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ORIGINAL PAPER

Distribution network reconfiguration and capacitor switching in the presence of wind generators

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Abstract

In this paper, the distribution network reconfiguration with simultaneous capacitor switching, in the presence of wind generators, by Simulated Annealing is presented. IEEE 69 bus network is analyzed which has 69 nodes including the slack one and 73 branches, all of which can commutate. Following assumptions are made: load in nodes is changed according to Gauss distribution and wind generator power with Weibull one, every hour, then there are two wind generators of 200 kW maximum power each (10% of total, nominal active power load) and they can be allocated to any node but the slack one. The same is valid for the capacitor banks regarding allocation. This switching logic is unrealistic. On its basis more realistic one was issued with fixed nodes for allocation of wind generators and capacitor banks (the most frequently visited nodes), by Monte Carlo graphical method. Input power factor is to be greater than 0.85 which is not fulfilled with commencing configuration (from the start) so that allocation of capacitor banks is mandatory. Another constraint is that the network should not be overcompensated. Four realistic scenarios are investigated. In the first one only network with wind generators is analyzed and the rest are dedicated to all possible combinations of the regulation. The programme is automated indicating the price of configuration, generated banks, input data (active and reactive load, power and location of wind generators) and savings which change on an hourly basis. The wind generators are uniformly distributed in accordance with nodes (for the less realistic scenario) and generate only active power complying with Weibull distribution. The graphical results are presented for a 1008-h operation (operation in one thousand and eight hours, every hour different) and the analysis is done for a thousand and eight-hour work. The presented method shows that considerable savings can be achieved by simultaneous application of reconfiguration method and capacitor switching with already allocated wind generators.

Keywords Reconfiguration · Capacitor banks · Wind generators · Simulated annealing (SA)

List of Symbols

Indices

j	Index of hours
i	Index of scenarios
TVPI	Total Voltage Profile Index
VPI	Voltage profile index of the certain network configuration
VPI^n	Voltage profile index when no switching scheme is performed
TPLI	Total Power Loss Index

Parameters, sets and variables

$f(x)$	Probability distribution density function
x	Stochastic variable
m	Expected power consumption value in one node
σ	Standard deviation (10%)
v	Wind speed (m/s)
A	Weibull scale parameter (m/s)
k	Weibull form parameter

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$P_{acc.}$	Probability of accepting the proposed network perturbation
Δf	A change in the price function corresponding to the proposed network perturbation
T	Artificial control parameter representing temperature
FINALCOST	One-hour cost of the operation ($)
I	Set of all scenarios
J	Set of all hours
CPA	Capacitor price annual interest rate (0.15)
PCB	Total price of the installed capacitor banks ($)
LPF	Loss penalty factor (120 $/kW)
P_{loss}	Active power loss of the certain network configuration (kW)
C_{int}	Cost of supply interruption ($)
c_{int}	Cost per unit of energy not delivered (4 $/kWh)
α	Load factor (0.6)
d	Repair duration (1 h)
λ_k	Branch failure rate (0.0001 fl./km, for simplicity 100 km is each branch length)
N_b	Number of branches
I_k	Current value of branch k (A)
U_r	Network rated voltage (12.66 kV)
ENERGY	Delivered electrical energy saving cost ($)
CDEL	Cost of delivered energy loss (0.03 $/kWh)
C_{com}	Cost of commutations for N^{hours} (one commutation amounts to 1 $ or 50 $)
V^{min}, V^{max}	Minimum and maximum voltage values
V_k	Voltage of the network node k p.u
$I_k^{max} I_k^{max} I_k^{max}$	Maximum current of branch$k$
Q_b	Total power of the installed capacitor banks
$Q_{b\max}$	Maximum total power of the installed capacitor banks
$Q_{initial}$	Reactive power loss for initial network, network without installed capacitor banks
Q_{dem}	Reactive power demand
$Q_{b\min}$	Minimal total power of installed capacitor banks
P_{00}	Active power at the slack node
N	Total number of nodes
N^{hours}	Duration of scenario (1008 h, equals 42 days)
r	Branch active resistance
N_H	Number of operating hours within which the allowed number of commutations is observed
$x_s^h x_s^h x_s^h$	State in which the switch s is performed during the hour$h$ (open = 0, closed = 1) and
$N_{SW}^{MAX} N_{SW}^{MAX} N_{SW}^{MAX}$	Maximum number of commutations tolerated for a single switch over a period ofN_H hours
Note	Bold capital letters denote sets

1 Introduction

Electric power companies have witnessed many changes in recent times. The current trend of deregulation in the energy sector is forcing these companies to improve their energy efficiency and reduce prices while consumers become increasingly sensitive to the reliability and quality of electricity supplied. Shunt capacitors and distributed generators are some of the essential components of the realization of the concept of smart distribution networks. Optimal production of active and reactive power from these devices in distribution networks reduces the energy that the distribution network takes from the power transformer station and this production regulates the flow of power through the lines.

The compensation problem is a NP difficult problem of combinatorial optimization with a non-differentiable objective function because the price of capacitor banks is a step-non-differentiable function. NP is an abbreviation of the term Non-deterministically in Polynomial-bounded time and denotes problems that are solved during time which is the exponential function of the problem dimension and not a polynomial one. When determining the optimal configuration, engineers are faced with a large number of constraints that must be met. First, it is necessary to form a radial configuration of the network by turning on or off the branches. As the state of the switch is open or closed the solution space is discontinuous. These are the problems of the "minimum spanning tree" which are also the NP difficult problems of combinatorial optimization. This means that all nodes must be connected and there must be no loops. Certainly, due to the direct impact on consumers, engineers must meet the condition that the voltages in the nodes are always within the allowed limits.

The main goal of reconfiguration is to reduce the losses of the active power of the network, increase the stability and reliability and relieve the network [1]. When talking about reconfiguration from the aspect of reducing active power losses, it is necessary to find the optimal scheme of inclusion, i.e., exclusion of branches when the objective function is minimal and the achieved configuration is radial. This is achieved by manipulating sectional (normally closed) and tie (normally open) switches. Reconfiguration of distribution networks belongs to the class of mixed-integer nonlinear optimization problems. Namely, the configuration of the distribution network is determined by the status of switches (open/closed) which are modeled with binary (0/1) variables. On the other hand, the distribution network regime (power flows, active power losses, etc.) is modeled by nonlinear algebraic equations in which continuous variables (modules and phase positions of voltage phasors in distribution network nodes) occur. The same is true for the compensation problem when the sizes of the built-in capacitor banks are discrete variables. The solution to these problems has also been extensively analyzed in the literature through a mathematical, heuristic and meta-heuristic approach.

Individual problems related to the reconfiguration and compensation of the distribution network have been studied in detail in the earlier period [2–9]. Coordination of compensation, location of distributed generators and reconfiguration provides a significant reduction in annual losses on supplied electricity and keeps the voltage profile within the limits required by regulations [10]. Voltage instability is not desirable because it leads to unreliability in the supply of electricity [11]. There are a large number of articles that deal with the problem of reconfiguration of the distribution network, in the nodes of which capacitor banks are also connected. Optimizing the minimization of voltage deviations from the nominal in the network is another important aspect that researchers are dealing with [10–17]. There is a smaller number of authors who are interested in these problems and consider them within an economic background [10, 15, 16, 18–23].

Through four scenarios, using a genetic algorithm (GA) on a 33-node test network, the authors [12] reduce the losses of the distribution network active power and improve its voltage profile without touching the problem of simultaneous network reconfiguration and penetration of distributed generation and capacitor banks. Namely, two last scenarios (placing of regulation apparatus alone and reconfiguration with them) are the same regarding penetration of additional devices. Distribution generators and capacitors, being these additional devices, are represented by discrete variables. The genetic algorithm was also applied in [11, 13, 14], minimization of losses, improvement of voltage stability and reduction of load on branches are considered, but the economic side of the problem is also neglected as in the previous reference [12]. An improved genetic algorithm, an improved particle swarm optimization (PSO) algorithm, and an improved cat swarm optimization (CSO) algorithm were used in [10] without considering the prices of power control equipment.

Recently, multi-objective optimization methods have been applied to solve the above problem. Harmony search algorithm (HSA) [24], ant colony search algorithm (ACSA) [22], bacteria foraging algorithm (BFA) [25] consider distributed sources and capacitor banks while taking into account voltage conditions and minimizing losses, but without commenting on the economic aspect. The particle artificial bee colony algorithm (PABC) [26] solved the problem of reconfiguration, compensation and installation of distributed generators, without working with loads higher than nominal and the principle of power hierarchy was not followed for installation of capacitor banks and distributed generators. The applied LSHADE-EpSin method of differential evolution (DE) [27] does not take into account the dynamics of load change or the financial side of the problem considering only the resulting reduction of active network losses. Modified meta-heuristic flower pollination algorithm (MFPA) is used to analyze the problems of reconfiguration, installation of static compensators and solar panels [17] with binding to one load level (nominal, minimum and maximum) whose dynamics of change is not taken into account. The superiority of individual algorithms cannot be estimated because Newton's power flow algorithm [25, 28] for a 69-node network does not converge in 10 iterations. A rare example of reconfiguration from the aspect of investment cost and reduction of losses by applying the Pareto principle of optimality is given in [23]. Recently, some of the authors are trying to speed up the problem of reconfiguring the network from the aspect of minimizing active power losses based on population reduction with a two-stage heuristic that includes optimal power flow (OPF) optimization with particle swarm optimization algorithm whereby the authors point to a tuning parameters required for good performance of the applied method [29]. In no case was the economic aspect taken into account.

In this paper, the optimization procedure of Simulated Annealing (SA) was used. The algorithm is adapted to a number of additional conditions. SA has proven to be very useful for implementing a number of limitations and additional factors that can be considered, such as reactive power compensation or limiting the number of commutations. The advantage of the work is that not only losses are considered, but attention is also paid to a broader economic analysis. When it comes to economic analysis, which is an unavoidable topic from the aspect of producers but also consumers, a large number of factors must be taken into consideration. One of them is the price of actions of switching equipment [15]. The number of commutations with switches is often neglected in the works, which is wrong. With the increased number of manipulations, the equipment wears out faster and the sooner they are replaced. By limiting the number of manipulations, the life of the equipment is extended. This prolongs the period of revitalization, which is not a cheap task. Economic analysis certainly includes respect for the price of undelivered electricity. Within the SA algorithm, a limit on the number of actions by switching equipment on a daily basis has been implemented. Also, within the optimization function, the price of undelivered energy is taken into account.

In this paper, the goal of the operator in charge of monitoring and managing the distribution network is to influence as much as possible the financial background of the objective function whose main component includes the losses of active network power and thus losses of delivered active electricity. The optimization method used by the operator is the simulated annealing. An important assumption of the applied algorithm is that the network already has wind generators whose penetration is located by the Monte Carlo graphical method. The presented analysis of the distribution network operation in regard to simultaneous reconfiguration and capacitor switching when loads are changing in accordance with Gauss distribution and Weibull changing output of wind generators is very realistic and omitted in mentioned literature. In this work, firstly sensitivity analysis is performed (for IEEE 69 bus network [30]) on the basis of 1008 times program run (for 1008 h) to locate wind generators and capacitor banks when generators are uniformly distributed to network nodes, two of them being of 200 kW maximum power each and capacitors are allocated in the buses in accordance with minimal objective function, to any of them but the slack one. The SA method is used in the previous stage. Then when the most attractive nodes for the location of the distributed generators and capacitors are defined the analysis is repeated (also by SA) with fixed placements and fixed capacitor output when an 1008-h energy loss savings are issued to see where the electricity utility stands economically. The considered number of hours must be divisible by 24, being the duration of one day, because that is how the program is conceived.

The presented method is characterized by the following features:

- Acceptable input power factor (greater than 0.85) is attained by the proposed algorithm (with allocation of capacitor banks).
- Financial minimization of the objective function is reflected in savings on active power losses, the cost of capacitor banks, as well as the number of commutations.
- The load change in network nodes is dynamic and subject to Gaussian distribution.
- The output power of wind generators is also of a stochastic nature and its value is shown by the Weibull probability function.
- A multi-criteria objective function used is not Pareto normalized and has the following components: maximum power loss cost, cost of installed capacitors, the cost of supply interruption, supply energy loss cost and price of commutations.
- For a better evaluation of the operational performance of the network, some operational indices are introduced.
- Finally, allowed number of commutations per branch, for the prescribed time duration, is incorporated in algorithm.

This paper is organized in the following manner. Section 2 explains Gauss and Weibull distribution. The network connectivity check and the applied power flow algorithm are presented in Sect. 3. The short description of the SA algorithm is elaborated in Sect. 4. IEEE 69 bus network data are laid out in Sect. 5. The description of the objective functions and of network operational indices with allowed number of commutations per branch for the prescribed time duration is given in the Sect. 6. Flow chart of the proposed algorithm as well as description of the programme SA block are given in the Sect. 7. The numerical results are exposed in the Sect. 8. The discussion regarding the reviewed literature is presented in the Sect. 9. Section 10 deals with the conclusions.

2 Normal and weibull distribution

For the stochastic consumption, normal Gauss–Laplace distribution is adopted. At the beginning, we start with the known expected load of the bus. It is adopted in accordance with nominal load (IEEE 69 bus network [30]). Any stochastic variable deviations of its expected value are considered "errors " and on the "error rule " are described with normal distribution. Probability rule is given in accordance with Eq. (1):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-m)^2}{2\sigma^2}} \quad (1)$$

where,m—expected consumption value in one node andσ—standard deviation, deviation from expected value, Forσ, 10% is considered.

The probability of production is defined by Weibull distribution because wind generators are of interest, Eq. (2). Their output depends on wind speed at the spot of location. The output depending on wind speed is given in Fig. 1a. For maximum power of wind turbine, 0.2 MW is adopted. The probability of wind blowing is defined by Weibull distribution. At first, the wind speed during the year is obtained. Then Weibull distribution probability curve with two parameters is formed. The best presentation of probability distribution density function is with the following Eq. (2)

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{\left(-\left(\frac{v}{A}\right)^{k}\right)} \quad (2)$$

where, v—wind speed (m/s), A—Weibull scale parameter (m/s) and k—Weibull form parameter.

Weibull scale parameter (A) is the measurement for wind characteristic speed and is proportional to the wind speed mean value. Weibull form parameter (k) defines Weibull distribution shape and is usually between 1 and 3. The low value of k denotes very changeable winds. The wind speed one year, probability distribution density function is depicted in

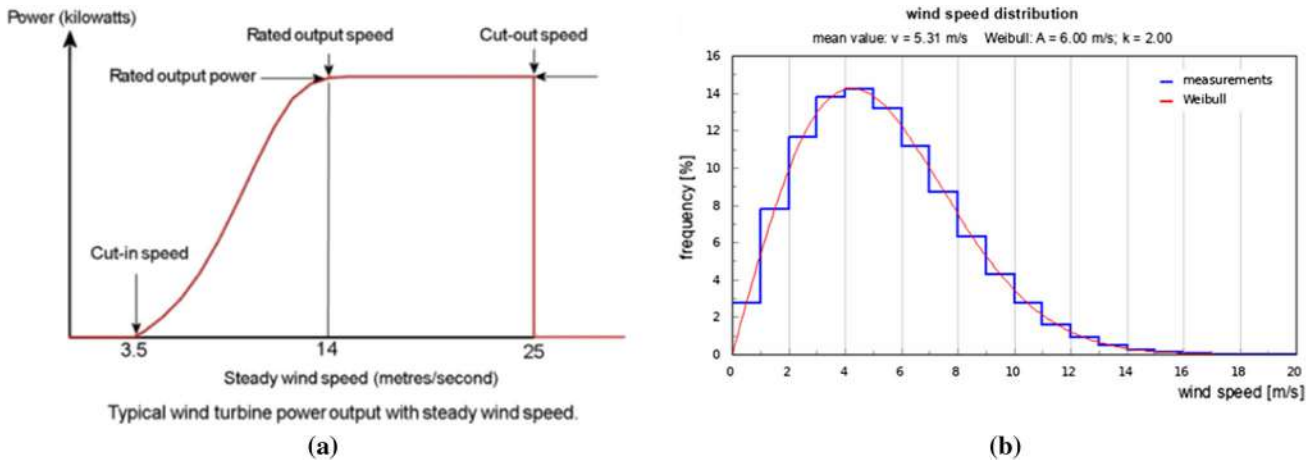

Fig. 1 Wind characteristics: **a** Typical wind turbine power output with steady wind speed. **b** Wind speed distribution

Fig. 1b. The following values are adopted $v_{\text{mean}} = 5.31$ m/s, $A = 6$ m/s and $k = 2$.

3 Network connectivity check and precise matpower-efficient power flow

The connectivity of the power network means that all its nodes must be connected to the source node. A distribution network is a graph with *m* branches and *n* nodes (buses). In order for the network to be radial, the following two requirements must be met [31]:

1. The network must have an *n*-1 branches;
2. The network must be connected.

The programme starts with the network incidence matrix for the meshed network (all tie switches closed). The number of rows corresponds to the number of nodes (including the slack one) and the number of columns equals the number of branches (the total number including ties), namely, for analysed network it is [69 rows, 73 columns] matrix. Then the first row is deleted (for the slack node) and the columns amounting to the number of opened branches (generated by the random number generator, the same number for the whole procedure comprising of different numbers denoting opened branches, 5 in question). The generated matrix is square and its determinant can be calculated which in the case of the connected network (which is also radial for the number of closed branches) must be 1 or -1 (not zero) [32]. The values 1 or -1 depend on the convention of defining the network incidence matrix (the branch incident to the node and oriented from it with element 1 and the incident branch to the node with -1 element or vice versa).

To solve optimization problems such as: compensation, voltage regulation, network planning, restoration, condition assessment, etc., an accurate algorithm is required to calculate the power flow, voltage and current flows of the distribution network. The method of forward and backward substitution is generally recognized and widely applied, which uses network scheme by levels and appropriate numbering of nodes what is not overcome in many articles. Precisely this numbering of nodes by levels is their main drawback because it requires that each new configuration be respected in that manner, which takes an enormous amount of time, so in the case of dynamic network problems, they are not applicable.

The MATPOWER program [28] application in this paper is relatively new, although its settings are classical. It is suitable for the static problems (compensation) as well for the dynamic (reconfiguration) which converges in ten iterations, of millisecond duration, depending on analyzed network. The default solver is Newton's method applied in polar coordinates with a Jacobian update in each iteration. There is no need to renumber the nodes in the new configuration and it is applicable to both radial and weakly meshed networks. Since the IEEE 69 bus network as a case is not included in the library [28], a 'casejiang' was formed with the following initial parameters $U_{\text{basic}} = 12.66$ kV and $S_{\text{basic}} = 100$ MVA.

Inflexibility or simplification is a characteristic of many power flow algorithms, so they cannot be used in the simulated annealing method, which solves the problem of network reconfiguration in order to reduce active power losses. The problem is entering network data that variy from configuration to configuration and can be quite time consuming if not already solved in some way. For Markov chain (through successive trials) of length 100 for each of these 100 configurations, it is necessary to enter new data for the network (accordingly 100 times). The "double linked-list data structure" method shown in reference [30] is not sufficiently developed. In the paper presented, it is only necessary to change the status of the branch from on to off or vice versa during switching, which is a powerful solution that can come in handy for any distribution engineer who deals with this issue.

4 Applied simulated annealing method

Simulated annealing is the probabilistic method of the combinatorial optimization, introduced by Kirckpatrick et al. [33, 34] and independently Černy [35] in early 80's which results in the global optimum under certain conditions such as the process of temperature decreasing which seeks zero lasting very long time and on each temperature stationary distribution is achieved (homogenous algorithm). The inhomogeneous algorithm also exists decreasing temperature before each application of the Metropolis criterion (the special procedure of accepting the more expensive configurations) which is much faster because it does not seek the thermal equilibrium, but because of fast cooling leads to suboptimal solutions. Metropolis criterion is given by the following equation:

$$P_{acc.}(\Delta f, T) = \min(1, e^{-\Delta f/T}) \tag{3}$$

where, $P_{\text{acc.}}$—probability of accepting the proposed network perturbation, Δf—a change in the price function corresponding to the proposed network perturbation and T—artificial control parameter representing temperature.

Exactly for the algorithm duration, in this research the authors adopt inhomogeneous algorithm for the programme at the swap of the solution quality. The SA parameters are: starting temperature $T_{\text{comm.}}$ 5000 °C, length of the Markov chain 3000 (ICOUNT), temperature (T) lowering rule T = 0.95*T, and acceptance ratio 0.001 (a.r.) [36].

5 IEEE 69 bus network data for the nominal load level

The tested system is a medium size, hypothetical 12.66 kV system [30] (given in Fig. 2), comprising of 68 branches and 5 tie switches forming 5 different loops when closed (dotted lines). System data are given in [30]. The total active and reactive load of tested network amounts to 3802 kW and 2694 kVAr, respectively. Total system active power loss is 225 kW which is 5.9% of total active power demand. The network is not well compensated. Its input cosφ is 0.8212 (<0.85). All holds for the nominal load level. Let maximum tolerances of node voltages be ±5% (of 12.66 kV). As per National Electrical Code (NEC), allowable voltage drop is 5% at the furthest node.

The lowest voltage at its start is 0.909 p.u. for the node of ordinal number 65 for the nominal load level so that the mentioned requirement for network voltages is not met. All network switches are assumed to be commutative and that capacitor banks in 300 kVAr step can be installed in any node but the slack one. The suggested solution methods are implemented in MATLAB R2010a (Pentium IV PC; Intel core i7-4770; 3.4 GHz; 32 GB RAM). The precise MATPOWER power flow is used for the power loss calculation ('casejiang').

6 Objective functions, constraints, operational indices, and allowed number of commutations per branch

6.1 Objective functions

Two objective functions are adopted which may not be general but depend on the respective authors' decision. In [15], the objective function is composed of the cost of power purchase, the cost of customer interruption penalties, Transformers Loss of Life expenses and the switching costs while in [22] DG installation, operation and maintenance costs, capacitor installation costs, cost of reconfiguration, line upgrades cost, power loss cost, reliability cost, and environmental impacts are parts of decision function. In this paper, authors decided for the construction of objective functions given below.

The first is one-hour cost of the operation *FINALCOST* (4) and it is minimized by SA algorithm

$$\min FINALCOST_{i,j} = CPA * PCB_{i,j} + LPF * P_{loss,i,j} + C_{\text{int},i,j} \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{4}$$

where, $FINALCOST_{i,j}$—one-hour cost of the operation in the i-th scenario and the j-th hour ($), I—set of all scenarios, J—set of all hours, *CPA*—capacitor price annual interest rate (0.15), $PCB_{i,j}$- total price of the installed capacitor banks in the i-th scenario and the j-th hour ($), *LPF*—loss penalty factor (120 $/kW), $P_{loss,i,j}$—active power loss of the certain network configuration in the i-th scenario and the j-th hour (kW) and $C_{\text{int},i,j}$—cost of supply interruption in the i-th scenario and the j-th hour ($).

The cost of supply interruption is given by the expression (5) [37], considering that in radial distribution networks the interruption of one branch excludes the power supply of all its "downstream" consumers.

$$C_{\text{int},i,j} = c_{\text{int}} * \alpha * d * \sum_{k \in N_b} \lambda_k * \text{Re}\left\{I_{k,i,j}\right\} * \sqrt{3} * U_r \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{5}$$

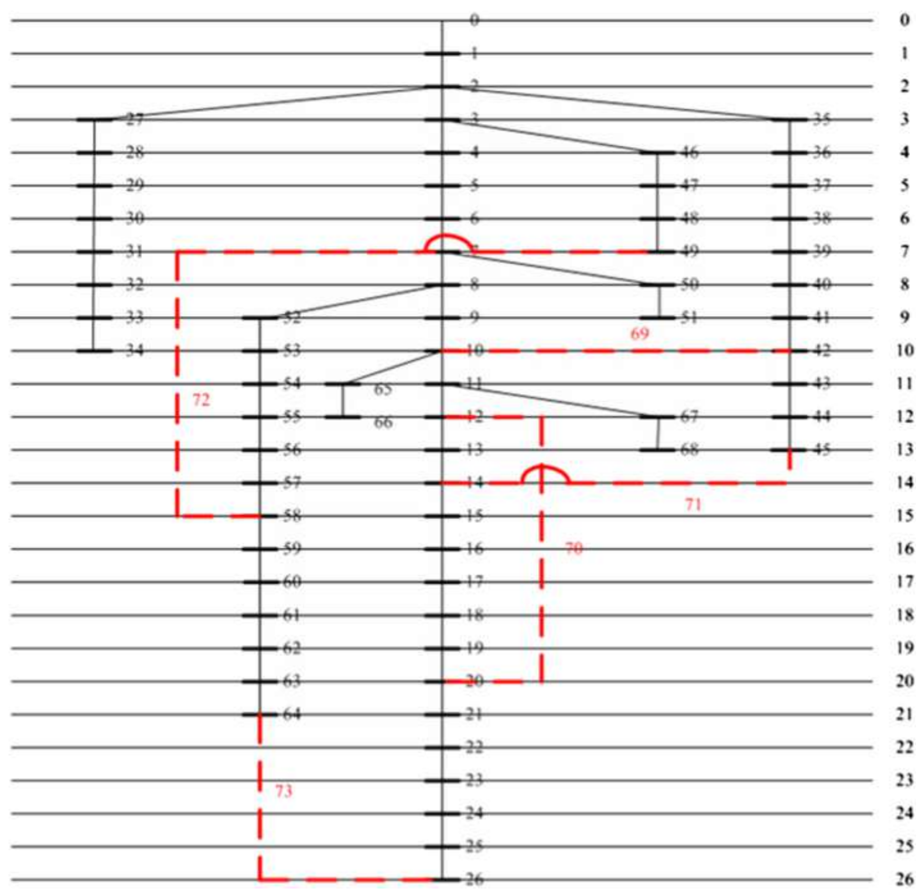

Fig. 2 IEEE 69 bus network [30]

In Eq. (5) following symbols are used: c_{int}—cost per unit of energy not delivered (4 \$/kWh), α—load factor (0.6), d—repair duration (1 h), λ_k—branch failure rate (0.0001 fl./km, for simplicity 100 km is each branch length), N_b—number of branches, $I_{k,i,j}$—current value of branch k in the i-th scenario and the j-th hour (A) and U_r—network rated voltage (12.66 kV).

In the case no switching scheme is performed:

$$INITIAL_{i,j} = LPF * P_{\text{loss,initial},i,j} + C_{\text{int,initial},i,j} \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J}. \tag{6}$$

$$SAVINGS_{i,j} = INITIAL_{i,j} - FINALCOST_{i,j} \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{7}$$

The second objective function is the delivered electrical energy saving cost $ENERGY$ calculated by (8)

$$\begin{aligned} ENERGY_i = {} & LPF * \max\left(P_{\text{loss,initial},i,j}\right) \\ & + CDEL * \sum_{j=1}^{N^{\text{hours}}} P_{\text{loss,initial},i,j} + \sum_{j=1}^{N^{\text{hours}}} C_{\text{int,initial},i,j} \\ & + (CPA * PCB_i + LPF * \max(P_{\text{loss},i,j}) \\ & + CDEL * \sum_{j=1}^{N^{\text{hours}}} P_{\text{loss},i,j} + \sum_{j=1}^{N^{\text{hours}}} C_{\text{int},i,j} + C_{\text{com},i}) \\ & \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \end{aligned} \tag{8}$$

where, $ENERGY_i$-delivered electrical energy saving cost in the i-th scenario (\$), *CDEL*- cost of delivered energy loss (0.03 \$/kWh) and $C_{\text{com},i}$—cost of commutations for N^{hours}in the i-th scenario (one commutation amounts to 1 \$ or 50 \$).

6.2 Constraints

$$V^{\min} \le V_{k,i,j} \le V^{\max} \quad \forall k \in N,\ i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{9}$$

$V^{\min}$, $V^{\max}$—minimum and maximum voltage values, $V_{k,i,j}$—voltage of the network node k in the i-th scenario and the j-th hour (p.u.) and N—total number of nodes.

$$I_{k,i,j} \le I_{k,i,j}^{\max} \quad \forall k \in N_b,\ i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{10}$$

$I_{k,i,j}^{\max}$—maximum current of branch k in the i-th scenario and the j-th hour.

$$Q_{b\min,i,j} \le Q_{b,i,j} \le Q_{b\max,i,j} \quad i = 3,4,\ \forall j \in \boldsymbol{J} \tag{11}$$

$$Q_{b\max,i,j} = Q_{initial,i,j} + Q_{dem,i,j} \quad i = 3,4,\ \forall j \in \boldsymbol{J} \tag{12}$$

Equation (12) considers network to be not overcompensated.

$$Q_{b\min,i,j} = Q_{initial,i,j} + Q_{dem,i,j} - P_{00,i,j} * \frac{\sqrt{1-0.85^2}}{0.85} \quad i = 3,4,\ \forall j \in \boldsymbol{J} \tag{13}$$

In Eqs. (11)–(13), following symbols are used: $Q_{b,i,j}$- total power of the installed capacitor banks in the i-th scenario and the j-th hour, $Q_{b\max,i,j}$- maximum total power of the installed capacitor banks in the i-th scenario and the j-th hour, $Q_{\text{initial},i,j}$- reactive power loss for initial network, network without inalled capacitor banks in the i-th scenario and the j-th hour, $Q_{\text{dem},i,j}$- reactive power demand in the i-th scenario and the j-th hour, $Q_{b\min,i,j}$- minimal total power of installed capacitor banks in the i-th scenario and the j-th hour and $P_{00,i,j}$- active power at the slack node in the i-th scenario and the j-th hour.

To have the power factor at the slack node 0.85 or greater [4] Eq. (13) is applied. In (12) and (13) to ground admittances are neglected which is valid for tested network. Total maximum power of the installed wind generators is approximately 10% of the network total load (3802.1 kW, IEEE 69 bus network [30]). The price of installed capacitors is given in Table 1.

6.3 Operational indices

Two parameters were introduced to assess the "validity" of the distribution network.

6.3.1 Total voltage profile index *TVPI*$_i$ [15]

This parameter gives the summary voltage deviation in the network nodes during hour j for the scenario i:

$$VPI_{i,j} = \sum_{k=1}^{N} \left|1 - V_{k,i,j}\right| \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{14}$$

$$TVPI_i = \frac{\sum_{j=1}^{N^{\text{hours}}} VPI_{i,j}}{\sum_{j=1}^{N^{\text{hours}}} VPI_{i,j}^{n}} \quad \forall i \in \boldsymbol{I} \tag{15}$$

In Eqs. (14), (15) *TVPI*$_i$ is total voltage profile index for scenario i, $VPI_{i,j}$ is voltage profile index of the certain network configuration in scenario i and the j-th hour and $VPI_{i,j}^{n}$ is voltage profile index when no switching scheme is performed. It is certainly better for the distribution network that $TVPI_i$ is as small as possible so that the voltage profile is as "ironed out" as possible.

6.3.2 Total power loss index *TPLI*$_i$ [15]

Given that the reduction of active power losses is the main task imposed on the operator in charge of its management, $TPLI_i$ is very important.

$$P_{\text{loss},i,j} = \sum_{k=1}^{N_b} r_k * I_{k,i,j}^2 \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{16}$$

$$TPLI_i = \frac{\sum_{j=1}^{N^{\text{hours}}} P_{\text{loss},i,j}}{\sum_{j=1}^{N^{\text{hours}}} P_{\text{loss,initial},i,j}} \quad \forall i \in \boldsymbol{I} \tag{17}$$

In Eqs. (16), (17) *TPLI*$_i$ is total power loss index for scenario i, N^{hours} is duration of scenario (1008 h, equals 42 days) and r_k branch active resistance. Evidently smaller values of $TPLI_i$ guarantee the lower losses of the network.

6.4 Branch commutations

Conducting algorithm regarding allowed number of commutations per branch for the prescribed time duration (switching operation constraints $s = 1, 2, \ldots, N_{SW}$) [38]:

$$\sum_{h=1}^{N_H} \left|x_s^h - x_s^{h-1}\right| \le N_{SW}^{\text{MAX}} \tag{18}$$

In the above expression, N_H stands for the number of operating hours within which the allowed number of commutations is observed, x_s^h for the state in which the switch s

Table 1 Capacitor price step up function [4]

Q_b	> 0, ≤ 300 kVAr	> 300, ≤ 600 kVAr	> 600, ≤ 900 kVAr	> 900, ≤ 1200 kVAr	> 1200 kVAr
PCB	1900 $	3200 $	4500 $	5400 $	6000 $

Maintenance and installation cost is included in fixed part of the price

is performed during the hour h (open = 0, closed = 1) and N_{SW}^{MAX} for the maximum number of commutations tolerated for a single switch over a period of N_H hours. Inequality (18) requires that the maximum allowed number of switching actions per observed switch is not exceeded. This value depends on the physical characteristics of the switch, i.e., on how long its "lifespan" is predicted. For N_H of 24 h and a switch that should be in operation for 15 years, a permitted number of 6 commutations is envisaged, 4 for reconfiguration and 2 for eventual restoration. In this paper, the authors assigned the same value for this parameter to all commutating switches.

7 A solution algorithm* of sa block and block diagram of the algorithm

This section provides additional explanation about SA and the applied algorithm. Figure 3 shows the flowchart of the proposed algorithm step by step, from the beginning to the end. Final step is actually the exit of programme. Special block in the flowchart needs description with more details. This is block defining Simulating Anneaing. This block could be detailed as follows:

After feeding in all input data, we start with Step 1.

Step 1- Input parameters:

1. Counter set to 0 (ICOUNT = 0, ICOUNA = 0), initial temperature $T = 5000$, temperature lowering rule $T =$ 0.95*T.
2. EOLD complies with initial open branches configuration with no installed capacitors and not considered undelivered energy cost. It includes only losses multiplied by loss penalty factor (EOLD = Ploss*120).
3. Algorithm stop criterion, ICOUNT (length of Markov chain) < 3000, or ICOUNA/ICOUNT < 0.001 (ICOUNA/ICOUNT is acceptance rate).

Step 2- Starting with above-mentioned initial configuration EOLD and initial temperature 5000.

Step 3- Subroutine generates first/new feasible configuration (connected and radial) by means of random number generator whose objective function (E) is sum of losses multiplied by loss penalty factor, price of capacitors multiplied by 0.15 and the cost of unsupplied energy. When adding capacitor banks inequalities (11) and (12) must be considered. First configuration is initial configuration.

Step 4- If objective function of generated configuration is less than EOLD accept perturbation, update EOLD (EOLD becomes E).

Step 5- If not, lower temperature by the rule $T =$ 0.95*T, find $\Delta E =$ E-EOLD and exp($-\Delta E/T$). In the case exp($-\Delta E/T$) is greater than the random number uniformly distributed in segment [0,1) replace EOLD with E. If not, retain current solution, update ICOUNT by ICOUNT = ICOUNT + 1 and go to Step 3.

In SA algorithm, configurations with greater decision function are accepted in certain conditions, which is the main difference with greedy search when only configurations with less objective function are accepted.

Step 6- Update ICOUNT by ICOUNT = ICOUNT + 1 and ICOUNA by ICOUNA + 1, check stop criterion. If it is satisfied continue, otherwise go to Step 3.

Step 7- Stop criterion checking.

The algorithm stops in two cases, whichever occurs first:

1. The length of Markov chain becomes greater than 3000 counted configurations.
2. Acceptance rate becomes less than 0.001.

Note 1: When 1 or 2 occurs, the system is cosidered frozen and the algorithm terminates.

Note 2: Inhomogeneous SA algorithm, described above, is performed for each scenario i ($i = 2$, 3 and 4) in each hour j ($j = 1$ to 1008).

*All losses in the solution algorithm are calculated by MATPOWER-efficient power flow.

8 The numerical results

At the beginning of calculation, the programme is run 1008 times to simulate operation of the network for 1008 h, but in the case the nodes for allocation of the wind generators and the capacitor banks are not fixed. Figure 4a–g. are obtained. The gained results comply to SA procedure adopted for performing the algorithm and with conclusion that wind generators are uniformly distributed to the nodes. Capacitors are added to the heaviest loaded node (node 60) mostly.

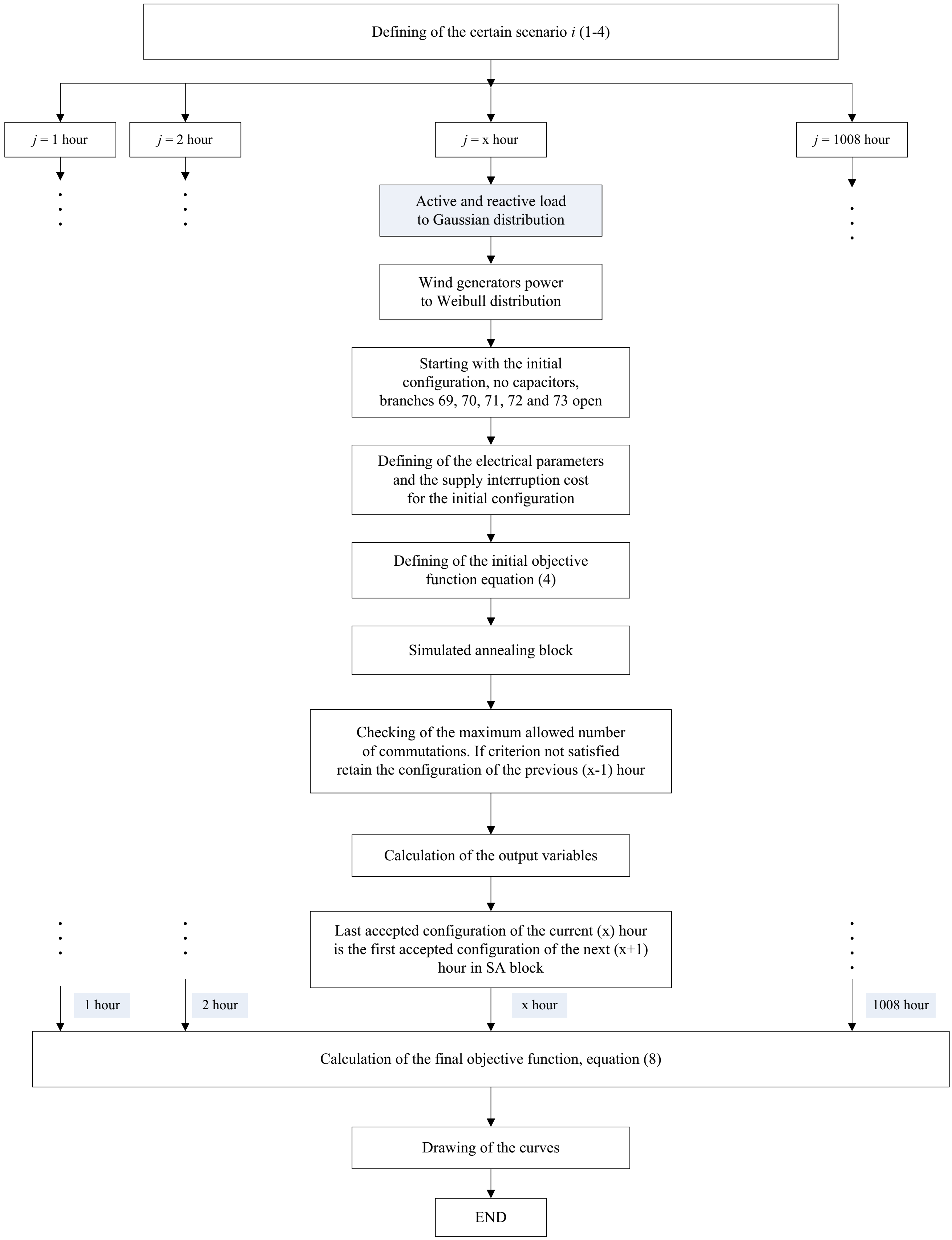

Fig. 3 Flowchart of the proposed algorithm

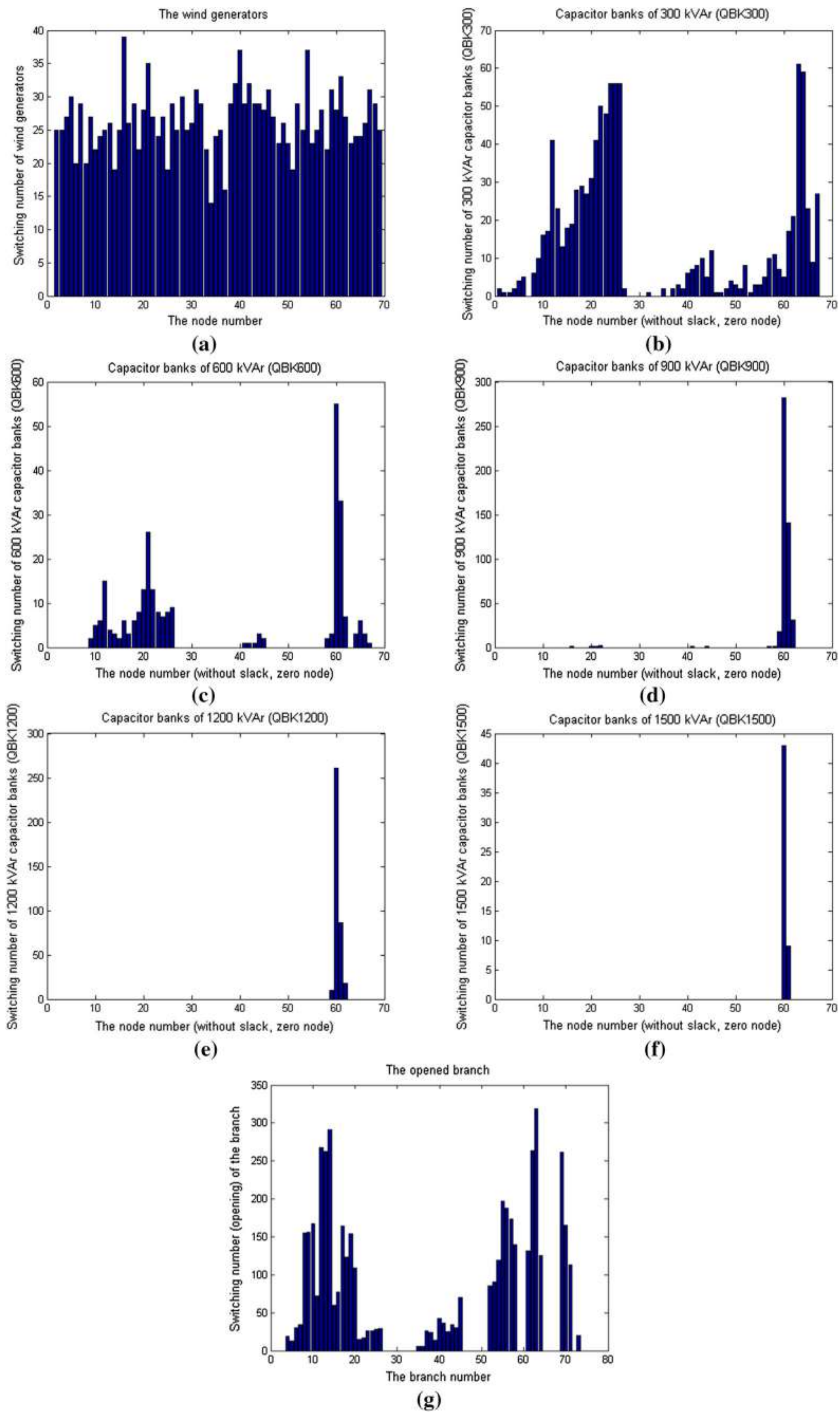

Fig. 4 Switching number of: **a** wind generators **b** 300 kVAr **c** 600 kVAr **d** 900 kVAr **e** 1200 kVAr **f** 1500 kVAr **g** the open branch

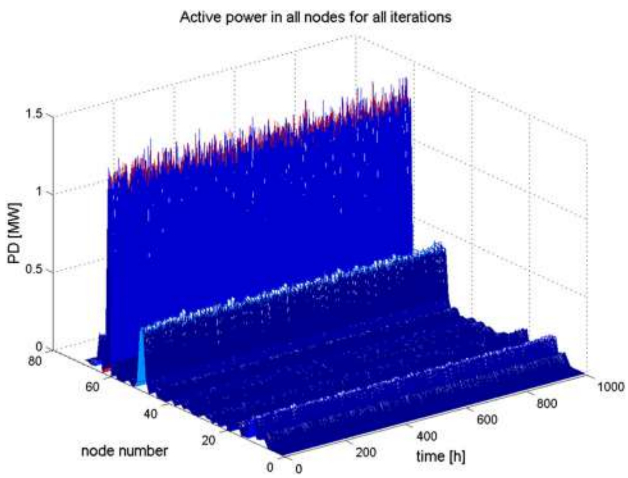

Fig. 5 Active load duration curve for the whole network

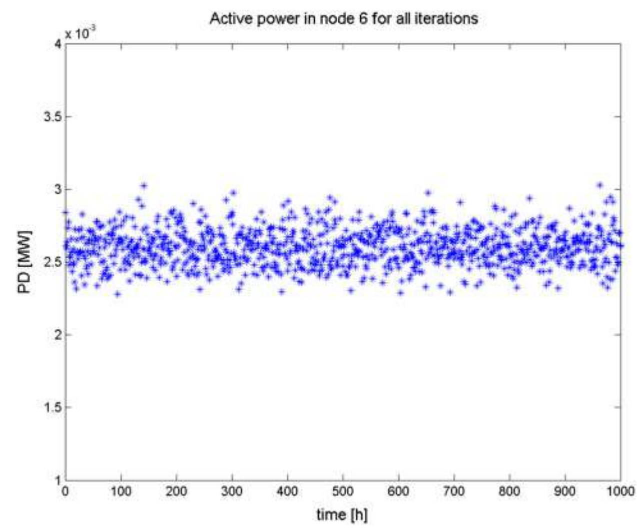

Fig. 6 Active load duration curve for the node 6

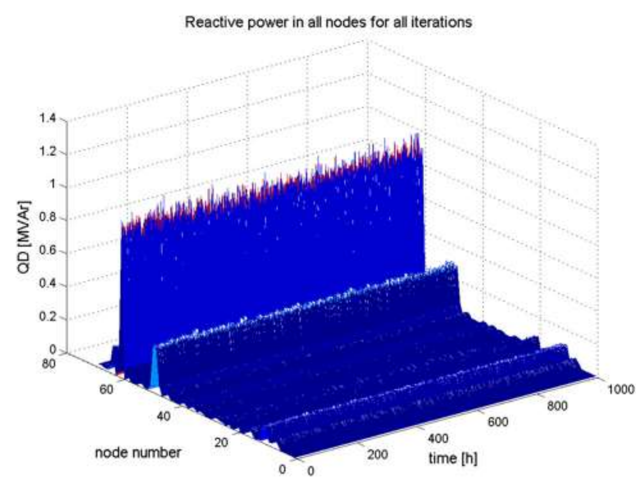

Fig. 7 Reactive load duration curve for the whole network

Then the sensitivity analysis is conducted. From Fig. 4a., it can be concluded that the most visited nodes for placing the wind generators are the node 16 and the node 40, so they are chosen for the further programme runnings. From Fig. 4b. to f., it can be observed that the same holds for the nodes 21 and 60 for the capacitor banks; they are picked for the capacitors (600 and 900 kVAr, respectively; in order not to be overcompensated). The assumption for choosing fixed nodes for the allocation of the wind generators and the fixed capacitor banks is fairly reasonable but not exactly precise. This is what we call Monte Carlo graphical method.

Subsequently, the programme is run the next 1008 times but with another initial conditions (the nodes 16 and 40 for the wind generators and 21 and 60 for the 600 and 900 kVAr capacitors, when allocating capacitor banks the 0 node is not counted). In this case, following graphics are obtained for analyzed four scenarios depicted later. Figures 5, 6, 7, 8 show active and reactive load duration curve for the whole network and for the node 6.

Active load varies in accordance with Gauss distribution, oscillating round its mean value. For randomly chosen node 6, it is 2.6 kW [30]. The same holds for the reactive load (reactive load in node 6 equals 2.2 kVAr). The wind turbines power vs hour curve for nodes 16 and 40 is presented in Fig. 9. The wind turbines power changes with Weibull probabilistic curve.

Following scenarios have been analyzed:

Scenario 1 is when no switching scheme is performed,
Scenario 2 is when only reconfiguration is performed,
Scenario 3 is when only compensation with the certain capacitor banks is performed and
Scenario 4 is when reconfiguration and compensation are performed simultaneously.

Using above-mentioned switching scheme, the delivered electrical energy saving cost $ENERGY_i$, operational indices $TVPI_i$ and $TPLI_i$ and cost of commutations are obtained and presented in Table 2, for 1008-h operation. In addition to these features in the same table, limiting values for the input power factor ($\cos\varphi$), the input reactive power (Q_{input}) and the minimal voltage ($V_{\min}$) are given.

The delivered electrical energy saving cost $ENERGY_i$ is best in scenario 4 (484,580$) which is completely reasonable because quality of the network depends on penetrated wind generators and capacitor banks. The best $TVPI_i$ is for scenario 4 and the worst for scenario 1 as scenario 4 has the best performing characteristics. The best $TPLI_i$ is for scenario 4 and the worst for scenario 1 with the same reasoning as in the previous sentence.

Final cost is the best in scenario 4. Then comes scenario 2. It is worse in the scenario 3 and of course maximum is for

Table 2 *ENERGY*$_i$, *TVPI*$_i$, *TPLIi*, cosφ, Qinput, Vmin and the cost of commutations for 1008-h operation

Scenario	*ENERGY*$_i$ ($)	*TVPI*$_i$	*TPLI*$_i$	cosφ	Qinput (MVAr)	Vmin (p.u.)	The cost of commutations
1	0	1	1	0.8 < cosφ < 0.82	2.4 < Qinput < 3	0.891 < Vmin < 0.921	–
2	446,100 (323,306)	0.5852	0.4598	0.775 < cosφ < 0.81	2.4 < Qinput < 3.3	0.93 < Vmin < 0.951	2506 (125,300)
3	59,042	0.7637	0.6843	0.95 < cosφ < 0.97	0.8 < Qinput < 1.25	0.91 < Vmin < 0.939	–
4	484,580 (340,814)	0.3804	0.3171	0.925 < cosφ < 0.97	0.8 < Qinput < 1.8	0.955 < Vmin < 0.972	2934 (146,700)

Cost per commutation 50$ [15]

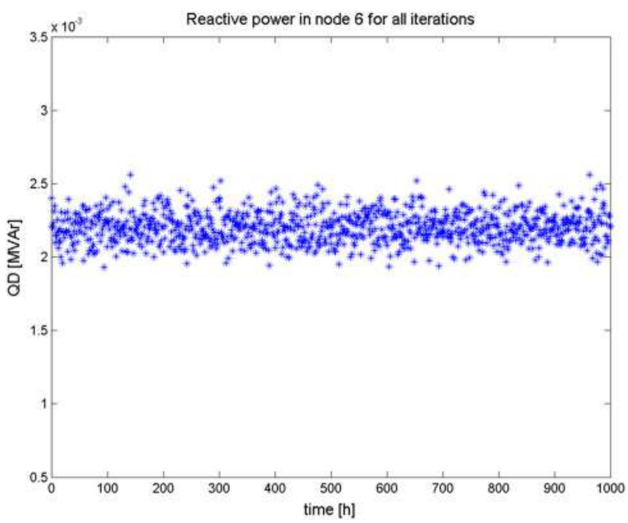

Fig. 8 Reactive load duration curve for the node 6

scenario 1 which is to be expected. Commutations alone are cheaper than compensation (scenario 3) as losses have more impact on final price than placing of capacitors. From Fig. 10, it is obvious that the 4-th scenario is the cheapest. Savings are the best for scenario 4 (simultaneous reconfiguration and compensation). They are greater for the reconfiguration alone than for compensation for the above-mentioned reason. The savings in regard of commutations price are less than presented, in the worst case for the amount of 10 times the commutation cost (the greatest amount of commutations per one hour interval equals 5 closings and 5 openings). There are no savings in scenario 1 as it is the basic one used for the comparing. Savings are presented in Fig. 11.

Input power factor (cosφ) is the best when only capacitors are switched to the network and little worse for the 4-th scenario in which reconfiguration accompanies capacitor banks showing that capacitors alone have the most impact on input power factor. It is worth noticing that cosφ is less in scenario 2 than in the basic case which is not expected. It could be seen from Fig. 12. Compensation alone has the strongest impact on input reactive power and it is the least in the 3-rd scenario, as it is shown in Fig. 13. The input reactive power

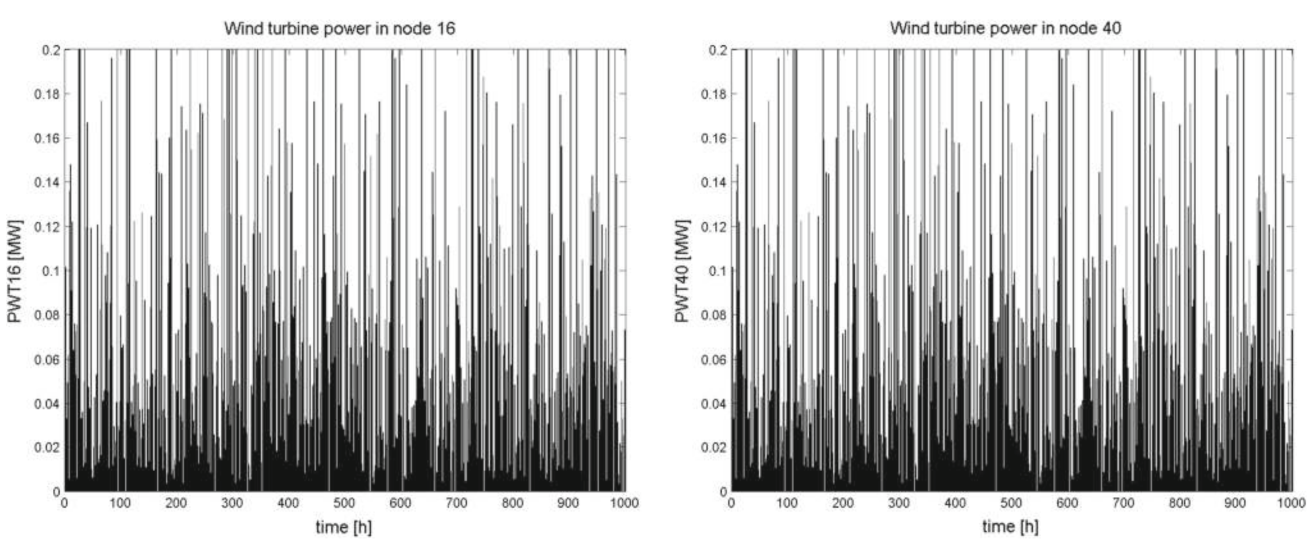

Fig. 9 The wind turbine power for node 16 and 40

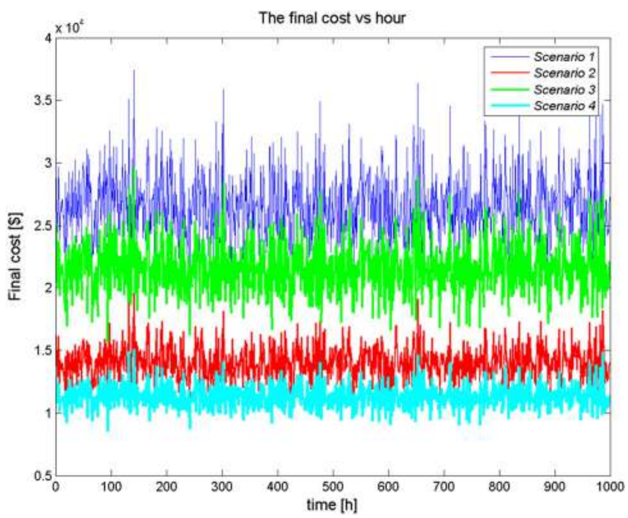

Fig. 10 The final cost vs hour curve

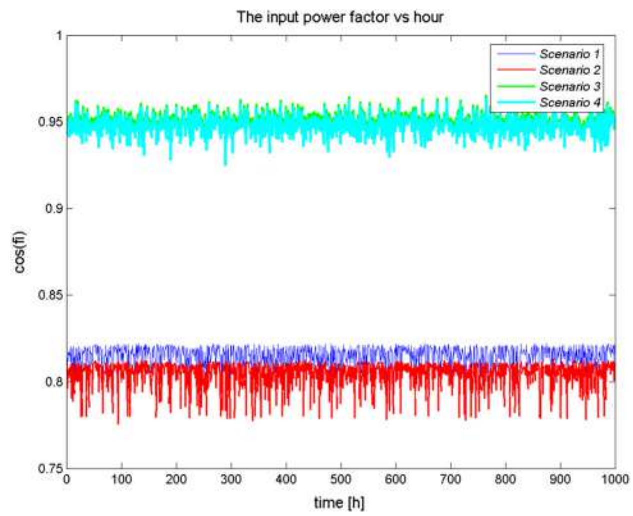

Fig. 12 The input power factor (cosφ) versus hour curve

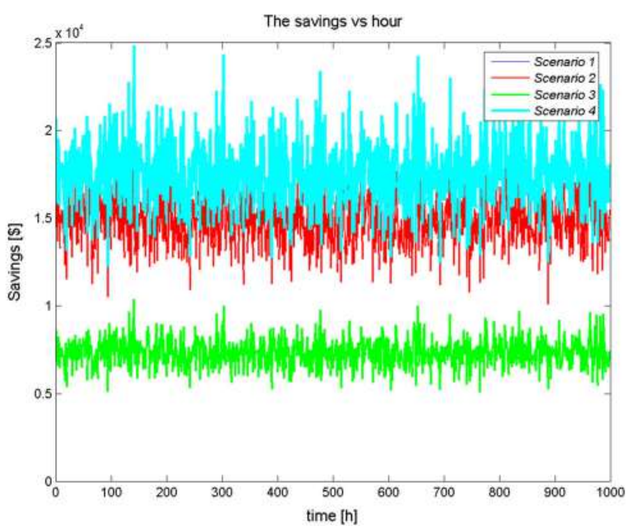

Fig. 11 The savings vs hour curve

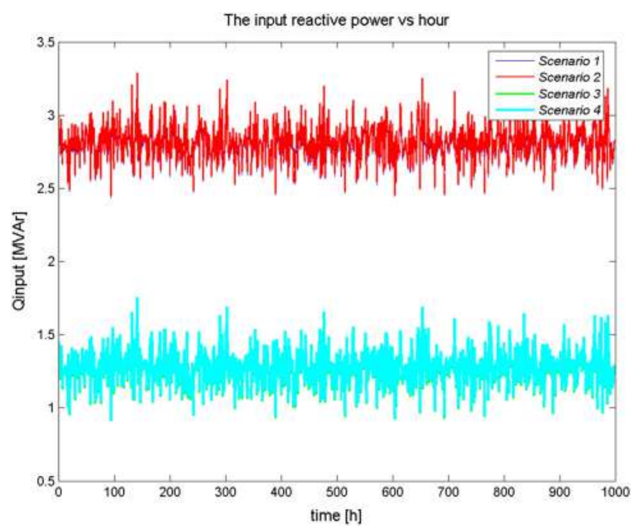

Fig. 13 The input reactive power versus hour curve

for scenario 3 and 4 as well as for cases 1 and 2 is almost the same which is reasonable as the capacitors result in lower input reactive power.

The best lowest voltage occurs in the 4-th scenario and is slightly less in the 2-nd scenario. In the scenario 4, it is above 0.95 p.u. so that on load tap changer on substation transformer can be avoided which is not the case in [16]. As per National Electrical Code (NEC), allowable voltage drop is 5% at the furthest node. This is shown in Fig. 14. The final voltage profile is better than the initial one. Compliance with standard regulations, for the lowest voltage, is obtained only for the 4-th case. Figure 15 represents the active power losses. The lowest power loss occurs in 4-th scenario and is slightly higher in scenario 2 which shows considerable impact of simultaneous reconfiguration and capacitor switching on them. Reconfiguration is better for losses than compensation case. The final losses are much lower than the initial ones. The quality of network is expressed with the voltage profile index. The best index occurs for scenario 4 (Fig. 16). This outcome is reasonable as the best performance of the network is achieved in 4-th case when capacitors and wind generators operate simultaneously. The supply interruption cost is lowest in the scenario 4, almost the same in scenario 2 and worse for the remaining scenarios 3 and 1 (Fig. 17). This parameter is closely related to the current values and for this reason it is almost the same for the cases 4 and 2 as well as for 3 and 1.

Important remark for the Figs. 10, 11, 12, 13, 14, 15, 16, 17 is that variables on them oscillate round their expected mean values. This is direct consequence of Gaussian changing load in the network nodes. Figures 18, 19 show that number of commutations on each network branch does not exceed 6

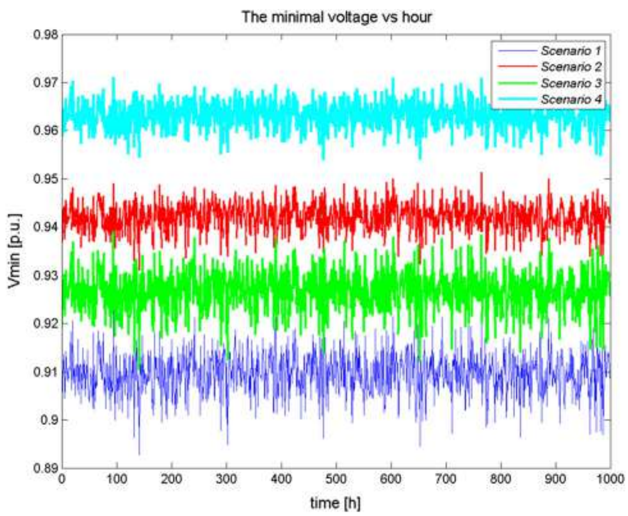

Fig. 14 The minimal voltage versus hour curve

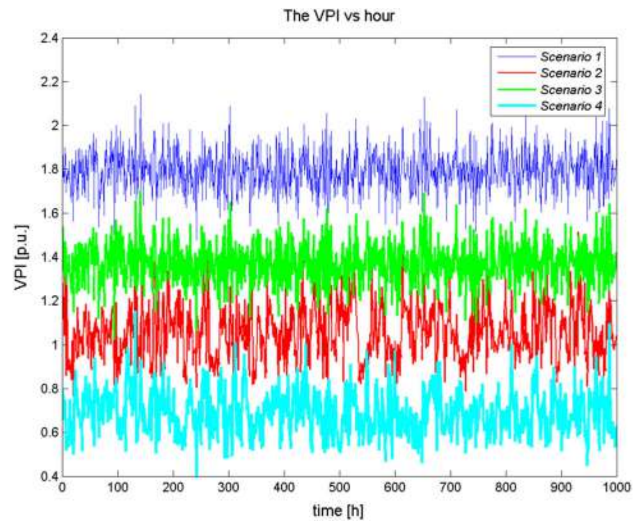

Fig. 16 The VPI versus hour curve

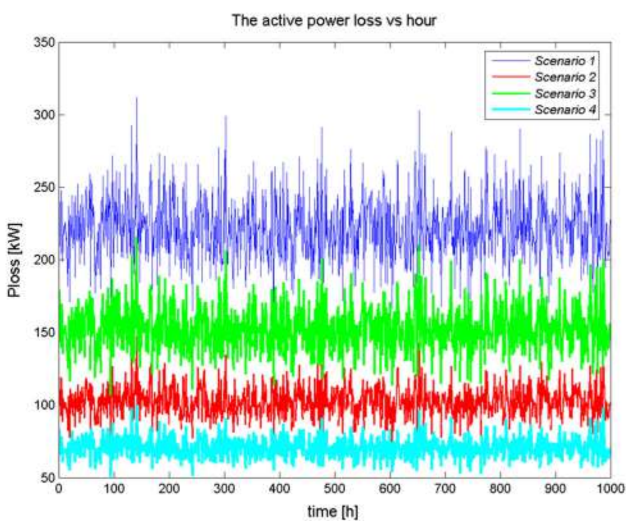

Fig. 15 The active power loss versus hour curve

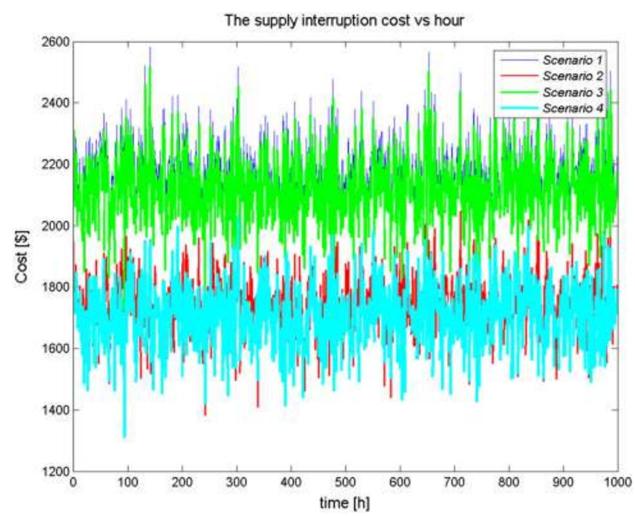

Fig. 17 The supply interruption cost vs hour curve

in 24 h. Two presented branches are randomly chosen (69 and 71) for the time period of 100 h (scenario 4). It is worth noticing that the sum of switching numbers (openings) of the branches when reconfiguration is applied amounts to 5040 (1008 h of operation, for each hour 5 openings). All initial configurations have open branches 69, 70, 71, 72 and 73 (Fig. 2), when no switching operation is implemented. The programme duration for 1008-h simulation (total number of iterations is 3024000) for the most demanding scenario 4 lasts 23 h (CPU) which is approximately 2.3% of the planning period. The branches 1–7, 21–39, 41, 42, 44, 46–52, 58–60, 64–68 and 72–73 (scenario 2), 1–7, 21–35, 38, 40–43, 46–52, 58–60, 64–68 and 72–73 (scenario 4) are never opened so that the switches on them can be omitted bringing additional savings.

9 Discussion

The advantages of reconfiguration and capacitors allocation with penetration of distributed generators have been recognized by the authors throughout the years. They resort to single or multi-criteria optimization with different components of the objective function. Of course, multi-objective functions are the best solution [10, 11, 13–23, 26, 38]. For clarity sake, the comparison between the proposed and algorithms explained in other research papers is presented in Table 3. A tabular approach of analysis of important articles from the subject area with the same evaluation parameters given by the authors of the reference [15] was applied.

The ordinal number of the reference is given in the first column of Table 3. Comparison was made according to follow segments: Loss reduction (LR), Reliability improvement

Table 3 Review of the previous literature in the field of reconfiguration and compensation in the presence of distributed-generators according to the parameters dealt with in the articles

Ref	LR	RI	VS	VP	EI	LB	CP	LM	DGP	Optimization method
[1]	x			x		x	x		x	Fuzzy ACSA
[6]	x					x				Branch exchange
[7, 8]	x									SA
[9]	x									Merlin and Back
[10]	x			x			x		x	Improved PSO, GA, CSO
[11]	x		x			x	x		x	Non-dominated sorting GA (NSGA-II)
[12]	x						x		x	GA, natural selection
[13]	x				x		x		x	GA, Kruskal deterministic algorithm
[14]	x		x				x		x	GA
[15]	x			x	x		x	x	x	ACSA, HSA
[16]	x			x	x		x		x	Gravitational search algorithm (GSA), GAMS
[17]	x		x				x		x	Modified flower pollination algorithm MFPA
[18]	x				x		x	x		Sensitivity analyses and system state characterization
[19]	x				x		x			Modified PSO
[20]	x				x		x			Modified dedicated GA
[21]	x				x		x	x		Mixed integer non-linear programming
[22]	x	x			x		x	x	x	GA
[23]	x		x		x					GA
[24]	x						x		x	HSA
[25]	x						x	x	x	BFA
[26]	x			x		x	x		x	Hybrid approach of HSA, particle artificial bee colony algorithm PABC
[27]	x						x		x	Success history-based parameter adaptation technique of DE
[29]	x			x						OPF and PSO
[30]	x						x			SA and GA
[38]	x				x			x		Lagrange relaxation
Proposed	x			x	x		x	x	x	SA, Monte Carlo graphical method, proposed algorithm

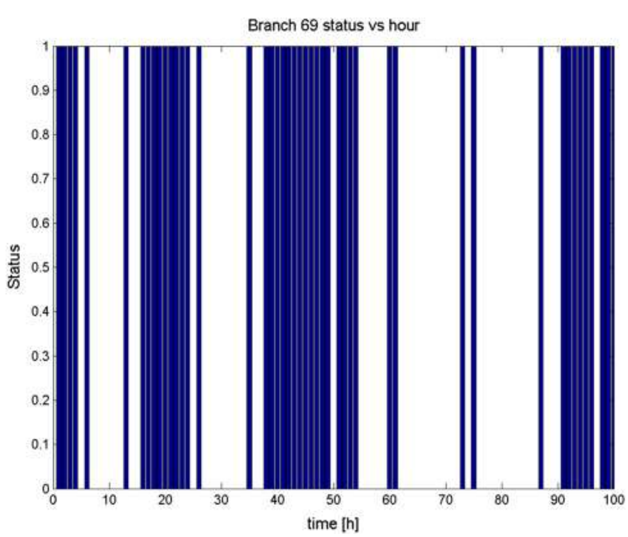

Fig. 18 Switch status changes in 100 h time optimization period for branch 69—scenario **4**

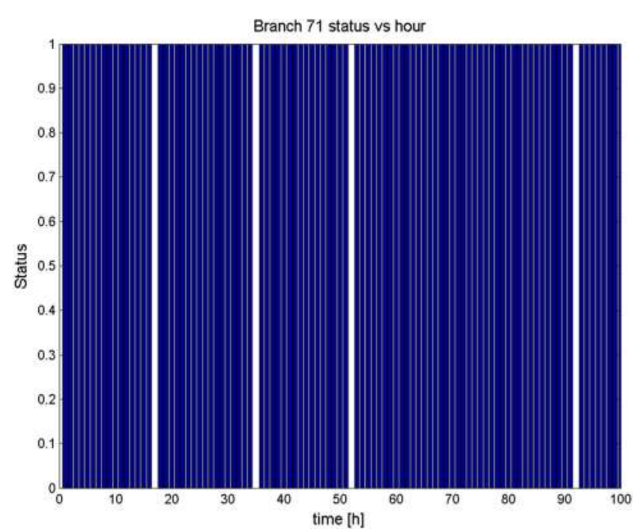

Fig. 19 Switch status changes in 100 h time optimization period for branch 71—scenario **4**

(RI), Voltage stability (VS), Voltage profile (VP), Economical issues (EI), Load balancing (LB), Capacitor placement (CP), Load model (LM), DG presence (DGP).

As it can be seen, the proposed algorithm addresses the problem considerably compared with mentioned papers with the similar topic.

10 Conclusions

In this paper, the distribution network reconfiguration with simultaneous capacitor switching, in the presence of wind generators, by SA is presented. IEEE 69 bus network is analyzed which has 69 nodes including the slack one and 73 branches, all of which can commutate. Performed computer simulations show that simultaneous reconfiguration and capacitor switching in the presence of wind generators after sensitivity analysis and allocating nodes for their switching achieves considerable savings. They keep changing within the one-hour operation periods and cannot be summed up. The final cosφ for some scenarios is greater than 0.85 and the initial is less. With two capacitor banks of 600 and 900 kVAr in the nodes 21 and 60, the network is not overcompensated. The final voltage profile is better than the initial one. For one scenario (4), minimal network voltage is greater than 0.95 p.u. so that the on load tap changer in slack node transformer is not necessary which leads to additional saving. The final losses are much better than the initial ones. The considerable saving in the delivered electrical energy is obtained. With the 2.3% programme running time of the planning period duration (1008 h), the developed programme can be adopted for the planning stage. Some branches are never opened so that the switches on them can be omitted bringing additional savings. It could be concluded that the obtained results presented on the figures confirm validity of applied Monte Carlo graphical method performed by means of simulated annealing algorithm.

References

1. Tolabi HB, Ali MH, Rizwan M (2014) Simultaneous reconfiguration, optimal placement of DSTATCOM, and photovoltaic array in a distribution system based on fuzzy-ACO approach. IEEE Trans Sustain Energy 6(1):210–218
2. Chiang HD, Wang JC, Cockings O, Shin HD (1990) Optimal capacitor placements in distribution systems: part 1: a new formulation and the overall problem. IEEE Trans Power Delivery 5(2):634–642
3. Chiang HD, Wang JC, Cockings O, Shin HD (1990) Optimal capacitor placements in distribution systems: part 2: solution algorithms and numerical results. IEEE Trans Power Delivery 5(2):643–649
4. Stojanović B (2004) Applying simulated annealing in general capacitor placement problem in large scale symmetrical radial distribution networks, ELEKTROPRIVREDA, No. 3, 35–49. paper in Serbian
5. Stojanović B (1997) Simulated annealing method and its application to capacitor placement problem in radial distribution networks, Master thesis in Serbian, University of electrical engineering, Belgrade, 96 pages (basic part)
6. Baran ME, Wu FF (1989) Network reconfiguration in distribution systems for loss reduction and load balancing. IEEE Trans Power Delivery 4(2):1401–1407
7. Chiang HD, Jumeau RJ (1990) Optimal network reconfigurations in distribution systems: part 2: solution algorithms and numerical results. IEEE Trans Power Delivery 5(3):1568–1574
8. Chiang HD, Jumeau RJ (1990) Optimal network reconfigurations in distribution systems: part 1: a new formulation and a solution methodology. IEEE Trans Power Delivery 5(4):1902–1909
9. Shirmohammadi D, Hong HW (1989) Reconfiguration of electric distribution networks for resistive line losses reduction. IEEE Trans Power Delivery 4(2):1492–1498
10. Kanwar N, Gupta N, Niazi KR, Swarnkar A (2015) Improved metaheuristic techniques for simultaneous capacitor and DG allocation in radial distribution networks. Int J Electr Power Energy Syst 73:653–664
11. Gallano RJ, Nerves AC (2014) Multi-objective optimization of distribution network reconfiguration with capacitor and distributed generator placement. In: TENCON 2014–2014 IEEE Region 10 Conference 2014 Oct 22 (pp 1–6), IEEE
12. Rugthaicharoencheep N, Nedphograw S, Wanaratwijit W (2011) Distribution system operation for power loss minimization and improved voltage profile with distributed generation and capacitor placements, In 2011 4th International conference of electric utility deregulation and restructuring and power technologies (DRPT) (pp 1185–1189), IEEE
13. Montoya DP, Ramirez JM (2013) A joint application of a genetic algorithm plus the minimal spanning tree for optimizing electrical energy systems. In: 2013 North American Power Symposium (NAPS), pp 1–6, IEEE
14. Saonerkar AK, Bagde BY (2014) Optimized DG placement in radial distribution system with reconfiguration and capacitor placement using genetic algorithm. In 2014 IEEE international conference on advanced communications, control and computing technologies, pp 1077–1083, IEEE
15. Ameli A, Ahmadifar A, Shariatkhah MH, Vakilian M, Haghifam MR (2017) A dynamic method for feeder reconfiguration and capacitor switching in smart distribution systems. Electr Power Energy Syst 85:200–211
16. Murty VVVSN, Sharma AK (2018) Optimal coordinate control of OLTC, DG, D-STATCOM, and reconfiguration in distribution system for voltage control and loss minimization. Int Trans Electr Energy Syst. Accepted 27 Sept 2018, pp 1–27
17. Ganesh S, Kanimozhi R (2018) Meta-heuristic technique for network reconfiguration in distribution system with photovoltaic and D-STATCOM. IET Gener Transm Distrib 12(20):4524–4535
18. Lin Y, Zhizhong G (2008) Comprehensive optimization for energy loss reduction in distribution networks. IEEE, 8 pp
19. Rezaei P, Vakilian M (2010) Distribution system efficiency improvement by reconfiguration and capacitor placement using a modified particle swarm optimization algorithm. In: Proceeding of electric power and energy conference (EPEC), p 6
20. Guimaraes MAN, Castro CA, Romero R (2010) Distribution systems optimization through reconfiguration and capacitor allocation by dedicated genetic algorithm. IET Gener Transm Distrib 4(11):1213–1222
21. De Oliveira LW, Carneiro Jr S, De Oliveira EJ, Pereira JLR, Silva Jr IC, Costa JS (2010) Optimal reconfiguration and capacitor allocation in radial distribution systems for energy loss minimization. Electr Power Energy Syst 32: 840–848
22. Salehi J, Oskuee MRJ, Amini A (2017) Stohastics multi-objective modeling of simultaneous reconfiguration of power distribution

network and allocation of DG's and capacitors. Int J Ambient Energy, p 15
23. Hayfa S, Omar K, Hsan HA (2019) Multi-objective distribution network reconfiguration optimization problem. Electr Eng. Accepted 7 Feb 2019
24. Pawar B, Kaur S, Kumbhar GB (2016) An integrated approach for power loss reduction in primary distribution system. In: 2016 IEEE 6th international conference on power systems (ICPS) 2016, Mar 4 (pp 1–6), IEEE
25. Mohammadi M, Rozbahani AM, Bahmanyar S (2017) Power loss reduction of distribution system using BFO based optimal reconfiguration along with DG and shunt capacitor placement simultaneously in fuzzy framework. J Central South Univ 24(1):90–103
26. Muthukumar K, Jayalalitha S (2017) Integrated approach of network reconfiguration with distributed generation and shunt capacitors placement for power loss minimization in radial distribution networks. Appl Soft Comput 52:1262–1284
27. Biswas PP, Suganthan PN, Amaratunga GA (2018) Distribution network reconfiguration together with distributed generator and shunt capacitor allocation for loss minimization. In: 2018 IEEE congress on evolutionary computation (CEC), pp 1–7, IEEE
28. Zimmerman RD, Murillo-Sanchez CE (2016) MATPOWER 6.0 User's Manual, p 205
29. Lindenberg IS., Edmarcio AB., Cassio G., Ivo CSJ. Reduced search space combined with particle swarm optimization for distribution system reconfiguration. Electr Eng. Accepted 3 Nov 2020
30. Jiang D (1994) Electric distribution system reconfiguration and capacitor switching, Master thesis, Worcester Polytechnic Institute, p 77
31. Lavorato M, Franco JF, Rider JM, Romero R (2012) Imposing radiality constraints in distribution system optimization problems. IEEE Trans Power Syst 27(1):172–180
32. Wright P (2000) On minimum spanning trees and determinants. Math Mag 73(1):21–28
33. Kirkpatrick S, Gelatt CDJ, Vecchi MP (1982) Optimization by simulated annealing, IBM research report RC 9355
34. Kirkpatrick S, Gelatt CDJ, Vecchi MP (1983) Optimization by simulated annealing. Science 220:671–680
35. Černy V (1985) Thermodynamic approach to the travelling salesman problem: an efficient simulation algorithm. J Optim Theory Appl 45:41–51
36. Stojanović B, Rajić T (2017) Novel approach to reconfiguration power loss reduction problem by simulated annealing technique. Int Trans Electr Eneg Syst e2464. https://doi.org/10.1002/etep.2464
37. Nahman J, Perić D (2008) Optimal planning of radial distribution networks by simulated annealing technique. IEEE Trans Power Syst 23(2):790–795
38. Kovački N, Vidović P, Sarić A (2018) Scalable algorithm for the dynamic reconfiguration of the distribution network using the Lagrange relaxation approach. Electr Power Energy Syst 94:188–202