	107.96
24	28	16	0.54	1.41	1.63	88.87	108.03
25	28	16	0.53	1.33	1.67	88.75	108.23
26	28	16	0.50	1.26	1.70	88.58	108.45
27	25	18	0.39	1.32	1.81	88.36	108.46
28	26	18	0.39	1.26	2.06	88.32	108.49
29	21	16	0.16	1.41	2.10	88.05	108.43
30	21	15	0.25	1.17	2.13	88.16	108.84
31	15	15	0.41	1.02	2.30	88.96	106.20
32	15	15	0.33	0.94	2.34	88.60	106.49
33	20	21	1.07	0.07	2.53	89.09	110.15
34	20	21	0.99	0.01	2.55	88.90	110.17
35	20	21	0.86	0.01	2.58	88.48	110.31
36	23	23	0.70	0.16	2.84	89.74	109.36
37	21	22	0.56	0.05	2.90	87.94	110.58
38	21	22	0.56	0.05	2.90	87.93	110.57
39	21	21	0.40	0.07	3.01	88.79	110.10
40	22	13	0.31	0.00	3.08	87.13	110.71

rated power of 1.56 Mvar). For this case, Fig. 7 shows how the average ten minute injected active power of DG and reactive power of SVC device are changing during the characteristic day. Taking into account the extreme conditions will narrow down the choices. By analyzing Table 5, it can be observed that the first 19 solutions satisfy the acceptable voltage limits, so in this scenario, the prospects

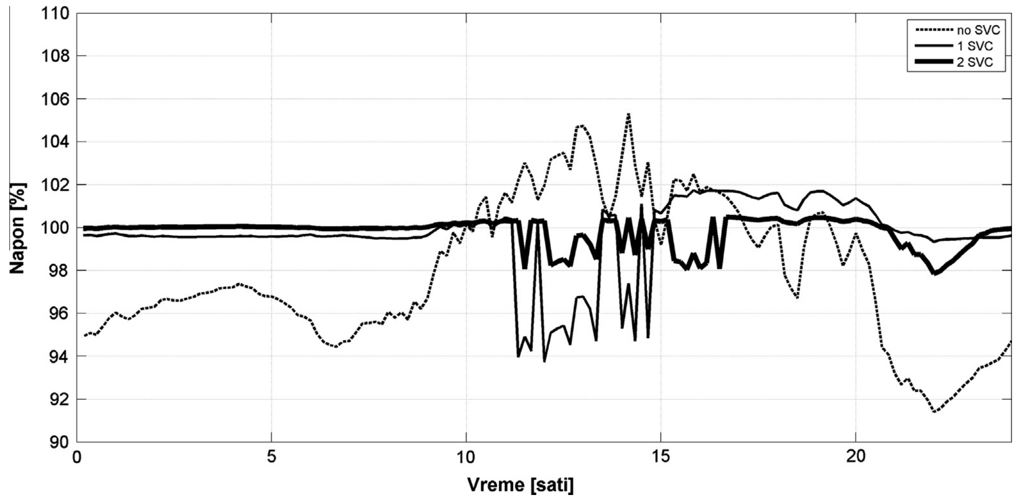

Fig. 9. Voltages in the node 27 in cases without SVC, with one SVC (solution 1) and with two SVC devices (solution 10).

are much more favorable. The minimum rated power of SVC device to satisfy the criteria of voltage deviations is solution 19 in Table 5.

6.4. Comparative analysis of the results

Based on the comparative analysis of the effects of installation of SVC devices on voltage conditions in the distribution network, it can be concluded that SVC devices are very effective in reducing voltage variations in the nodes of a complex distribution network with dispersed intermittent generation plants. In terms of the number of SVC devices, it can be concluded that much better results are achieved with two SVC devices than with one SVC device. For example, if solution 1 shown in Table 4 for one SVC device is compared with solution 10 for two SVC's given in Table 5, it can be observed that the achieved standard deviation with one SVC device is 1.7%, whereas with two SVC devices, whose total rated power is smaller than the rated power of one device, the achieved standard deviation in the most critical node is only 1%. Fig. 8 shows the comparison of how the maximum standard voltage deviation in the network depends on the total rated power of optimal located SVC devices, for the cases of one SVC device and two SVC devices. Fig. 8 clearly demonstrates that the solutions with two SVC devices are better than the solutions with one SVC device.

Fig. 9 shows average ten minute voltage values in the node 27 for the characteristic day for different scenarios. Node 27 is selected for graphical representation of the effects of installation of SVC devices on voltage deviation, since this node had the largest voltage deviation in the network before installation of SVC devices. For the comparison, the following solutions were taken: solution number 1 in case of one SVC device and solution number 10 in case of two SVC devices. From Fig. 9, it can be observed that smaller voltage variations and more even distribution of the effective voltages is achieved by installing two SVC devices in different network nodes.

Better comparison of the two analyzed cases can be done by evaluation of the installation costs of SVC devices. However, available literature does not provide installation cost curves for small power SVC devices. The literature provides installation cost curves for SVC's larger than 100 Mvar [30] and use of such cost curves would not be adequate in this case. Calculation was also performed for the case of three SVC devices. In such case, results are marginally better than in case of two SVC devices. Due to space constraints in this paper, calculation results for the case of three SVC devices are not presented. With that in mind, scenario with two SVC devices was selected as optimal for the analyzed network. In case of two SVC devices, results are significantly better that with one SVC device. In addition, when two SVC devices are used, large number of solutions is satisfactory with respect to the two extreme scenarios, which is not the case when installation of only one SVC device is considered.

7. Conclusion

In a complex distribution network with dispersed intermittent sources, such as photovoltaic and wind power plants, the problem of voltage variations exists for the network nodes. In case of a weak network, such voltage variations may not be acceptable to the power utility company and to the consumers. Efficient way to resolve this problem is to install SVC devices. This paper analyzed optimal location and rated power of SVC devices by using genetic algorithm, to achieve minimum standard voltage deviation in the most critical node in the network. For optimal location, it is necessary to know the power demand and dispersed units generation time profiles.

Analysis shows that in complex networks with larger number of dispersed sources, it is suitable to use larger number of SVC devices with smaller rated power. Such approach ensures smaller voltage variations in the network. Number and rated power of SVC devices is determined by the criterion of the maximum allowable standard voltage deviation. For the case study analyzed in this paper, it is shown that by using two optimal located SVC devices of a total rated power of 3.45 Mvar, standard voltage deviation in the network nodes is less than 1%, whereas standard voltage deviation for one optimal located SVC device is greater than 1.7%. Based on obtained results, methodology proposed in this paper can successfully address the problem of voltage variations in distribution networks with larger number of DG units.

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