PAPER • OPEN ACCESS

Optimal reconfiguration of active distribution network considering flexible load scheduling

To cite this article: Mingchao Xia *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **563** 052100

Optimal reconfiguration of active distribution network considering flexible load scheduling

Mingchao Xia[1], **Shuai Yang**[1] **and Qifang Chen**[1,2]

[1]School of Electrical Engineering, Beijing Jiaotong University, Beijing, China.

[2]Author to whom any correspondence should be addressed

chenqf@bjtu.edu.cn

Abstract. At present, most of the existing optimal reconfiguration method of active distribution network (ADN) aims at the change of network topology, without considering flexible load. This situation makes a low efficiency of the existing method when facing the situation with large amount of flexible load in ADN. A bi-layer optimal reconfiguration model including an outer layer and inner layer is presented considering flexible load optimal dispatching to improve the efficiency of ADN reconfiguration. Unlike the conventional method, the two layers of the proposed bi-layer method are combined in each iteration. At each iteration the reconfiguration scheme is obtained by solving a binary optimal model in the outer layer, and the flexible loads are optimized in the inner layer. So, the optimal network topology and the optimal flexible load scheme are obtained at the same iteration. This would increase the efficiency of the reconfiguration scheme than that get by the conventional two-stage method. Finally, the importance of flexible load during ADN reconfiguration is proved, and the validity of the proposed method is verified by the comparison simulations.

1. Introduction

Optimal reconfiguration is an effective way to reduce the network loss [1] by changing the network structure through controlling the state of segment switch and contact switch in distribution network [2-4]. Several researches have been reported on the optimal reconfiguration of ADN. In [5] taking network loss and voltage deviation minimization as two optimization objectives, authors presented an optimal reconfiguration method for ADN containing Distributed Generation (DG). Ref. [6] researches on the location of DG and capacity selection in distribution network. The problem of DG location and distribution network reconfiguration double-layer programming model is solved by GUROBI solver. Ref. [7] presents a reconfiguration methodology based on a fuzzy multi-objective approach for achieving the minimum active power loss and the maximum voltage magnitude of radial distribution networks with DG. Although the optimal reconfiguration of ADN with DG has been studied a lot, however the Flexible Loads (FL) [8] have not been considered. With the large-scale construction and application of energy storage equipment, electric vehicle and micro-grid the amount of FL in ADN will increase quickly. Besides, some traditional loads can also adjust their electricity demand according to incentive or electricity price, they are called adjustable load. The load characteristics of active load and adjustable load are flexible and controllable.

With the development of ADN, the distribution network will become more complex in the future, grid structure and flexible load are controllable components of ADN. If they can be optimized as variables at the same time, a more effective optimization result of complex network can be obtained. But how to optimize the grid structure and flexible load together is a hard problem.

To solve the above problem, the most used method is the two-stage method. The first stage is to get the optimal network topology, and then the optimal flexible load scheme is obtained at the second stage based on the result get by the first stage. However, this would result in low efficiency of the reconfiguration scheme due to the separated two stages. To solve these problems, a multi-variable reconfiguration strategy is proposed as a bi-layer optimization model, which aims at minimizing network loss. Unlike the conventional two-stage method, the two layers of the proposed bi-layer method are combined in each iteration. At each iteration the reconfiguration scheme is obtained by solving a binary optimal model in the outer layer, and the flexible loads are optimized in the inner layer. So, the optimal network topology and the optimal flexible load scheme are obtained at the same iteration. Finally, to verify the validity of the proposed method, network loss and voltage magnitude are taken as two indices, and comparison cases are conducted.

2. Mathematical Model of Flexible Load

2.1. Active load

2.1.1. Energy Storage System. Usually the battery state of the Energy Storage System(ESS) is expressed by the State of Charge(SOC), the formula is as in (1):

$$SOC = \frac{E_{rem}}{E_{max}} \times 100\% \tag{1}$$

E_{rem} is the current energy storage capacity. Emax is the maximum capacity of EES.

2.1.2. Electric vehicle charging station. The charging power of each electric vehicle is optimized to respond to the scheduling, it can be calculated by

$$SOC_{ev} = SOC(0) + \frac{\left(P_{charge} + P_{out}\right)}{E_{\max}} \tag{2}$$

SOC(0) is the initial SOC of the electric vehicle. P_{charge} is the charge power. Pout is the discharge power. SOC_{ev} is the expected SOC value at the end of charging.

2.2. Adjustable Load

There are some loads which can be dispatched for a short time by power companies through compensation or incentives in the distribution network. This paper calls them adjustable load.

Adjustable load is the load which generally has a relatively low demand for power quality and supply demand in industrial production, or a load which has a low impact on user comfort in residential power consumption. This kind of load can be agreed with the power grid to respond to the dispatch of the power grid on the premise of obtaining certain economic compensation. The amount of electricity it can be adjusted within a certain range, it is as in (3):

$$P_{IL\min} \le P_{IL} \le P_{IL\max} \tag{3}$$

P_{ILmax}/P_{ILmin} is the upper/lower limit of adjustable load capacity, respectively.

Adjustable load can respond to some adjustments of distribution network within its dispatching range.

3. Active Distribution Network Reconfiguration with Flexible Load Optimal Dispatch

3.1. Mathematical Model of Distribution Network Reconfiguration

3.1.1. Objective function and constraints. Distribution network reconfiguration is to change the power flow among different feeders by controlling the contact switches and sectional switches to optimize the operation of the whole network.

In this paper, the objective function is to minimize the network loss. The network reconfiguration model is constructed with power flow equation constraints, node voltage constraints, branch capacity constraints, radial network topology constraints and flexible load regulation range constraints as constraints.

- Objective Function.

In this paper, the objective function is to minimize the network loss of the system, calculated by:

$$f_{P_{loss}} = \sum_{b=1}^{N-1} k_b r_b \frac{P_i^2 + Q_i^2}{U_i^2} \tag{4}$$

Ploss is the active network loss of the system. *N* is the number of network nodes. *i* is the node number of the branch. *b* is the branch number. k_b is the 0-1 discrete state variable of branch *b*. 0 means open and 1 means closed. r_b is the resistance of branch *b*. U_i is the voltage magnitude of node i. P_i/Q_i is the active/reactive power injected into node i, respectively.

- Constraints

$$\begin{cases} P_i + P_{DGi} - P_{Li} - U_i \sum_{j=2}^{N} U_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \\ Q_i + Q_{DGi} - Q_{Li} - U_i \sum_{j=2}^{N} U_j (G_{ij}\sin\theta_{ij} + B_{ij}\cos\theta_{ij}) = 0 \end{cases} \tag{5}$$

P_i/Qi is the active/ reactive power injected into node *i* by the network. P_{DGi} /Q_{DGi} is the active power/reactive power injected by DG into node *i*. P_{Li} /Q_{Li} is the power/reactive power injected into load node *i*. G_{ij}/B_{ij} is the conductance/admittance between nodes *i* and *j*. θ_{ij} is the angular difference between nodes *i* and *j*.

- Power flow equality constraintsNode Voltage Constraints

$V_i^{\min} \le V_i(t) \le V_i^{\max}$ (6)

$V_i(t)$ *is* the actual node voltage at *t* of the node i. V_t^{max}/V_t^{min} is the upper/lower limit of the node voltage.

- Branch capacity constraints

$$S_i(t) \le S_i^{\max} \tag{7}$$

$S_i(t)$ *is* the actual power value of branch *i* at *t* time. S_t^{max} is the maximum allowable power of the line.

- Topological constraints of networks

$$\mathrm{g_i} \in \mathrm{G} \quad g_i \notin G_{island} \tag{8}$$

G is the network set that satisfies the radial network. Gisland is the network set with isolated islands.

- Flexible Load Scheduling Scope Constraints

$$P_{FL\min} \le P_{FL} \le P_{FL\max} \tag{9}$$

P_{FLmin}/P_{FLmax} *is* the upper limit/lower limit of power of flexible load.

3.1.2. Optimal scheduling of flexible loads. Not all loads in the system are flexible loads. The number, types and schedulable capacity of flexible loads are limited. In a certain time period, the value of flexible load is defined according to the different types of flexible load. Different kinds of flexible loads define their dispatching scope according to their own constraints such as power quality, power supply demand and users' comfort. The calculation method is as:

$$FL = [x_1, x_2, \cdots, x_n] \left(P_{n\min} \le x_n \le P_{n\max} \right) \quad (10)$$

x is the load of flexible load participating in dispatch, it means increases if the *x* is positive numbers, it means decreases if the x is negative numbers, and the *x* is always 0 if the nodes are without scheduling or flexible load. P_{nmin}/P_{nmax} is the upper limit/lower limit of adjustable power of flexible load.

The load value of the node can be calculated as (13):

$$Load = \mathrm{NL}+(\mathrm{NL}_{\mathrm{FL}}+\mathrm{FL}) \quad (11)$$

NL is the initial load of nodes without flexible loads. $\mathrm{NL}_{\mathrm{FL}}$ is the initial load of nodes with flexible load. FL is the scheduling value of flexible loads.

The change of power of flexible load in the system will change the power flow and the voltage of each load node, under reasonable optimal scheduling. These changes will tend to be beneficial to the whole system, this is the significance of flexible load optimal dispatch.

*3.1.3. Looped Network with Integer Coding.*In distribution network, all the switches are variables, the combination of all switches is the reconfiguration scheme of distribution network. The closure of each contact switch results in a small looped network in the system, this state does not meet the requirement of open-loop operation of distribution network. So, when a contact switch is closed, a sectional switch must be disconnected. There are two coding schemes for distribution network structure [9]: integer coding and binary coding, in this paper, the former one is used for coding.

The looped network with integer coding is shown in figure. 2. Five contact switches in a network are represented by dotted lines, which are numbered 33, 34, 35, 36 and 37. Section switch is represented by solid line, and the numbers indicate switch (line) number. The looped network composed of contact switch and sectional switch is divided into five parts, and numbered respectively. The result is shown in Table 1.

And all switches are assumed to be closed before reconfiguration to avoid appearing unknown lines.

Table 1. Integer loop coding for 33-node systems

Ring net number	Contact switch	Intra-loop switch	Switch Number in Loop Network
1	33	2,3,4,5,6,7,18,19,20,33	1-10
2	34	9,10,11,12,13,14, 34	1-7
3	35	2,3,4,5,6,7,8,9,10,11,18,19,20,21,35	1-15
4	36	6,7,8,9,10,11,12,13,14,15,16,17, 25,26,27,28,29,30,31,32,36	1-21
5	37	3,4,5,22,23,24,25,26,27,28,37	1-11

3.1.4. Judgment method of infeasible solution. In distribution network reconfiguration, the grid structure needs to satisfy the following two constraints at the same time:

- Radial constraints: There is no ring network in the network.
- Connectivity constraints: There are no islands in the network, and all nodes are connected.

Solutions that do not satisfy constraints are called infeasible solutions. In this paper, switch loop matrix is used to determine whether there is a loop or not. And Switch Loop matrix and Node Stratified(SLNS) strategy is used to determine whether there are islands or not.

There are two matrices to describe parameters: BranchM, which includes head node of branch, tail node of branch and impedance parameters of branch. NodeM, which includes node number, node active power and node reactive power.

Based on the matrix mentioned above, two auxiliary matrices can be defined, Node Layered Matrix(LayerN) and Upper node matrix(UN). LayerN is determined by the specific network structure, the list represents the number of layers, and the elements represent the node numbers contained in the layer. UN is a matrix of 1*N, N denotes the number of network nodes, the element on a column represents the upper node number of the column in which the element resides. The decision pattern of infeasible solutions is shown in figure. 2.

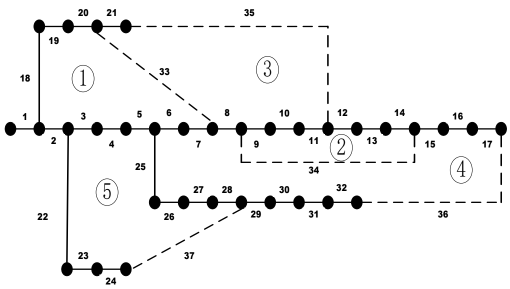


Figure 1. Branch diagram of IEEE 33-bus distribution system.

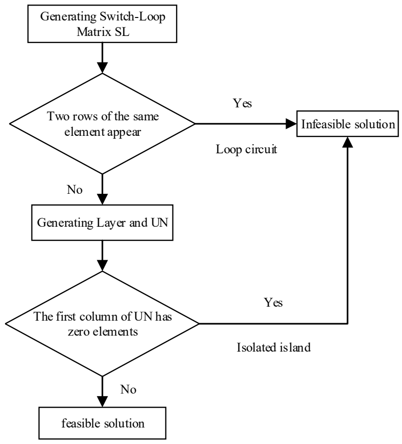


Figure 2.Flow chart for determining infeasibility

*3.1.5. Quantum Particle Swarm Optimization.*QPSO was improved by Sun and his team in 2004 [10], the state of particles in the algorithm is described by wave function $\psi(X,t)$.The probability density function of the particle appearing at a certain point in the searching space of the feasible solution is obtained by solving the Schrodinger equation, then Monte Carlo stochastic simulation is carried out to obtain the iteration equation of particle position, the equation is as in (14) [10]:

$$X(t) = p \pm \frac{L}{2}\ln(\frac{1}{u}) \tag{12}$$

u is a random number with uniform distribution in the range of [0,1], L is as in (15):

$$L(t+1) = 2*\beta\left|mbest - X(t)\right| \tag{13}$$

The evolution of QPSO is as in (16), (17), (18):

$$mbest(t) = \frac{1}{N}\sum_{i=1}^{N} P_i(t) = \left[\frac{1}{N}\sum_{t=1}^{N} P_{i1}(t), \frac{1}{N}\sum_{t=1}^{N} P_{i2}(t), \bullet\bullet\bullet, \frac{1}{N}\sum_{t=1}^{N} P_{iD}(t),\right] \tag{14}$$

$$P_{id}(t) = \varphi * P_{id}(t) + (1-\varphi) * P_{gd}(t) \tag{15}$$

$$X_{id}(t+1) = P_{id}(t) \pm \beta * \left|mbest(t) - X_{id}(t)\right| * \ln(\frac{1}{u}) \tag{16}$$

N is the number of particles in the population, D is the dimension of the particle, u and φ are random numbers that are evenly distributed on [0,1], $P_{i(t)}$ is the current optimal position of the first particle in the iteration t, $P_{g(t)}$ is the global optimum position for the first particle in the iteration t, $P_{id(t)}$ is the d-dimensional position of the first particle, β is the contraction expansion coefficient, the calculation equation is as(19):

$$\beta = m - (m-n) \times \frac{t}{\max Iters} \tag{17}$$

This algorithm which deals with the cross-boundary situation of particles in the process of optimization and mutation are as in (20):

$$\begin{cases} if(X_{id} > X_{\max}), X_{id} = X_{\max} - c*(X_{id} - X_{\max})*rand(\ ) \\ if(X_{id} < X_{\min}), X_{id} = X_{\min} - c*(X_{\min} - X_{id})*rand(\ ) \end{cases} \tag{18}$$

c is the boundary coefficient of variation, X_{max}/X_{min} is the upper/lower boundaries of particle.

Traditional QPSO is mainly used to solve continuous numerical problems. However, for the problem of distribution network reconfiguration, it is required that all dimensional components of particles are positive integers, which causes the traditional QPSO no longer applicable. So we use Integer Coded Quantum Particle Swarm Optimization (ICQPSO) to solve this problem. In this case, formula (18) needs to be modified to the formula (21), it is as in:

$$X_{id}(t+1) = round(P_{id}(t) \pm \beta * \left| mbest(t) - X_{id}(t) \right| * \ln(\frac{1}{u})) \tag{19}$$

The function round () is used to round the values by the specified number of digits, thus ensuring that the particle solution is a positive integer solution.

The particle limitations are as in (22), (23):

$$\begin{cases} Ub = [Ub_1, Ub_2, \ldots, Ub_n] \\ Lb = [Lb_1, Lb_2, \ldots, Lb_n] \end{cases} \tag{20}$$

Ub/*Lb* is the upper/lower bound matrix for each dimension of particle initialization, Ub_i/Lbi is the upper/lower limit of the particle's initialization in the i dimension.

The boundary restrictions need to be changed as in (22) to avoid the particles from crossing the boundary:

$$\begin{cases} if\left(Xid_i > Ub_i\right), Xid_i = randint\left(1,1,\left[Lb_i, Ub_i\right]\right) \\ if\left(Xid_i < Ub_i\right), Xid_i = randint\left(1,1,\left[Lb_1, Ub_1\right]\right) \end{cases} \tag{21}$$

The coding method for flexible load optimal dispatch is as in (11).

3.2. *Algorithmic Flow of Active Distribution Network Reconfiguration.*To do the optimal reconfiguration of ADN considering flexible loads faces two problems: First, it will be difficult to converge if the two variables are considered as combined one for calculation. Second, the conventional two-stage method which gets the optimal network structure and optimal scheme of flexible load separately is with low efficiency.

The bi-layer optimization model is proposed to solve the problems above. The quantum particle swarm optimization algorithm is used get the optimal reconfiguration result of ADN. The outer layer algorithm uses ICQPSO to optimize network structure. The feasible solutions of particles in each iteration will take as the inputs to the inner layer. The inner layer algorithm completes the optimal scheduling of flexible load through QPSO. During each iteration there would be a best solution which is the combination of network structure and optimal flexible load scheme. The final result obtained after iteration renewal is the optimal combination result of grid structure and flexible load. The process is shown in figure. 4:

- Initialize distribution network parameters which include branch parameters, node parameters and number of loops. Number the switches and loops.
- Set up upper and lower bound matrices, population size and maximum iteration times based on the encoding rules of integer loop network. Set the initial iteration number k = 1.

- Judge the feasibility of the solution. According to switch-loop matrix and SLNS, the feasibility of each initial particle solution is judged. If the solution is feasible, the next step is continued. If the solution is infeasible, the initial local optimal solution of the particle is set to a larger positive number.
- Substitute feasible solution into grid structure, input flexible load, the parameters of distribution network are consistent with those in a), initial iteration number n = 1.
- Optimize flexible load based on inner layer algorithm which is quantum particle swarm optimization. The fitness of flexible load is calculated by fitness function.
- Update the population iteratively according to the objective function of flexible load optimal dispatch until the optimal value of flexible load under the grid structure is obtained.
- When n reaches the maximum number of iterations or particles do not get a better value within the maximum number of iterations, the algorithm stops.
- The grid structure which is matched the flexible load as a feasible solution to the outer layer algorithm will be output. And update particle positions of local and global optimum according to the fitness of optimization function. If it is not feasible, the initial local optimal position of the particle is set as a larger positive number. Continue the iteration, k=k+1.
- Arithmetic Stop Criteria. When k reaches the maximum number of iterations or particles do not get a better value within the maximum number of iterations, the algorithm stops and outputs the reconstructed results.

4. Example analysis

In this paper, the network shown in figure3 is optimized and reconstructed to verify the correctness and feasibility of the proposed ideas and strategies. There are 33 nodes and 37 branches in the system, including 32 sectional switches and 5 contact switches. The reference voltage is 12.66 kV. The original active and reactive loads of the whole network are 3715 kW and 2300 kvar respectively. Parameters of DG are shown in Table 2 and parameters of flexible load are shown in Table 3.

Coding according to the network partition is shown in figure.3, and its results are shown in Table 1. The lower limit of each dimension of a particle is 1, the upper limits of each dimension of particles are 10, 7, 15, 21 and 11, respectively. The boundary variation coefficient c is 0.02, all DGs are processed as PQ nodes, convergence accuracy is 10-6, the dimension of particle is 5, the population size is 50, the maximum number of iterations is 100.

Table 2. DG grid-connected parameters

DG number	Grid connected node	Active Power (kW)	power factor
1	3	50	0.8
2	6	100	0.9
3	24	200	0.9
4	29	100	1.0

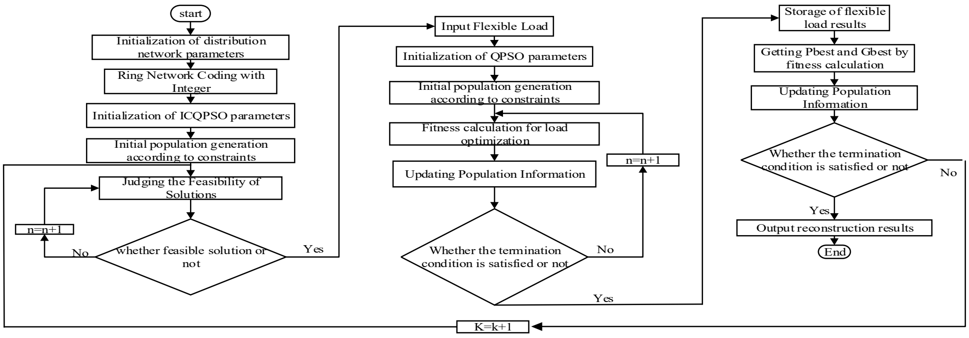


Figure 3. Reconstruction Flow Chart.

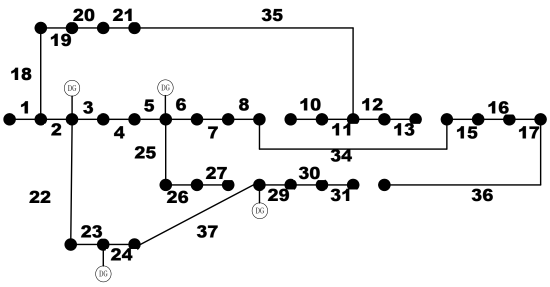
Table 3. Load types and adjustable capacity

Load type	Node number	Load classification	Controllable range
Resident load	3、5、6、10、15、19、21、22、27、33	Adjustable Load	-15%-15%
Commercial load	2、8、14、32	Adjustable Load	-10%-15%
Industrial load	24、25	Adjustable Load	30%
Energy storage system	13、29	Active load	-80%-80%
Electric Vehicle Load	7	Active load	-80%-80%

In this paper, four cases are compared and analyzed, Case 1 is the normal operation of the 33-node grid structure with DG. Case 2 uses quantum particle swarm optimization to reconstruct the network of Case 1. Case 3 dispatches the flexible loads based on the results of Case 2. Case 4 uses the optimization strategy which is proposed in this paper to optimize and reconstruct the network architecture and flexible load of the IEEE 33-node network with DG, the result is shown in Table 4, and the network topology is shown in figure. 4. The convergence result is shown in Fig. 5. The results of all of Cases are shown in Table 5.

Table 4. The result of the Example 4

Disconnect switch combination	network loss (kW)	Node minimum voltage (pu)
33 14 9 32 28	86.5280	0.9515



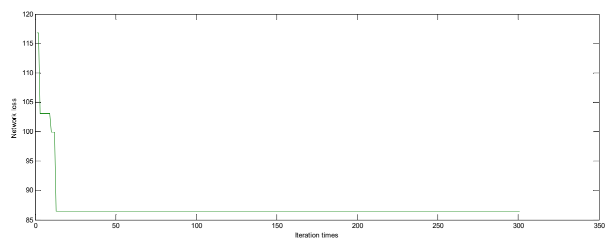


Figure 4. Reconstructed Result Diagram. Figure 5. Convergence Result

Through the analysis of Table 5, it can be seen that the network loss of Case 4 is 47.74%,22.90% and 1.85% lower than that of the Case 1, Case 2 and Case 3. From the comparison and analysis, we can see that the result of reconfiguration of distribution network is more effective by using the proposed strategy to optimize the grid structure and flexible load scheduling.

Table 5. Comparisons of results of Examples

	Disconnect switch combination	network loss (kW)	Node minimum voltage (pu)
Case 1	33 34 35 36 37	169.7386	0.9183
Case 2	7 14 9 32 28	114.6500	0.9478
Case 3	7 14 9 32 28	90.1217	0.9512
Case 4	33 14 9 32 28	86.2580	0.9515

5. CONCLUSION

In this paper, the influence of flexible load participation on optimal reconfiguration of active distribution network is studied. Optimal scheduling based on its own demand for power supply and its impact on user comfort can make positive impact on reducing the active network loss of the system. Combining flexible load regulation with network reconfiguration makes the network reconfiguration have a better effect on reducing network loss of the system. A co-optimization strategy of flexible load and distribution network reconfiguration is used in this paper, and it is implemented by using bi-layer quantum particle swarm optimization algorithm. The algorithm solves the problem of joint optimization of grid structure and flexible load, and it is suitable for multivariable optimization problems. The validity of the proposed method is verified by the comparison cases. The case results show that the optimization strategy proposed in this paper is with better performance than the conventional two-stage method.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [Grant Number 51677003]

Rferences

[1] D'Adamo C, Jupe S and Abbey C 2009 Global survey on planning and operation of active distribution network-update of CIGRE C6.11 working group activities *20th International Conference on Electricity Distribution*. **1**4

[2] Chen Fang, Zhang Li and Han Xue-shan 2014 Line loss evaluation and application in distribution network *Power System Protection and Control*. 1339-44

[3] Wang Jing, Jin Yao and Huang Ze-hua 2015 Risk assessment of distributed network integrated with intermittent energy *Electrical & Energy Management Technology*. 1314-18

[4] Yan Qing-guo, Meng Xue-yang and Cui Yu 2014 Comprehensive benefit evaluation based on interaction of micro-grid and distribution network *Electrical & Energy Management Technology*. 2147-52

[5] Zhang D, Zhang T and Xu X 2017 Optimal reconfiguration of the active distribution network with distributed generation and electric vehicle *The Journal of Engineering*. 1453-56

[6] Xing H and Sun X 2017 Distributed Generation Locating and Sizing in Active Distribution Network Considering Network Reconfiguration *IEEE Access*. 14768-74

[7] R Syahputra, I. Robandi and M. Ashari 2012 Reconfiguration of Distribution Network with DG Using Fuzzy Multi-objective Method Int *Conference on Innovation Management and Technology Research (ICIMTR)*. **21** 22

[8] Wang Ke and Yao Jian-guo 2014 Summary of Research on Flexible Load Dispatching of Electric Power *Automation of Electric Power Systems*. **127** 135

[9] Valle Y D, Venayagamoorthy G K and Mohagheghi S 2008 Particle Swarm Optimization: Basic Concepts, Variants and Applications in Power Systems *IEEE Transactions on Evolutionary Computation*. **171** 195

[10] Sun J, Feng B and Xu W 2004 Particle swarm optimization with particles having quantum behavior *Proceedings of the 2004 Congress on Evolutionary Computation (IEEE Cat. No.04TH8753)*