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Distribution network reconfiguration and reactive power compensation using a hybrid Simulated Annealing – Minimum spanning tree algorithm

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ABSTRACT

Change of the climate, environmental pollution and lack of classical energy sources forced many countries to address renewables. In modern strategies of smart distribution network reconfiguration should be applied in order to minimize power losses and economic costs. Also, capacitors switching (placement of shunt capacitors) and presence of distribution generation are always incorporated in modern networks. Further, On Load Tap Changer in the supplying substation has to be used. Simulated Annealing and Minimum spanning tree algorithms work separately in order to find the best appropriate solution. The main goals are minimization of power losses and costs. In addition, many constraints are attended to find the hourly reconfiguration and capacitor banks position. Distributed generators involve both wind generators and solar panels. Two methods described in literature are mixed and implemented for locating fixed nodes for distributed generators. Gauss and Weibull changing nodal loads and wind generators output respectively, as well as daily load curves for working and weekend day with insolation of solar panels are included in analysis. Per unit load diagrams are determined according to real one-year measurement results in one substation in Belgrade, Serbia. IEEE 69 bus network is analyzed. The main contribution of exposed research is near optimal solution for wide time range, realistic network operation/planning forecast (stochastic variation of consumption and production on hour basis) with satisfaction of all technical constraints that are minimum and maximum nodal voltages, limiting feeder's capacities and not-overcompensation of the network, accompanied with elaborate economic background.

1. Introduction

Distribution network reconfiguration is a current problem that electrical engineers are struggling with. First, it is necessary to find the most optimal configuration and define objective functions and constraints as well. Power losses are emphasised in distribution network because of the feeder's parameters, so the authors of recent papers focused on them. On the other hand, economic costs rely and directly depend on losses. Further, this is the reason why power losses are an urgent problem for network organization. The first issue is the radiality and connectivity of distribution network. Apparently, modern researches and literature obtain different solutions for solving this problem. Some of them are focused on heuristic approach [1,2], or metaheuristic instead [3,4]. Some of them rely on artificial [5,6] or finally mathematical methods [7,8]. Papers give both single-objective and multi-objective optimization functions instead. Mixed integer nonlinear programming approach by taking into account different levels of consumption during the day [9], *meta*-heuristic bee algorithm [10] or multi-criteria objective function analyzed by fuzzy technique [11] are some of them. This paper considers distribution networks and their utilization. Modelling of different power system elements such capacitor banks and renewable sources and their implementation in this kind of networks are presented.

A great number of solutions have no possibilities to consider so many constraints during the calculation. The real networks include changeability of demand, presence of distributed generators (DG), optimal position and power of capacitor banks and number of switching equipment commutations as well. Some authors involve unbalanced loads, which is a step further [12].

This paper explains a new optimal solution calculation using combination of Simulating Annealing technique (SA) [13] and Minimum spanning tree algorithm (MST). The advantage of the presented idea is not only concentration on power losses, but also a wide economic analysis consideration. Speaking about economic issue is extraordinary

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topic for both producers and consumers. Hence, great number of circumstances has to be analyzed. In addition, switching equipment commutations costs are some of them. This is rarely included in optimization calculations in recent papers [8]. Thus, the number of commutations is often neglected, which is wrong. With an increased number of manipulations, the equipment faster deteriorates and needs to be replaced earlier. By limiting the number of manipulations, the life of equipment is extended. Within the SA algorithm, a limitation of manipulations per day is implemented.

In order to reach the best reconfiguration solution, usage of capacitor banks and static compensators has not been avoided using multi-objective decision function [14]. The elitist non-dominant sorting genetic algorithm (NSGA-II) and the fuzzy concept are implemented for the purpose in [15]. Price of the installed equipment is not shown, reconfiguration with penetration of renewables and capacitors is implemented [16] and only static compensators are analyzed [17]. Reactive power compensation has distinguished benefit. Obviously, the economic aspect imposes costs of these compensation tools. The paper offers optimal solution for capacitor banks power and node position including their cost with minimum power losses. Hence, this leads to greater power factor value and lower losses. In this paper, the SA algorithm is adapted for calculation and optimal placement of capacitor banks in the network, as well as their required power.

Research focused on new technologies like renewable ones and their impact in changing power systems. The presence of the renewables is implemented in the paper. More often, the papers discussed many network reconfiguration solutions with penetrated renewables [18,19]. Some of them consider just wind turbines [20], the others solar panels [21], but rarely both wind and solar renewables at the same time [22]. This research discussed both mentioned distributed types. Weibull distribution defines velocity density.

Recent references show that distribution engineers keep finding new aspects of network optimization in both the exploitation and planning phases. Set of data and test system which can not be found in previous literature representing European style distribution grids in contrast to North American ones are presented [23] that can be very useful for European distribution network engineers. This paper tries to implement real measurements to model load changeability also. State-of-the-art analyses for planning of distribution networks with high-penetration of renewables and dynamic loads are exposed in [24]. In present time tendency exists of “moving towards a more sustainable and decarbonized future that supports higher penetration of clean and renewable sources“. Planning process is made difficult on account of uncertainty at both supply and demand side. Neglecting economic side of the problem is knowledge gap of undertaken analyses, mostly.

In this research IEEE network is analyzed with 69 nodes and 73 branches. Further, which is also avoided in recent literature, hourly demand changeability is considered as well. For sure, demand is changeable so the reconfiguration should follow this inconsistency [25]. This paper gives an hourly reconfiguration solution. Changeability of daily demand diagram is adopted according to real one-year measurement results in one substation in Belgrade, Serbia.

MST uses branch-weighting factors and shows excellent speed and accuracy for changing network reconfiguration during the simulation. SA has proven to be very grateful for a great number of implementations of constraints and additional considered factors. The newly formed hybrid algorithm provides the most favourable configurations at the hourly level, taking into account all the mentioned factors and limitations.

Highlights of the research representing findings/novelties/contributions are:

- Stochastic change of the consumption in the network nodes (Gaussian distribution),
- Stochastic change of wind generators output (Weibull distribution),

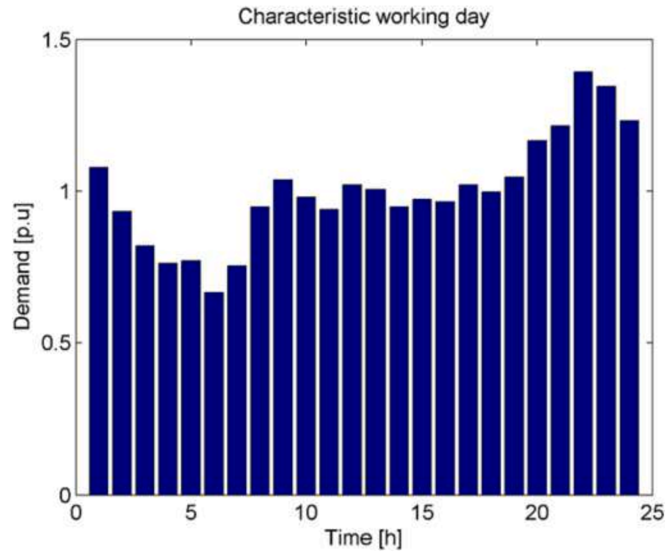

Fig. 1. Typical load curve of working day.

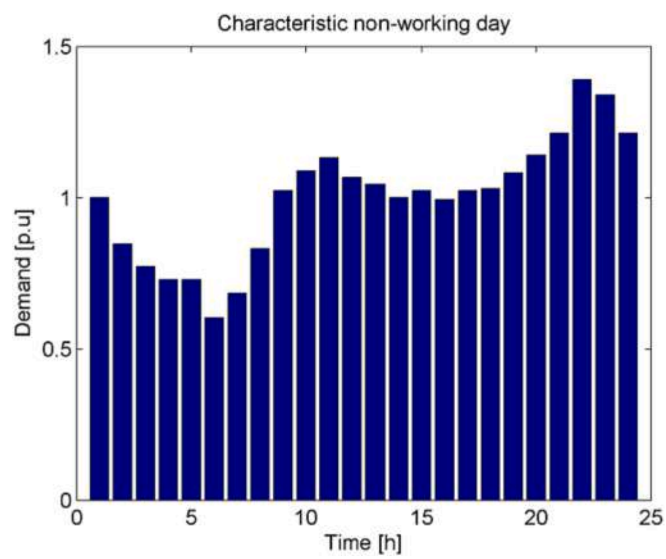

Fig. 2. Typical load curve of non-working day.

- Uniform distribution of wind generators to the nodes in the first stage of algorithm application,
- Inclusion of the On Load Tap Changer (OLTC) in the slack node,
- Achieving of input power factor>0.85,
- Multi objective function that includes besides maximum power loss in the whole range of investigated period (power loss varies every hour in the scope of 1008 h) and capacitors price, also the cost of electric energy losses, of undelivered energy and commutations,
- Limiting the number of commutations in 24 h per single switch,
- Using Monte Carlo method and heuristic method for most valuable position of distribution resources,
- Implementing Minimum spanning tree algorithm to reconfiguration problem previous to the compensation by Simulated Annealing,
- Inclusion of daily load curves for working and non-working days,
- Taking daily insolation of solar panels, in the most loaded nodes, into account and
- Wide range of network operation/planning forecast with satisfaction of all technical constraints (minimum and maximum voltages, limiting feeders’ capacities and not-overcompensation of the network).

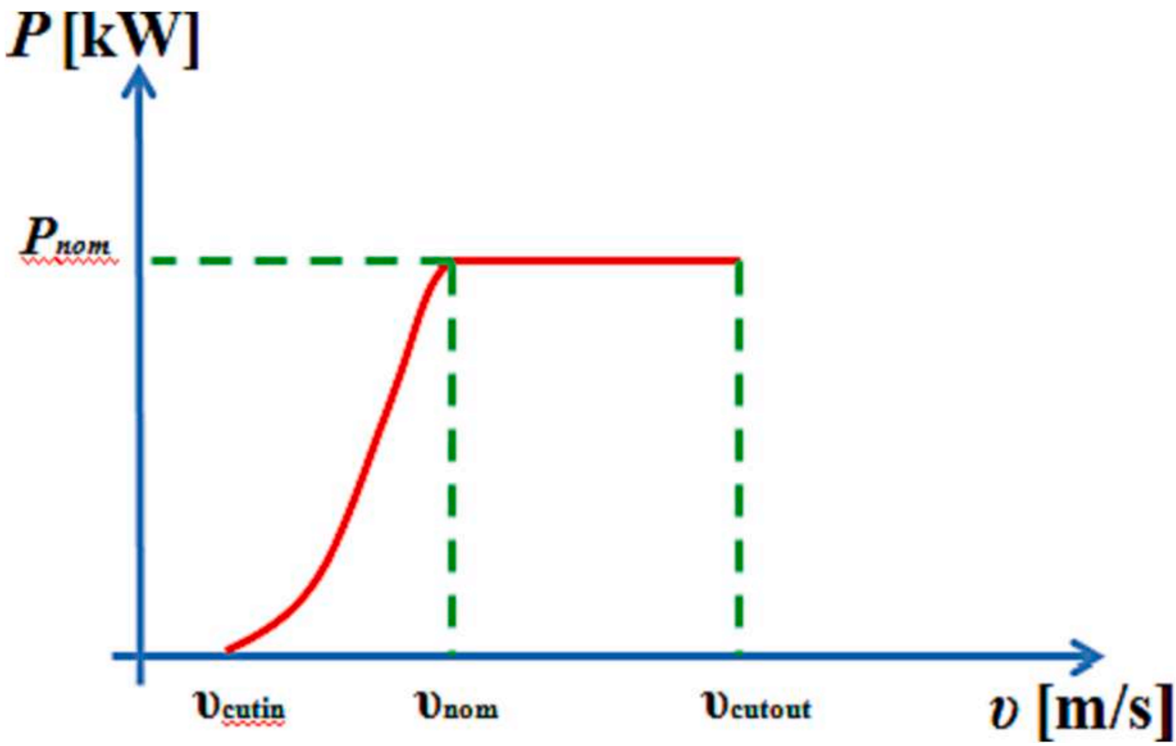

Fig. 3. Active power of wind turbine.

2. Changeability of consumption power, wind speed and solar irradiation

In modern research, consumption is always constant. Thus, this is definitely unusual in practice. Load diagrams during the day are useful information for network reconfiguration issues. This paper tackles this problem. There is determination of the characteristic work and weekend days for some town consumption. Dominant consumption includes homes and places for living. In addition, all these diagrams were results of one-year measurements in a specific town substation in Belgrade, Serbia. All demands for one characteristic day are scaled to nominal power of station transformer. Measurements are divided in hour resolution. Thus, there are 24 results for characteristic working or non-working day instead. Figs. 1 and 2 represent these characteristic days for specific demand.

Since, there are not all 8760 measurements during the year, but only characteristic diagrams, some assumptions were adopted. Random number generator made uncertainty of the consumption. Using Gauss-Laplace distribution, changing of demand is adopted for every single hour. In other words, every relative hour demand oscillates around characteristic value by mentioned distribution. This leads to different daily load shapes (Monday, Tuesday, etc). Probability rule is given in accordance with equation (1):

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

Where:

x – stochastic variable denoting a probable value of consumption in respective network node,

m – expected consumption value in one node and

σ – standard deviation, deviation from expected value.

For σ, 10 % is considered.

Test network was IEEE 69 bus network (69 nodes and 73 branches). The total active and reactive load of tested network amounts to 3802 kW and 2694 kVAr respectively. Nominal nodal loads are given in absolute values. Typical load values (measurements) are given in per unit. Thus, absolute values should participate in the load flow calculation. Product of relative values and nominal load values in every 69 nodes gives appropriate demand for calculation. This means the nominal demands are different from hour to hour and shape during the day is close to realistic one. Uncertainty of load provides more realistic demand, which is very important for power loss determination.

The paper deals with renewable sources and their integration in distribution network. These circumstances could not be neglected in modern research. Renewables are the most important part of distribution systems especially from gas emission point of view, for sure. This research considered presence of both wind generators and solar panels.

In urge to make a more realistic scenario, Weibull distribution for wind generators is of interest. Power generated from wind turbine depends of wind speed. 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 equation (2)

$$f(\nu) = \frac{k}{A}\left(\frac{\nu_{mean}}{A}\right)^{k-1} e^{\left(-\left(\frac{\nu_{mean}}{A}\right)^{k}\right)} \tag{2}$$

Where:

ν_{mean} – mean value of the 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 following values are adopted $v_{mean} = 5.31$ m/s, $A = 6$ m/s and $k = 2$.

The output depending on wind speed is given in Fig. 3. For nominal power of wind turbine 0.2 MW is adopted. This is very low value for real wind turbines, but it was adopted in order to be proportional with nominal power demand.

For wind speed lower than υ_{cutin}, there is no generated power. If speed is between υ_{cutin} and υ_{nom}, power will be determined according to

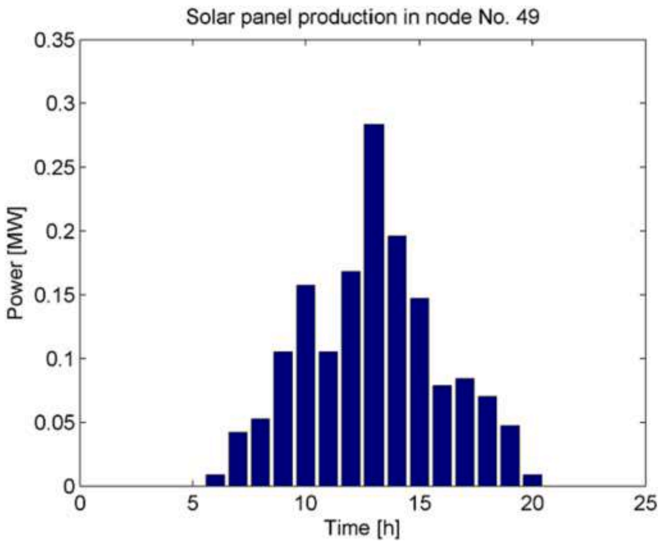

Fig. 4. Insolation of the solar panel attached to node 49.

υ^3 (υ is wind speed). Finally, power is equal to nominal power for all speeds between υ_{nom} and υ_{cutout}. For higher values, wind turbine is cut out for avoiding mechanical damages. Random number generator makes uncertainty wind speed in every single step of simulation.

Solar panels are also considered. Ideal solar irradiation is adopted for one day. It means a symmetrical diagram. Cloudy weather conditions lead to uncertainty. In that way, cloudiness is included in calculation. This leads to more realistic scenario when irradiation diagram is not the same for every day. Fig. 4 represents solar radiation for one random day used in simulation. It assumes that solar panel is located in node 49 and nominal power is 300 kW. Insolation per day is maximal at 1p.m. It varies from symmetrical curve within range of 0 to 10 % every hour because of daily cloudiness, representing the realistic situation. During the night solar panel production is zero.

With such modelling of consumption for wind turbines and solar panels, more realistic scenario (compared to other papers) is achieved.

2.1. Location of the renewables

As already mentioned before, renewable resources are present in the network. There are two wind generators and two solar panels. It is supposed that all of them belong to same geographical area, so the same wind speed and solar irradiation are adopted for both wind generators and both solar panels. Two different ways for renwables locations are used, one for wind generators and another for solar panels. Wind generator locations (nominal power 200 kW each) determined by Monte Carlo graphical method are in nodes 34 and 66 [13]. The second way is mathematical one [26]. Solar panel in node 49 is of 300 kW power and in the node 61 of 500 kW. These power values are introduced in the closing to the feasible solution procedure. All these locations are fixed during the optimal procedure.

3. Applied Simulated Annealing method and Minimum spanning tree algorithm

Minimum power loss should be achieved for as much as possible realistic scenario. Two calculation types are implemented for finding optimal solution. One is Minimum spanning tree algorithm (MST) and another is Simulating Annealing method (SA). This paper describes the idea of finding both optimal installation power and location of capacitors banks. The result is the appropriate reconfiguration and minimum power loss for each hour, considering changeable demand, wind speed and solar irradiation.…

The MST treats network as graph with branch weighing coefficients that represent negative branch current values of the completely meshed network. The result is a connected and radial network with low power losses in short optimality gap to the global optimum (the lowest losses). It should be noted that the active power losses are the heaviest factor in the objective function represented in one of the following Sections and they can be used as main objective in the MST. For the tested network, computing with MST is almost instant ($O(e\log N)$) but SA compensation takes much more time, of an hour order, for 1008 predicted iterations (1008 h = 42 days, each iteration equals one hour). Choosing of 1008 as a number of iteration was defined just because that was the first number>1000 that shows a round number of days.

Main steps in MST are following:

- For completely meshed network branch weighting coefficients are set that represent effective branch current values,
- first vertex (node) is slack node that is noted as number 1,
- the branch with the smallest coefficient is closed avoiding making a loop,
- newly added node is included in the set of nodes,
- if all nodes are visited the algorithm terminates,
- if not we proceed following the same logic until all vertices are included.

Simulated Annealing is the probabilistic method which results in the global optimum under certain conditions such as the process of temperature decrease which seeks zero lasting a very long time and at 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 the fast cooling leads to suboptimal solutions. Metropolis criterion is given by the equation (3):

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

Where:

$P_{acc.}$ - 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_{comm} 5000 °C, length of the Markov chain 3000, temperature (T) lowering rule T = 0.95*T and acceptance ratio 0.001.

MST is an algorithm with fast convergence. This is the reason why this solution was implemented, although this algorithm does not offer the global minimum (considering power loss). It results in the radial network. SA is the algorithm that requires certain conditions to be fulfilled in network reconfiguration problem (network to be connected and radial). The authors chose the SA algorithm to solve the optimization problem, because, this method can be easily implemented when it comes to functions with several objectives. Applied MST is used for the reconfiguration and SA for compensation afterwards.

Power flow calculation performed by MATPOWER is implemented in MATLAB. It is worth noticing that for MST only one MATPOWER flow calculation is necessary, which is one of the reasons for its scalability.

Fig. 5 shows the flow chart of the proposed algorithms systematically, from the beginning to the end. The final step is actually the exit of the programme.

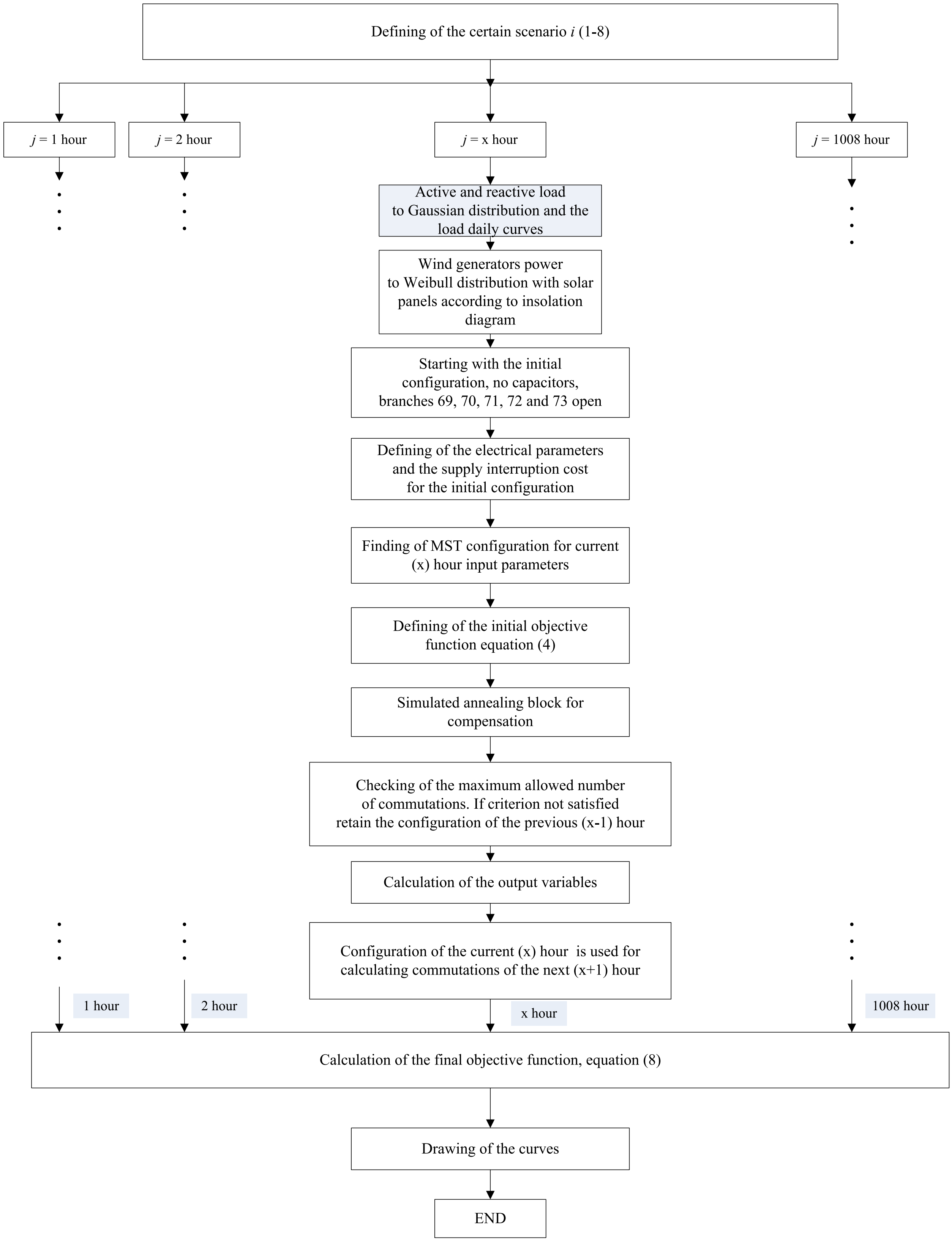

Fig. 5. MST plus SA hybrid algorithm.

4. Objective functions, constraints and operational indices

4.1. Objective functions

Two objective functions are adopted which may not be general but depends on the respective authors' decision. In [14] 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 [5] 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. Hence the authors of the paper decided on the construction of objective functions as follows.

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

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

Where:

$FINALCOST_{i,j}$- one-hour cost of the operation in the *i*-th scenario and the *j*-th hour ($),

$\boldsymbol{I}$ - set of all scenarios,

$\boldsymbol{J}$ - 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

$C_{int,i,j}$- cost of supply interruption in the *i*-th scenario and the *j*-th hour ($).

The one-hour cost of the operation (4) consists of three addends, the cost of the installed capacitor banks, the cost of losses and the cost of supply interruption (all for the respective hour and corresponding scenario). The cost of pertaining commutations are neglected as the greatest amount of switchings per one hour interval equals 5 closings and 5 openings which equals 500$ at most and can be omitted compared with other addends.

The cost of supply interruption is given by the expression (5) [27], considering that in radial distribution networks, the interruption of one branch excludes the power supply of all its "downstream" consumers.

$$C_{int,i,j} = c_{int} \times \alpha \times d \times \sum_{q \in N_b} \lambda_q \times l_q \times Re\{I_{q,i,j}\} \times \sqrt{3} \times U_r \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{5}$$

In equation (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_q- branch failure rate (0.0001 fault/km),

l_q- length of branch *q* (km), for simplicity 100 km is each branch length,

N_b- number of branches,

$I_{q,I,j}$- current value of branch *q* 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:

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

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

The second objective function is the delivered electrical energy saving cost *ENERGYsavings* calculated by (8).

$$ENERGYsavings_i = LPF \times \max(P_{loss,initial,i,j}) + CDEL \times \sum_{j=1}^{N^{hours}} P_{loss,initial,i,j} + \sum_{j=1}^{N^{hours}} C_{int,initial,i,j} + \left(CPA \times PCB_i + LPF \times \max(P_{loss,i,j}) + CDEL \times \sum_{j=1}^{N^{hours}} P_{loss,i,j} + \sum_{j=1}^{N^{hours}} C_{int,i,j} + C_{com,i} \right) \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{8}$$

Where:

$ENERGYsavings_i$- delivered electrical energy saving cost in the *i*-th scenario ($),

CDEL- cost of delivered energy loss (0.03 $/kWh),

N^{hours}- duration of scenario (1008 h, each iteration equals one hour) and

$C_{com,i}$- cost of commutations for N^{hours} in the *i*-th scenario (one commutation amounts to 1 $ or 50 $).

The second objective function, the delivered electrical energy saving cost (8) consists of two terms, three addends in the first term valid for initial configuration when no switching is performed and five in the brackets valid for respective scenario, duration of each is 1008 h. The initial maximal power loss, the initial delivered electric energy loss and the initial supply interruption for commencing 1008 h are calculated. There is no price of commutations and capacitor banks as there are no commutations and capacitors. The network demand changes with Gaussian distribution equally for no switching and switching scenarios. The same holds for the distribution resources. The second term (in the brackets) is composed of the price of capacitor banks, the maximum power loss cost, the delivered electric energy loss cost, the undelivered electric energy price and the lump sum cost of the commutations for pertaining 1008 h lasting scenario.

4.2. Constraints

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

$V^{\min}, V^{\max}$- 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.

$$I_{q,i,j} \leqslant I^{\max}_{q,i,j} \quad \forall q \in N_b,\ i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{10}$$

$I^{\max}_{q,i,j}$- maximum current of branch *q* in the *i*-th scenario and the *j*-th hour.

$$Q_{b\min,i,j} \leqslant Q_{b,i,j} \leqslant Q_{b\max,i,j} \quad i = 3,\ 6,\ \forall j \in \boldsymbol{J} \tag{11}$$

$$Q_{b\max,i,j} = Q_{initial,i,j} + Q_{dem,i,j} \quad i = 2,\ 3,\ 5,\ 6,\ \forall j \in \boldsymbol{J} \tag{12}$$

Equation (12) considers network not overcompensated.

$$Q_{b\min,i,j} = Q_{initial,i,j} + Q_{dem,i,j} - P_{00,i,j} \times \frac{\sqrt{1-0.85^2}}{0.85} \quad i = 3,\ 6,\ \forall j \in \boldsymbol{J} \tag{13}$$

In equations (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,

$Q_{bmax,I,j}$- maximal total power of the installed capacitor banks in the *i*-th scenario and the *j*-th hour,

$Q_{initial,i,j}$- reactive power loss for initial network, network without installed capacitor banks in the *i*-th scenario and the *j*-th hour,

$Q_{dem,i,j}$- reactive power demand in the *i*-th scenario and the *j*-th hour,

$Q_{bmin,i,j}$- 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.

Table 1
Capacitor price step up function [29].

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.

To have the power factor at the slack node 0.85 or greater [28] equation (13) is applied. In (12) and (13) to ground admittances are neglected which is valid for tested network.

Nodal power balance equations (14) – (17):

$$P_{ij} = \text{tap}^2 V_i^2 G_{ij} - \text{tap}^2 V_i V_j \left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j) \right] \tag{14}$$

$$Q_{ij} = -\text{tap}^2 V_i^2 B_{ij} - \text{tap}^2 V_i V_j \left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j) \right] \tag{15}$$

$$P_{slack} + \sum_{d=1}^{NDG} P_{DG}(d) = \sum_{i=1}^{N-slack} P_{dem}(i) + \sum_{ij=1}^{N_{br}} P_{loss}(ij) \tag{16}$$

$$Q_{slack} + \sum_{k=1}^{NCB} Q_{CB}(k) = \sum_{i=1}^{N-slack} Q_{dem}(i) + \sum_{ij=1}^{N_{br}} Q_{loss}(ij) \tag{17}$$

In nodal power balance equations (14) – (17) following symbols are used:

P_{ij} - active power injected from node *i* in branch *ij*,
Q_{ij} - reactive power injected from node *i* in branch *ij*,
tap - tap position of OLTC in p.u. (for example 1p.u. or 1.025 p.u.),
V_i - voltage in node *i* (no regulation applied),
G_{ij} - conductance of branch *ij*,
B_{ij} - susceptance of branch *ij*,
δ_i - voltage angle at bus *i*,
P_{slack}- active power injected into slack node,
Q_{slack}- reactive power injected into slack node,
NDG- number of distributed generators,
P_{DG}- distributed generator power,
NCB- number of capacitor banks,
Q_{CB}- capacitor banks power,
P_{dem}- active power demand of node (Gaussian distribution),
Q_{dem}- reactive power demand of node (Gaussian distribution),
N_{br}- total number of switched on branches,
$P_{loss}(ij)$ - active power loss of branch *ij* and
$Q_{loss}(ij)$ - reactive power loss of branch *ij*.

The number of taps on the OLTC is standardized by its manufacturers. This paper analyzes five positions in steps of 2.5 % of the rated voltage (-5%, −2.5 %, 0 %, 2.5 % and 5 %). In normal operating mode, the tap is selected in the zero position (i.e. the rated network voltage). The legal regulations for the permissible distribution network voltage range are 0.95 to 1.05p.u. These limits are met only when the position of the OLTC is 2.5 %, that is, when 1,025 p.u. is taken for the input grid voltage. In all other positions the achieved voltage limits do not meet the prescribed range since the critical node voltage is lower or higher than allowed.

The price of installed capacitors is given in the Table 1.

Conducting algorithm regarding allowed number of commutations per branch for the prescribed time duration (switching operation constraints $s = 1, 2, \dots, N_{SW}$) [8]:

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

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* 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. The maximum number of commutations for a single switch is important for its' life period and is rarely considered in recent references.

4.3. *Operational indices*

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

4.3.1. *Total voltage profile index $TVPI_i$ [14]*

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

$$VPI_{i,j} = \sum_{k=1}^{N} \left| 1 - V_{k,i,j} \right| \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{19}$$

$$TVPI_i = \frac{\sum_{j=1}^{N^{hours}} VPI_{i,j}}{\sum_{j=1}^{N^{hours}} VPI_{i,j}^n} \quad \forall i \in \boldsymbol{I} \tag{20}$$

In equations (19), (20) $TVPI_i$ 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 “flattened” as possible.

4.3.2. *Total power loss index $TPLI_i$ [14]*

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.

$$P_{loss,i,j} = \sum_{q=1}^{N_b} r_q \times I_{q,i,j}^2 \quad \forall i \in \boldsymbol{I},\ j \in \boldsymbol{J} \tag{21}$$

$$TPLI_i = \frac{\sum_{j=1}^{N^{hours}} P_{loss,i,j}}{\sum_{j=1}^{N^{hours}} P_{loss,initial,i,j}} \quad \forall i \in \boldsymbol{I} \tag{22}$$

In equations (21), (22) $TPLI_i$ is total power loss index for scenario *i*, N^{hours} is duration of scenario (1008 h) and r_q branch active resistance. Evidently smaller values of $TPLI_i$ guarantee the lower losses of the network.

5. Numerical results

Validation of the proposed new concept is done by the conducted sensitivity analysis. Implementing computer simulation in accordance with objective function (4) Fig. 6 a-f is obtained. From it can be concluded that the most visited nodes for placing the wind generators are the node 10 and the node 20. Following Fig. 6 b. to f. it can be observed that the same holds for the nodes 26, 63 and 60 for the capacitor banks; they are picked for the capacitors (300, 300 and 900 kVAr, respectively). This is what we call Monte Carlo graphical method [13]. Any wind turbine positioning that does not lead to the convergence of the power flow algorithm (MATPOWER) is rejected, until the most optimal position is found, which satisfies all the constraints. The position of the solar panels is determined by mathematical method [26]. Two wind turbines are installed in nodes 10 and 20, and solar panels in 61 and 49.

These positions are fixed for further calculations. After that, the joint application of MST and SA leads to the optimal position of capacitor

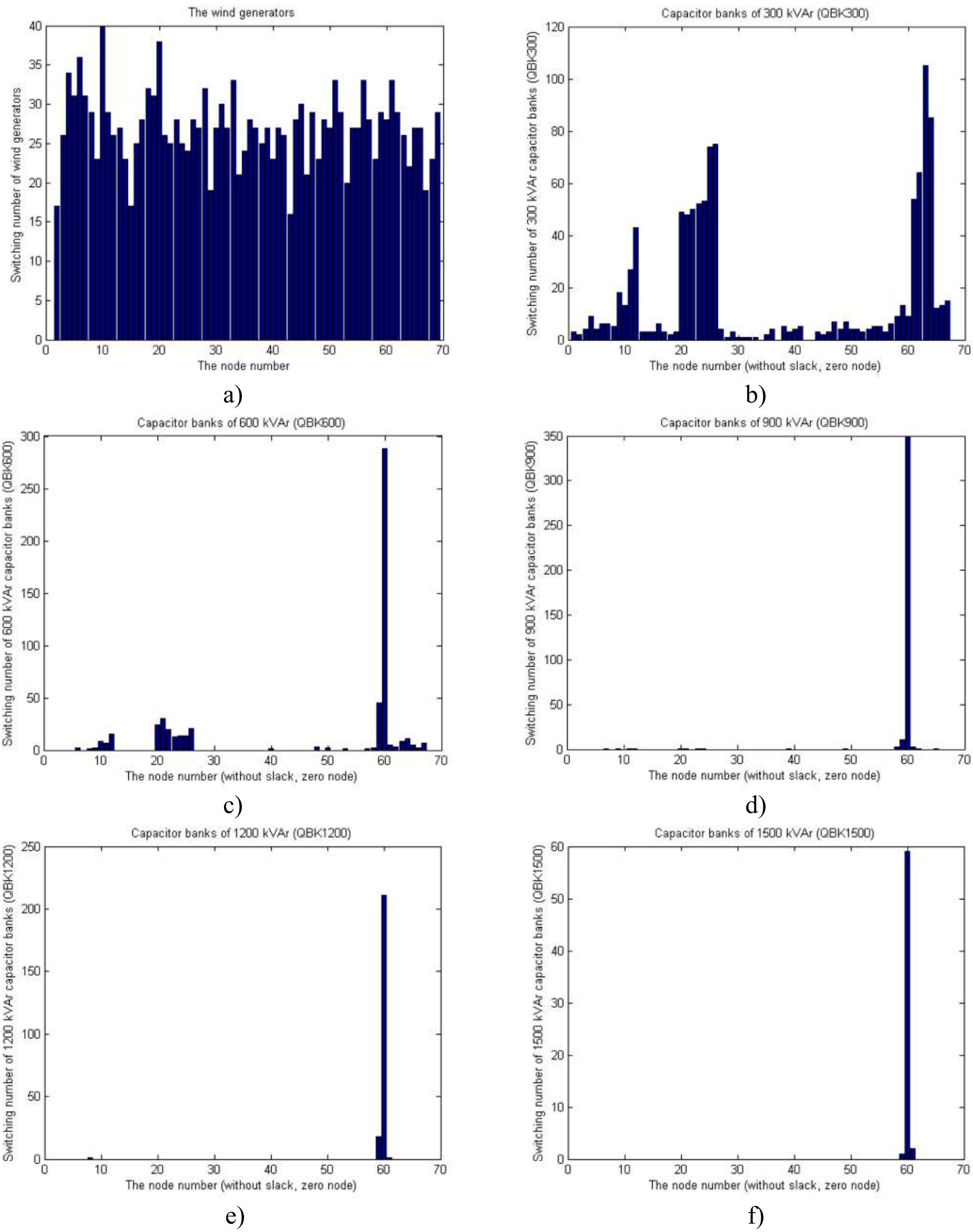

Fig. 6. Switching number for the hybrid algorithm of: a) wind generators b) 300 kVAr banks c) 600 kVAr banks d) 900 kVAr banks e) 1200 kVAr banks f) 1500 kVAr banks.

Table 2
Using simultaneous SA for reconfiguration and compensation.

Scenario	Uinput	Energy OLTC price not included	Energy Savings OLTC price considered	TVPI	TPLI	commutations	ΔIinitial	ΔIfinal	Umax initial	Umax final	Umin final	cosφ	Qinput	Supply interruption cost
number	p.u.	mil $	mil $	p.u.	p.u.	$	A	A	p.u.	p.u.	p.u.		overcompensated	$
1	1.025	1.69	0.43	–	–	2 351	−85.2970	−68.7312	1.0286	1.0286	0.9354	<0.85	no	1 657 400
		1.81	**0.32**			**117 550**								
2	1.025	2.04	0.08	–	–	0	−85.2970	−14.5369	1.0286	1.0286	0.9077	<0.85	no	1 997 400
3	1.025	1.66	0.47	–	–	2 707	−85.2970	−0.6406	1.0286	1.0286	0.9628	>0.85	no	1 629 400
		1.79	**0.34**			**135 350**								
4	1.000	1.47	0.44	0.7897	0.4564	2 353	−102.9836	−82.8855	1.0037	1.0037	0.9086	<0.85	no	1 704 500
		1.86	**0.32**			**117 650**								
5	1.000	2.10	0.08	0.8865	0.6452	0	−102.9836	−29.4254	1.0037	1.0037	0.8790	<0.85	no	2 052 800
6	1.000	1.70	0.48	0.7017	0.3088	2 573	−102.9836	−13.9360	1.0037	1.0037	0.9299	>0.85	no	1 674 500
		1.83	**0.35**			**128 650**								

Note: - bold values refer to the 50$ price per commutation [14],
- Energy is second term of the equation (8) in the brackets,
- OLTC, manufacturer M.Reinhausen, type VVIII, 600 A, 40 kV, motor drive mechanism ED100S and accessories, price 54 463.5 $.

Table 3
Using hybrid MST and SA algorithm.

Scenario	Uinput	Energy OLTC price not included	Energy Savings OLTC price considered	TVPI	TPLI	commutations	ΔIinitial	ΔIfinal	Umax initial	Umax final	Umin final	cosφ	Qinput	Supply interruption cost
number	p.u.	mil $	$	p.u.	p.u.	$	A	A	p.u.	p.u.	p.u.		overcompensated	$
1a	1.025	1.57	0.52	–	–	1 505	−85.2258	−67.4908	1.025	1.025	0.9383	<0.85	no	1 543 000
		1.65	**0.44**			**75 250**								
2a	1.025	2.01	0.08	–	–	0	−85.2258	−14.4121	1.025	1.025	0.9088	<0.85	no	1 965 500
3a	1.025	1.55	0.54	–	–	1 505	−85.2258	−1.1354	1.025	1.025	0.9602	>0.85	no	1 529 900
		1.63	**0.46**			**75 250**								
4a	1.000	1.62	0.53	0.2795	0.4675	1 115	−102.9055	−83.2742	1	1	0.9107	<0.85	no	1 584 100
		1.67	**0.47**			**55 750**								
5a	1.000	2.07	0.07	0.3961	0.6411	0	−102.9055	−29.2878	1	1	0.8801	<0.85	no	2 020 000
6a	1.000	1.59	0.55	0.1957	0.3096	1 115	−102.9055	−14.6927	1	1	0.9333	>0.85	no	1 569 900
		1.65	**0.49**			**55 750**								

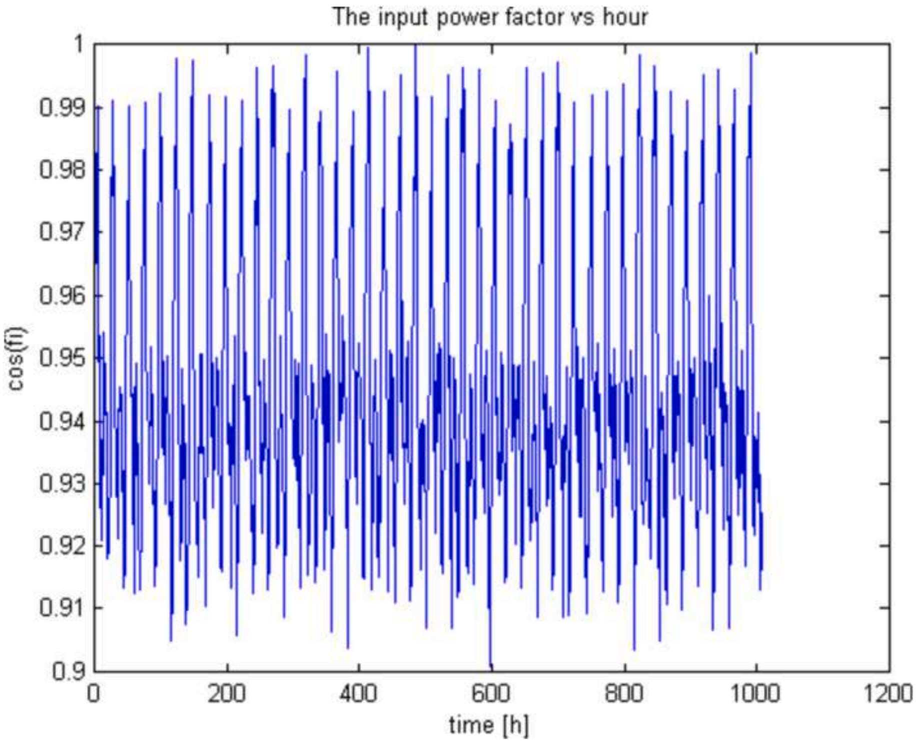

Fig. 7. The input power factor (cosφ) vs hour curve - scenario **3a.**

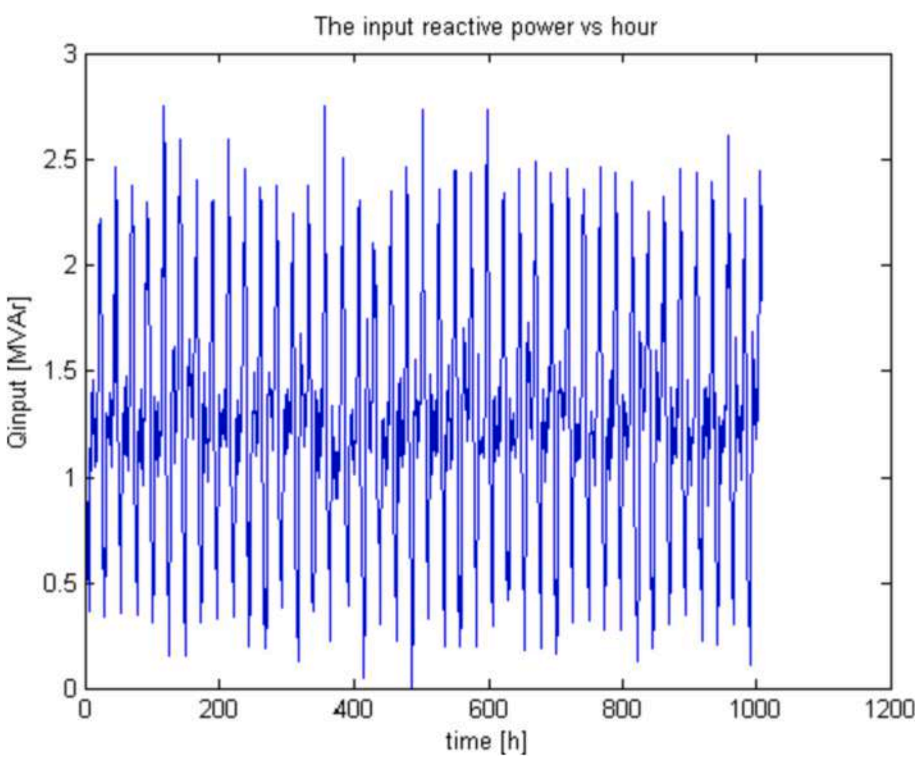

Fig. 8. The input reactive power vs hour curve - scenario **3a.**

banks. In addition, a favourable network configuration is determined for each hour (1008 h in total). In doing so, all constraints are taken into account.

5.1. Comparison of two types of calculations

In this chapter, the results of two different calculations will be presented. In one, only SA is used, and in the other, the combination of MST and SA. For six different scenarios calculation was performed in two ways.

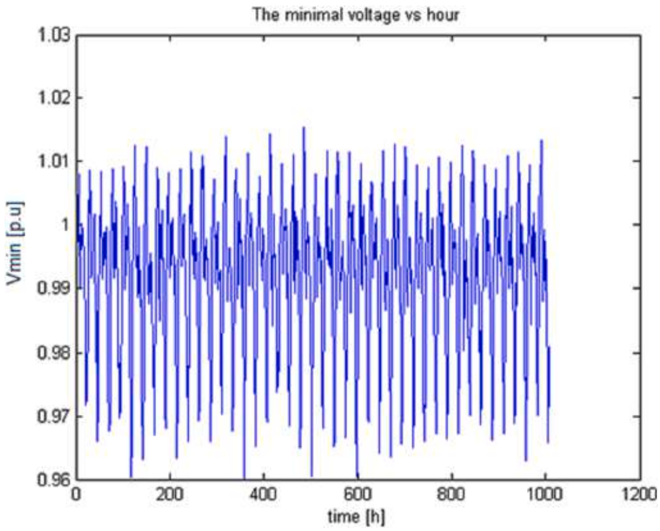

Fig. 9. The minimal voltage vs hour curve - scenario **3a.**

Following scenarios have been analyzed:

1 and **1a** scenario is when only reconfiguration is performed, 1.025 p.u. OLTC tap,

2 and **2a** scenario is when only compensation with the certain capacitor banks is performed, 1.025 p.u. OLTC tap,

3 and **3a** scenario is when reconfiguration and compensation are performed, 1.025 p.u. OLTC tap,

4 and **4a** scenario is when only reconfiguration is performed, 1.000 p.u., no OLTC,

5 and **5a** scenario is when only compensation with the certain capacitor banks is performed, 1.000 p.u., no OLTC, and

6 and **6a** scenario is when reconfiguration and compensation are performed, 1.000 p.u., no OLTC.

Note: Numbers without **a** denote simultaneous SA algorithm and with **a** hybrid MST and SA method.

Using aforementioned switching scheme, the following results are obtained and presented in Table 2 and 3.

It would be cumbersome task to display all obtained graphics in the paper for all six scenarios and two mentioned algorithms especially because some curves will overlap (six of them) making figures not so clear. This is the reason for displaying only four curves (Figs. 7-10) for economically the best technically feasible scenario, scenario **3a,** (as others don't satisfy operational requirements), which represents near optimal realistic solution.

Important remark for the Figs. 7 to 10 is that variables on them oscillate round their expected mean values. This is direct consequence of Gaussian changing load in the network nodes.

Input power factor (cosφ) is>0.85 only when reconfiguration is accompanied with compensation (scenarios **3, 3a** and **6, 6a**). It becomes very close to 1 (0.9999) in iteration 486 (hour) for scenario **3a**. The input reactive power becomes almost zero in this case (0.569 kVAr). The minimal voltage of the network is>0.95 only in scenarios **3** and **3a**. In these cases, OLTC is added in the supplying node. This means that only mentioned scenarios comply technically. The active power loss is the smallest in the scenario **3a**. The reason is the aforementioned implementation and reconfiguration with compensation application.

It is interesting to see how the program generated wind speeds. Only the wind speed of wind turbine at location 1 (node 10) is shown. This can be seen in Fig. 11. Also, Fig. 12 shows the status of the switch in branch number 18. This is one of the branches that have been commutated more often. Fig. 12 shows that number of commutations of this network branch does not exceed 6 in 24 h. The branch 18 is randomly chosen and is monitored for the time period of 100 h (scenario **3a**). It is worth noticing that the branches 1–12, 14–17, 21–55, 59, 60, 62, 64–68 and 71–73 (Scenario **3a**) are never opened so that the switches on them can be omitted bringing additional savings (Fig. 13).

5.2. Comparison of the proposed algorithm and solutions in other papers

The proposed algorithm is a combination of MST and SA. In doing so,

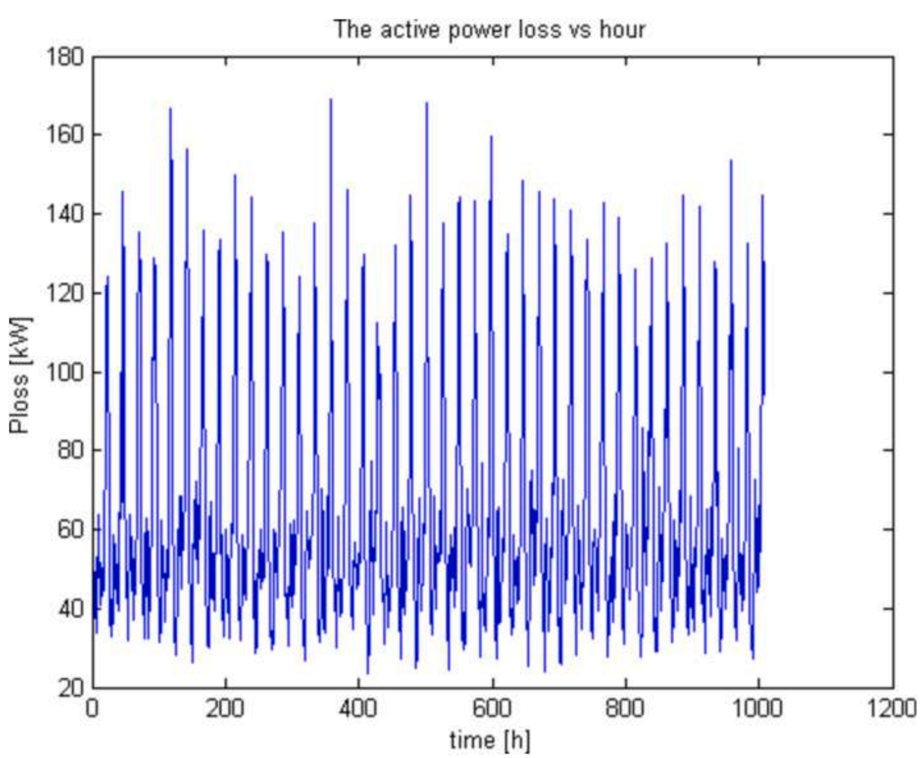

Fig. 10. The active power loss vs hour curve - scenario **3a.**

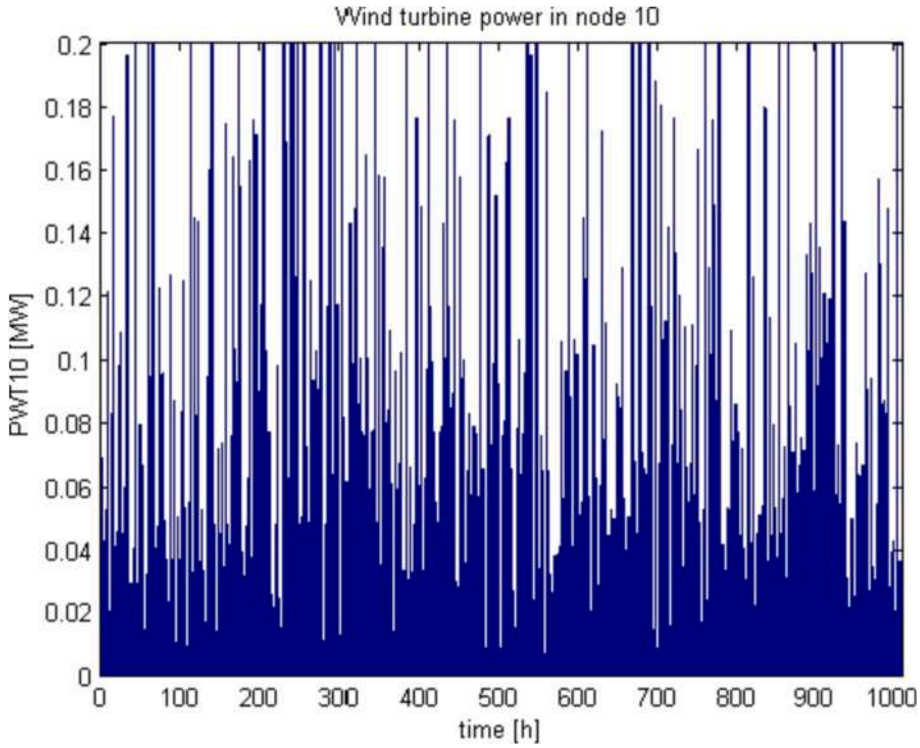

Fig. 11. The wind turbine power for node 10.

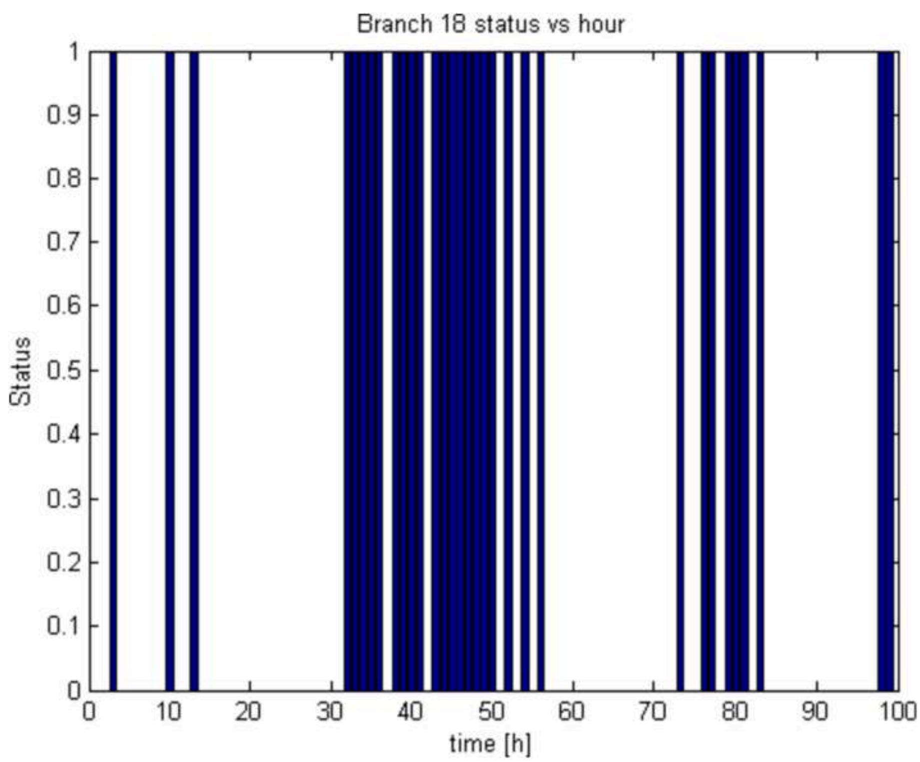

Fig. 12. Switch status changes in 100 h time for branch 18 - scenario **3a.**

MST is used for reconfiguration and SA for compensation. Section 4 discusses the constraints used to obtain an optimal solution. Table 4 shows a comparison of the mentioned solution and other solutions described in the literature from the aspect of limitations and factors that are analyzed.

The ordinal number of the reference is given in the first column of Table 4. Comparison was made according to following segments: Voltage profile (VP), Economical issues (EI), Load unbalance (LU), Capacitor placement (CP), Load model (LM), DG wind generators presence (DGW), DG solar panels presence (DGS), Number of circuit breaker commutations (CBC) and Demand response (DR). Minimization of Power Losses is the primary aim for all papers.

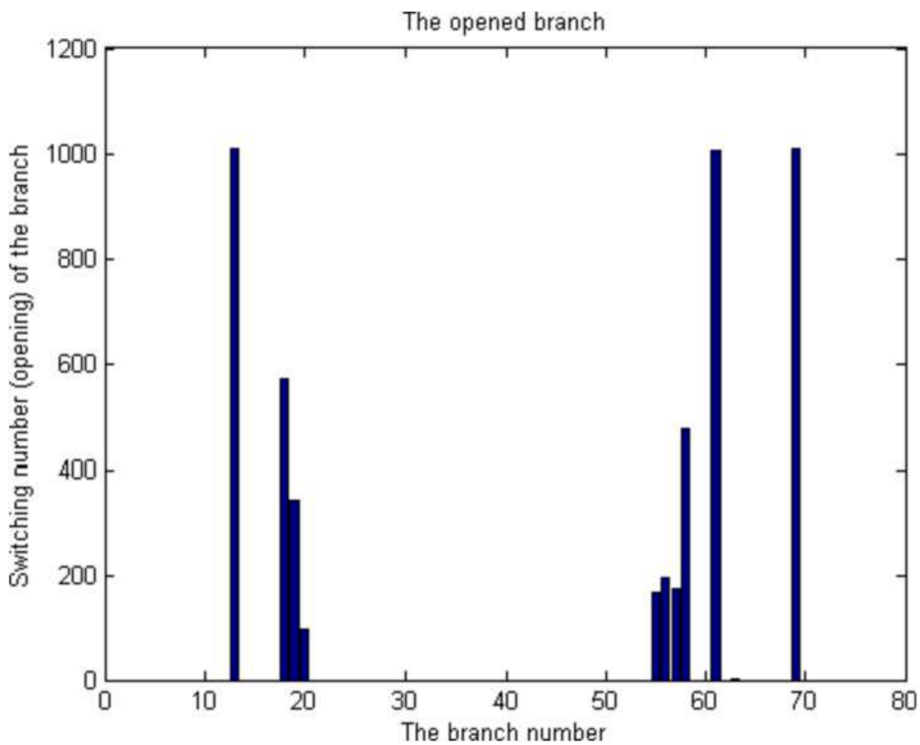

Fig. 13. Switching number (opening) of the branches - scenario **3a.**

Table 4
Review of the previous literature in this topic.

Ref	VP 1	EI 2	LU 3	CP 4	LM 5	DGW 6	DGS 7	CBC 8	DR 9	Optimization method
[5]	x	x		x	x	x				Genetic algorithm (GA)
[8]	x	x			x					Lagrange relaxation
[9]	x	x		x	x					Mixed integer non-linear programming
[10]	x			x	x					Meta-heuristic bee algorithm
[11]	x		x			x				Multi-criteria fuzzy technique
[12]	x	x	x		x					Order estimation algorithm and modified branch and bound method
[14]	x	x		x	x	x				Ant colony search algorithm (ACSA), Harmony search algorithm (HSA)
[15]	x		x	x		x				Non-dominant sorting GA II (NSGA-II)
[16]	x	x		x	x	x				Elgerd's formula
[18]	x		x	x		x				Hybrid approach of HSA,Particle artificial bee colony algorithm (PABC)
[19]	x			x	x	x				Non-dominant sorting genetic algorithm II (NSGAII)
[20]	x	x			x	x			x	Markov Decision Process and dynamic programming
[21]	x	x			x		x			Pareto solutions
[22]	x	x			x	x	x			Security limits method
proposed	x	x		x	x	x	x	x		SA and MST - proposed algorithm

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

6. Conclusion

In this paper, the distribution network reconfiguration with simultaneous capacitor switching, in the presence of wind generators and solar panels is presented. Using of Minimum spanning tree algorithm shows fast convergence for reconfiguration. Simulating annealing optimization is good for capacitor banks determination (power and location). Combination of these solutions leads to satisfactory results. Many constraints are considered. Comparison with using SA for both reconfiguration and compensation simultaneously shows that proposed hybrid method gives better results. In addition, research offers comparison of the mentioned solution and other solutions described in the literature from the aspect of limitations and factors that are analyzed. Hence, new algorithm provides great number of constraints to be satisfied, including number of equipment commutations during the day. The developed programme can be adopted for the planning stage as well as for operation because of its scalability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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