A Fast Method of Removing Infeasible Solutions for Distribution Systems Reconfiguration

Guangsong Hou[1], Yanda Wu[1], Ying Zhen[1], Jingfang Deng[2], Kejun Li[2], and Mingqiang Wang[2]
[1]Heze Power Supply Company, Heze, China
[2]School of Electrical Engineering, Shandong University, Jinan, China
Email: m18366113169@163.com, lkjun@sdu.edu.cn

***Abstract*—Network reconfiguration technology is one of the most important means to realize the self-healing control function of intelligent distribution network, and the key point of which is avoiding infeasible solution. This paper puts forward the concept of branch groups and analyse the defects of existing network reconfiguration algorithm according to the requirements of the distribution network and the characteristics of the harmony algorithm. The system topology is coded so that it can be effectively integrated with the intelligent optimization algorithm. Taking the harmony algorithm as an example, this paper gives the implementation steps of the algorithm and the four branch break rules. IEEE 33-node system example results show that this paper summarizes the situation of infeasible solutions into five kinds, which improves the search efficiency compared to the existing method. At the same time, it avoids missing viable solutions and ensures the spatial completeness of solutions. It effectively improves the speed of network reconfiguration and the search ability of global optimal solution.**

***Index Terms*—network reconfiguration, harmony search algorithm, encoding rules, eliminating infeasible solutions**

I. Introduction

Network reconfiguration, one of the most important optimizing methods of distribution network, is the basis of achieving self-healing control of distribution network through fast network reconfiguration technology. By network reconfiguration, rapid power of non-fault power loss area after the fault can be achieved, line load can be balanced when the line overload, and the voltage distribution quality can be improved when the node voltage is out-of-limit. The essence of network reconfiguration is finding the optimal combination of the switches opening and closing states which satisfy certain constraints. Distribution systems reconfiguration is considered as NP problem, the key lies in the reconfiguration algorithm can find the global optimal solutions fast [1]-[5]. The use of artificial intelligence algorithm to solve the reconfiguration problem is easy to find the global optimal solution, but the search process will produce a large number of solutions which do not satisfy the topological constraints, so the search efficiency is reduced significantly. The use of artificial intelligence algorithm to solve the reconfiguration problem is easy to find the global optimal solution, but the search process will produce a large number of solutions which do not satisfy the topological constraints, so the search efficiency is reduced significantly [6]. There are two main ways to deal with the infeasible solution generated in network reconfiguration: one is to using effective coding to reduce the probability of infeasible solution or avoid the generation of infeasible solutions; The other is to quickly determine the feasibility of the solution, and then remove the invalid solution, or invalid solution for the effective solution.

In this paper, according to the network structure requirements of the distribution systems reconfiguration and the characteristics of the harmony algorithm [7], the concept of the branch group is proposed. Remove the infeasible solutions by setting the principle of branch disconnection and classifying the infeasible solution conditions into five categories. In addition, iterations are used to improve search speed and efficiency. The simulation results of IEEE 33-node system show that the method has high computational efficiency, fast convergence and good stability, and the convergence characteristic does not change with the scale of the network [8]-[10].

II. Mathematical Model of Distribution Network Reconfiguration

The network reconfiguration optimizes the power flow by switching the state of the contact switch and the segment switch. There are many kinds of optimization objectives for distribution network reconfiguration, such as minimum network loss, uniform load distribution, and improved power supply system stability and reliability. How to effectively reduce the distribution network running when the active loss, it is the most basic goal.

This article takes the network loss minimum as objective function:

$$minf=minP_{loss}=\sum_{j=1}^{b}k_j r_j \frac{P_j^2+Q_j^2}{U_j^2} \quad (1)$$

where, P_{loss} is the network loss; k_j represents the state of the branch *j*, when k_j is 1, the branch is closed and when k_j is 0, the branch is opening; r_j is the resistance of branch *j*; P_j and Q_j are the active power and reactive

Manuscript received March 12, 2018; revised June 19, 2018.

doi: 10.18178/ijoee.6.1.41-46

power flowing through branch j; U_j is the terminal voltage of branch j; b is the number of network branches.

III. Concept and Principle of Harmony Algorith

The network reconfiguration optimizes the power flow by switching the state of the contact switch and the segment switch. There are many kinds of optimization objectives for distribution network reconfiguration, such as minimum network loss, uniform load distribution, and improved power supply system stability and reliability. How to effectively reduce the distribution network running when the active loss, it is the most basic goal.

The harmony algorithm comes from the musicians' understandings of the melody. The core idea of harmony algorithm is described in following paragraph.

First, its initial scale is the harmony memory database whose size is set. Then, new harmony will be generated randomly from the harmony memory database and allowable range (generally where to generate new harmony is determined by the probability). If the new harmony is better than the worst harmony in the harmony memory database, the worst harmony in the harmony memory database will be replaced with the newly generated harmony. The cycle is followed by the above steps until the stop condition is satisfied. The flow chart of harmony algorithm is shown in Fig. 1.

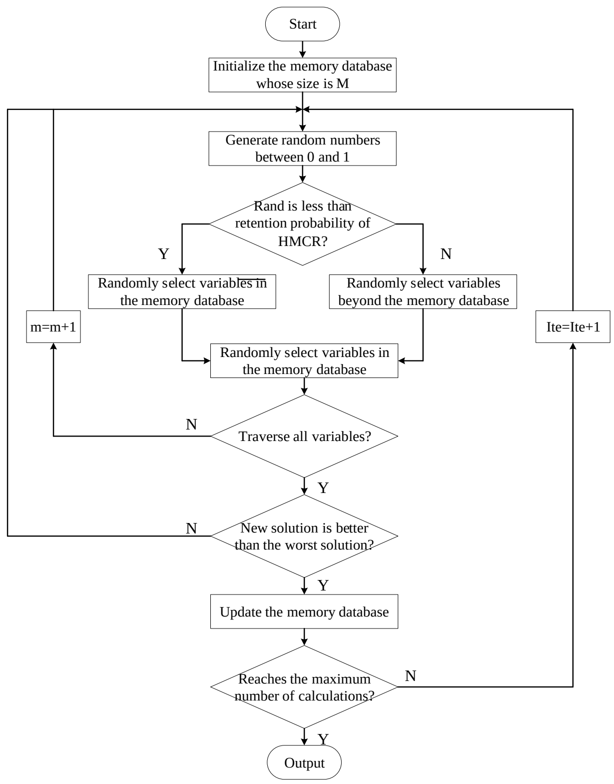

Figure 1. Flow chart of harmony algorithm.

IV. Reconfiguration of Special Branch Groups and the Principle of Branch Breaking

A ring network will be formed after closing a contact switch in the radiation type distribution network. This paper calls the ring network the reconstructed ring. The broken branch can be determined as long as the open switch in reconstructed rings is determined and a structure of the distribution network can be gotten. In this paper, the harmony search algorithm is applied to the distribution network reconfiguration, using decimal coding. The dimension of the solution vector is the number of reconstructed rings in the network and the value of the solution vector in each dimension is the number of the disconnection branch in the respective reconstructed ring. The range of each dimension variable is the number of branches in the corresponding reconstructed ring [11].

A. The Reconfiguration of Special Branch Group

Due to the characteristics of random search of harmony algorithm, infeasible solutions are inevitable. This article introduces the concepts of "large node" and "branch group" to reduce the generation of infeasible solutions. Here take the IEEE 33-node system [1] as an example. The topology of the system is shown in Fig. 2.

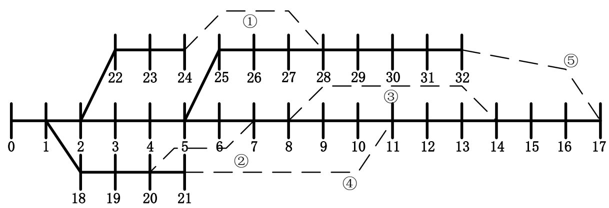

Figure 2. IEEE 33-node distribution system.

- The large node is that the number of branches connected to this node exceeds 2. As shown in Fig. 2, the nodes 2, 5, 28, 7, 8, 11, 14, 20 are large nodes.
- The branch group is a collection of all branches between two big nodes.

A simplified system wiring diagram can be produced as shown in Fig. 3 according to the concept of branch group and the removal of all branch branches (such as 0-1 branch). Branch groups can be formed after inputting the adjacency matrix of the system according to the program and each branch group will be numbered. The order of the numbers is shown below.

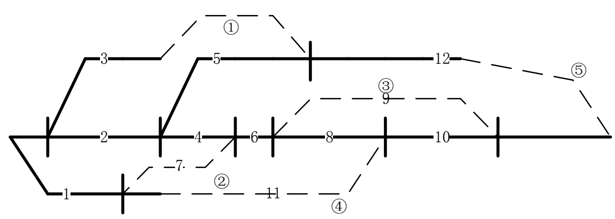

Figure 3. Branch groups wiring diagram.

B. The Principle of Branch Breaking and the Generation of Initial Solutions

The harmony algorithm needs to form initial solutions before the computation, that is, the memory database. so that it is necessary to declare the meaning of the solution in the reconfiguration of the distribution network. If the 5 branch groups are broken, the system can be re-radiated and there is no island and the running state of the acyclic network, then the sequence number of the 5 branch groups is the solution. When breaking a branch group, the middle branch of the branch group should be disconnected.

It is easier to find the initial solution by breaking the branch by the following four rules [12].

- The broken branch group is selected according to the loop sequence, and each loop can only be disconnected a branch group in the loop.
- Each branch group can only be broken one of the branches, that is, each branch group can't be disconnected twice. Obviously, if a branch group breaks off two branches, it will inevitably form an island
- Whether or not only the last branch group is left on the large node connected by the branch group should be judged before breaking a branch group. If yes, the branch set can't be disconnected. As shown in Fig. 4, once the branch 4 and 7 are broken which the 5 nodes are connected, then the branch 6 can't be disconnected.

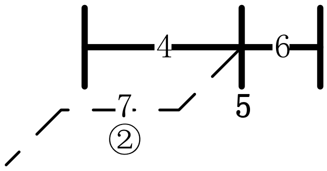

Figure 4. Prevent a node from being isolated.

- If there is only one branch of a branch group left which is connected with the large note, it is necessary to find another large node connected with the branch group. If one of the branches of the branch group which is connected with another large node is broken apart from this common branch and another branch maintains connected, then the connected branch can't be broken. As shown in Fig. 5, If the branch groups connected with 5 nodes only remains branch 4 which is not disconnected, then another large note 7 connected with branch 4 should be founded. One of the branch groups connected with note 7 has been broken except branch 4 so that the connected branch 6 can no longer be broken. Otherwise, it will form a local island with 5 nodes and 7 nodes as the center.

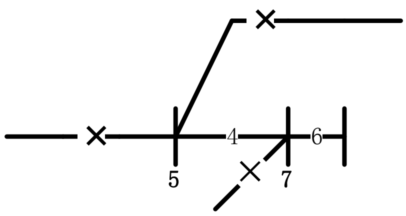

Figure 5. Prevent the emergence of local islands.

V. Remove the Infeasible Solution

The initial solutions and the new solutions generated according to the harmony algorithm are not necessarily feasible solutions. To determine whether these solutions are feasible, they can be judged when these solutions are used to form the power supply network. According to the flow chart shown in Fig. 6, the corresponding power supply circuit can be formed according to the solutions and the network loss can be calculated after removing the infeasible solutions.

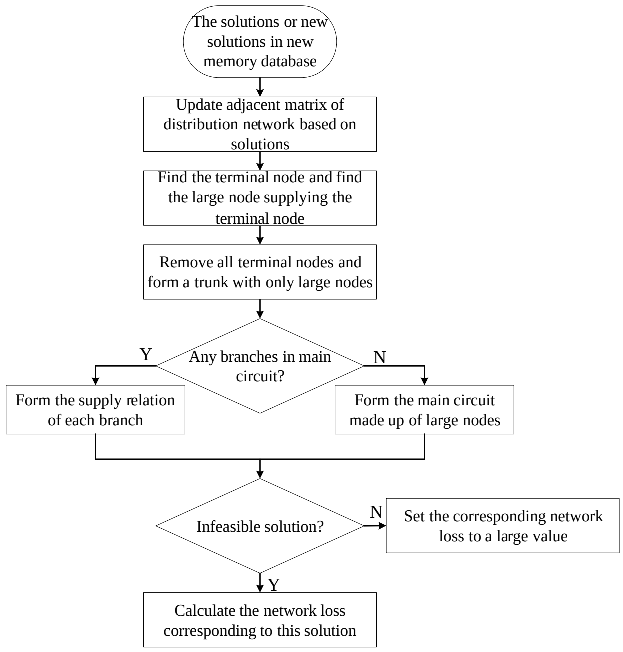

Figure 6. Remove the infeasible solution.

The main circuits are the remaining circuits which have been removed all the end branches of the new network. If there is a large node on the main circuit connected with more than one large node, then the circuit has branches. In order to form the supply network correctly, the source node 0 which is removed from the branch group is added so that it is necessary to introduce the node 1 which is directly connected with the source node in the network. Then, Node 1 becomes a large node and 0-1 branch becomes a branch group which doesn't belong to any loop and cannot be disconnected.

A. *Reconfiguration of Special Branch Group*

If the solution is [3, 1, 10, 6, 4], that is, disconnecting the branch groups 3, 1, 10, 6, 4. The resulting network is shown in Fig. 7.

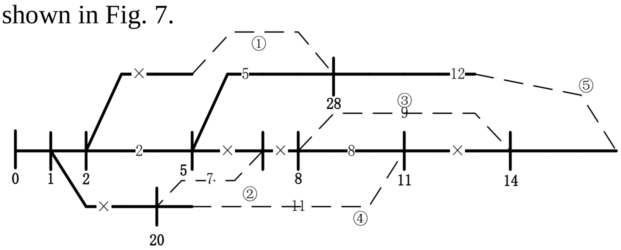

Figure 7. Main circuit without branches.

Obviously, this is a network whose large nodes are on the main circuit and without branches. The order of power supply is 0-1-2-5-28-14-11-20. There is no island in the situation shown in Fig. 7, but a number of different main circuits will be formed when the main circuit are without branches and islands exist. While there is only one main circuit in the program. When the number of nodes on the main circuit don't match with the number of large nodes remaining after the end node removed, it means that this main circuit does not cover all the large nodes and there are islands. This solution is infeasible.

B. Main Circuit with Branches

When the main circuit has branches, the terminal large node traverses upstream. If the large node which are on the branches is searched, the search can be stopped. Then, the next terminal large node traverses upstream until every terminal large node has been traversed. Next, from the large node which has been searched on the branches traversing upstream until the next node is searched. By that analogy, until the 0-1 branch of the source is searched. When the following situations occur, it shows that the network topology does not meet the requirements and there is a ring network and an isolated island running state.

As shown in Fig. 2, the nodes 2, 5, 28, 7, 8, 11, 14, 20 are large nodes.

- Case1: After removing the terminal node, you can't find another large node to traverse to the source node. When a solution is [3, 7, 9, 8, 4], the network is formed as shown in Fig. 8. In the network shown in Fig. 8, it forms a huge ring of 1-2-5-28-14-11-20-1. Although it forms branches at the node 1, no terminal large node can be found in the network. It can be judged as infeasible solution.

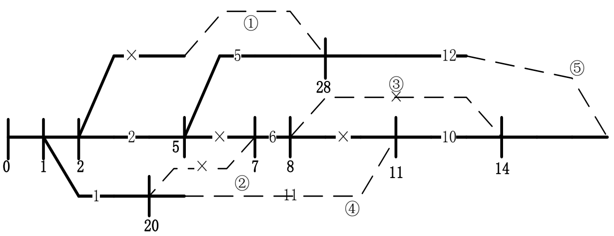

Figure 8. Network corresponds to case 1.

- Case2: After removing the terminal node, you can find only one large node to traverse to the source node. If the circuit begins to bifurcate after passing the large node on the main circuit and there is no loop, there must be at least two branches to the terminal large node. Then when there is only one terminal large node, there must be a loop in the network. Obviously, this solution is infeasible.
- Case3: There are end to end branches in the network. When a solution is [5, 1, 10, 2, 12], the network is formed as shown in Fig. 9. In the network shown in Fig. 9, the local ring network, 7-8-11-20, is formed. When the branches of the network are formed, the results are as follows:
  Branch 1: 8-11-20-7
  Branch 2: 7-8
  Branch 3: 0-1-2-28
  Branch 4: 7-5

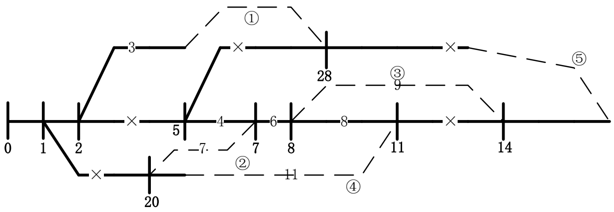

Figure 9. Network corresponds to case 3.

- Case4: There is no node connected with the source node on the first branch of the network (the most important branch). When a solution is [2, 1, 10, 4, 12], the network is formed as shown in Fig. 10. In the network shown in Fig. 10, the local ring network, 7-8-11-20, is formed. When the branches of the network are formed, the results are as follows:
  Branch 1: 7-20-11-8
  Branch 2: 8-14
  Branch 3: 0-1-2-28-5

Because the power of the root of the main circuit must be supplied by 0-1, this situation is wrong, that is infeasible solution. The case in case 4 is also applicable to case 3.

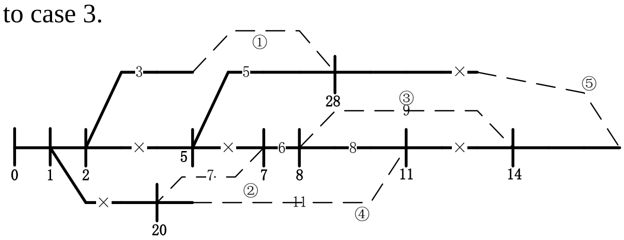

Figure 10. Network corresponds to case 4.

VI. Example Analysis

This paper uses the IEEE 33-node system, whose wiring diagram is shown in Fig. 2, as an example to validate the algorithm. There are 37 branches and 5 contact switches in the IEEE33-node system. Its bus bar voltage is 12.66 kV and the total system load is 3802.19+j2693.6kV·A. The detailed parameters of the lines are shown in documents [13].

A. Generation of Initial Solutions

The initial solutions (capacity of the memory database is 4) which are generated by the simulation analysis of the example using MATLAB are shown in Table I.

TABLE I. Initial Network Loss in IEEE 33-Node System

Initial solution	Network loss (kW)
[5, 1, 8, 6, 4]	54625
[2, 7, 10, 6, 12]	34420
[5, 2, 8, 1, 6]	88085
[3, 7, 10, 4, 8]	35786

As can be seen from the above table data, the initial four solutions are feasible and the network loss is diverse.

B. Generation of New Solutions by Harmony Algorithm

Set the number of iterations is 20 and the output results are shown in Table II.

TABLE II. RECONFIGURATION RESULTS OF NETWORK LOSS IN IEEE 33-NODE SYSTEM

Calculation times	New solution	Network loss (kW)
1	[3,2,8,11,12]	49997
2	[3,4,9,11,12]	30019
3	[3,4,8,11,6]	45925
4	[5,1,10,4,12]	110000
5	[3,4,8,11,6]	45925
6	[3,4,9,2,8]	63149
7	[3,2,10,11,12]	49547
8	[3,4,8,11,12]	28329
9	[3,4,10,11,12]	27879
10	[3,1,9,11,8]	44349
11	[3,4,10,11,12]	27879
12	[3,4,9,11,12]	30019
13	[2,4,8,11,12]	34321
14	[2,7,9,11,12]	65545
15	[5,1,8,11,12]	36061
16	[3,4,8,11,12]	28329
17	[2,4,10,11,12]	33871
18	[3,4,10,11,12]	27879
19	[5,4,9,8,12]	24377
20	[2,4,10,1,12]	110000

The solutions whose network loss is110000 in the Table III are infeasible solutions. It is defined artificially that the infeasible solution has large network loss.

TABLE III. FINAL RESULTS OF NETWORK LOSS IN IEEE 33-NODE SYSTEM

Final solution	Network loss (kW)
[5, 4, 9, 8, 12]	24377
[5, 4, 10, 11, 12]	26839
[3, 4, 10, 11, 12]	27879
[3, 4, 10, 11, 12]	27879

According to the network loss of the previously generated solutions shown in Table II, the network loss tends to decrease gradually except for occasional infeasible solutions. The remaining solutions of the memory database all have smaller network loss after 20 calculations. These solutions can be used in network reconfiguration schemes.

VII. CONCLUSION

This paper is based on the network structure requirements of the distribution network and the characteristics of the harmony algorithm and puts forward the concept of branch groups on the basis of analysing the defects of existing network reconfiguration algorithms. The system topology is coded so that it can be effectively integrated with the intelligent optimization algorithm. Taking the harmony algorithm as an example, this paper gives the implementation steps of the algorithm and the four branch break rules. IEEE 33-node system example results show that this paper summarizes the situation of infeasible solutions into five kinds, which improves the search efficiency compared to the existing method. At the same time, it avoids missing viable solutions and ensures the spatial completeness of solutions. It effectively improves the speed of network reconfiguration and the search ability of global optimal solution.

ACKNOWLEDGEMENT

This paper is supported by the Heze Power Supply Company (52061416000R), and National Natural Science Foundation of China (51407106).

REFERENCES

[1] A. Y. Abdelaziz, F. M. Mohammed, and S. F. Mekhamer, “Distribution systems reconfiguration using a modified particle swarm optimization algorithm,” *Electric Power Systems Research*, vol. 12, pp. 1521-1530, July 2009.

[2] S. J. Civanlar, J. Grainger, and H. Yin, “Distribution feeder reconfiguration for loss reduction,” *IEEE Trans. on Power Delivery*, vol. 3, pp. 1217-1223, May 1988.

[3] P. X. Bi, J. Liu, and C. X. Liu, “A refined genetic algorithm for power distribution network reconfiguration,” *Automation of Electric Power Systems*, vol. 26, pp. 57-61, Jan. 2002.

[4] C. Chen, F. Wang, and B. Liu. “Network reconfiguration based on basic ring matrix and improved harmony search algorithm,” *Automation of Electric Power Systems*, vol. 38, pp. 55-60, July 2014.

[5] L. X. Xu, L. Liu, and J. Y. Liu, “Modified particle swarm optimization for reconfiguration of distribution network,” *Automation of Electric Power Systems*, vol. 30, pp. 27-30, July 2006.

[6] Y. Q. Jiang, Z. F. Chen, and C. Huang, “Distribution network reconfiguration based on heuristic rules and harmony search algorithm,” *Journal of Hunan University: Natural Sciences*, vol. 41, pp. 61-67, 2014.

[7] X. C. Huang and Y. Yang, “Network reconfiguration in distribution systems based on genetic algorithm with current point coding technique,” *Automation of Electric Power Systems*, vol. 19, pp. 74-79, July 2013.

[8] J. J. Yang, Z. Hong, and L. Yang, “Optimization of distribution network reconfiguration based on loop and improved genetic algorithm,” *High Voltage Engineering*, vol. 33, pp. 109-113, May 2007.

[9] X. Z. Dong, S. Y. Huang, and R. Y. Chen, “Self-healing control technology for smart distribution system,” *Automation of Electric Power Systems*, vol. 18, pp. 17-21, Jan. 2012.

[10] M. T. Fan, Z. P. Zhang, and A. X. Su, “Enabling technologies for active distribution systems,” *Proceedings of the CSEE*, vol. 22, pp. 12-18, July 2013.

[11] J. K. Lin, G. Pan, and Y. P. Li, “A fast determination method of topological radial property of distribution network based on basic-tree and distribution network reconfiguration,” *Proceedings of the CSEE*, vol. 25, pp. 156-166, July 2013.

[12] X. F. Ma and L. Z. Zhang, “Distribution network reconfiguration based on genetic algorithm using decimal encoding,” *Transactions of China Electrotechnical Society*, vol. 19, pp. 65-69, July 2004.

[13] Z. K. Li, X. Y. Chen, and K. Yu, “Hybrid particle swarm optimization for distribution network reconfiguration,” *Proceedings of the CSEE*, vol. 28, pp. 35-41, May 2008.

Jingfang Deng was born in March, 1995. She is a Master Degree Candidate in electrical engineering and automation, School of Electrical Engineering, Shandong University, Jinan, Shandong, China. Her research is on reactive power optimization of distribution of distribution network.

Ke-Jun Li (M'07–SM'15) received the B.S. and M.S. degrees from Shandong University of Technology, Jinan, China, and the Ph.D. degree from Shandong University, Jinan, in 1994, 1999, and 2005, respectively, all in electrical engineering. From 2007 to 2008, he was a Postdoctoral Researcher in the Department of Electrical Engineering, University of Texas at Arlington, TX, USA. He is currently a Professor with the School of Electrical Engineering and the Deputy Director of Institute of Renewable Energy and Smart Grid, Shandong University. His research interests include renewable energy integration, microgrid operation and control, modeling and control for high-voltage direct-current and flexible ac transmission system devices, online equipment protection, monitoring, and control system.