

PAPER • OPEN ACCESS

A New Distribution Network Structure for Maximizing the Allowable Penetration of Distributed Energy Resource

To cite this article: S S Zhao *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **486** 012064

View the [article online](#) for updates and enhancements.

A New Distribution Network Structure for Maximizing the Allowable Penetration of Distributed Energy Resource

S S ZHAO^{1,*}, X H SONG¹, Y J LI¹, F GAO¹, Y ZHANG¹, J F LI¹ and Z Y JIA²

¹China Electric Power Research Institute (CEPRI), Beijing, China

²State Grid Yangquan Power Supply Company, China

*E-mail: zhaoshanshan@epri.sgcc.com.cn

Abstract. The traditional network structure cannot be suitable for the connection of large-scale distributed energy resources, thus the high penetration of distributed energy resource (DER) will have destructive effects on the security and reliability of the traditional distribution network. The paper proposes a new distribution network structure to increase the maximum allowable penetration of DER. Firstly, the model and method of the new distribution network structure are presented. Secondly, the theory basis of increasing the DER penetration by the new network structure is proved. Finally, the proposed model and method are applied to the typical test case. And the simulation results show that compared with the traditional structure, the new distribution network structure can not only increase the maximum penetration of distributed energy resource greatly, but also realize the high energy efficiency, reliability and sustainability. Therefore, the issue of future distribution network security with high penetration of distributed energy resource can be well solved by the new distribution network structure proposed in the paper.

1. Introduction

Distributed energy resource (DER) has become an inevitable trend of development in the future distribution network so that the sustainability and security of energy utilization can be realized [1,2]. However, the allowable penetration of DER has been low in the traditional distribution network nowadays [3]. The high penetration of DER will have destructive effects on the security and reliability of the traditional distribution network, such as power quality, short-circuit current or relay protection [4,5]. That's because that the traditional network structure cannot be suitable for the connection of large-scale distributed energy resources. Therefore, a new distribution network structure has to be proposed so as to increase the maximum allowable penetration of DER.

At present, most research on maximizing the allowable penetration of distributed energy resource focused on the optimization algorithm of DER position and capacity [6,7]. Some others also studied the operation and control measures to increase the DER penetration [8,9]. However, the traditional network structure were used in all of these research, thus the DER penetration was still not high and the demand of DER cannot be met in the future distribution network.

In [10], the structural framework of Future Renewable Electric Energy Delivery and Management (FREEDM) system was put forward in America to meet the demand of large-scale DER in future distribution network. Some other research results indicated that meshed distribution network could be suitable for the safe connection of large-scale DER, such as the distribution network in Singapore [11]. The new structure of Active Network Management and Control System (ANMCS) was presented in



the project of the Flexible Plug and Play (FPP) in the UK [12]. However, these new network structures mentioned above were too expensive to invest nowadays, such as FREEDM or ANMCS.

Therefore, the paper proposes a new distribution network structure to increase the maximum allowable penetration of distributed energy resource. Firstly, the model and method of the new distribution network structure are presented. Secondly, the theory basis of increasing the DER penetration by the new network structure is proved. Finally, the proposed model and method are applied to the typical test case. And the simulation results and conclusions are followed.

2. Model and method of the new distribution network structure

The new distribution network structure is accomplished by constructing new flexible power lines and common power lines among key buses in the existing distribution system. The new flexible power lines are the power lines on which the appropriate UPFC is installed so as to allocate various energy resources optimally and increase the penetration of distributed energy resource. The aim of constructing the new common power lines is to realize electric power balance further.

The advantages of the new distribution network structure model are small investment, high penetration of distributed energy resource and high energy efficiency. Therefore, it can solve the issue of increasing the allowable penetration of distributed energy resource well.

2.1. Model of the new distribution network structure

The model of the new distribution network structure can be described as follows:

$$\begin{cases} M_F = \langle \{R\}, \{A_R\}, \{B_{i,j}\} \rangle \\ R = \langle G\%, L\% \rangle \\ A_R = \langle X^R, e_0, E^R, Y^R, \varepsilon^R, \phi^R \rangle \\ B_{i,j} : Y^i \rightarrow X^j \\ \min F = \lambda_1 \cdot IC + \lambda_2 \cdot OC + \lambda_3 \cdot LC - \lambda_4 \cdot VII \end{cases} \quad (1)$$

In equation (1), M_F is the model of the new distribution network structure, $\{R\}$ is the group of multi-dimensional resolutions, $\{A_R\}$ is the group of multi-dimensional models with the corresponding resolutions, $\{B_{i,j}\}$ is the group of inputs and outputs for different multi-dimensional models, $G\%$ means the output of distributed energy resource in percentage of total power supply, $L\%$ means the power load in percentage of total power supply, X^R represents the inputs for the multi-dimensional model with the corresponding resolution R , e_0 represents the group of initial states for the model with resolution R , E^R represents the group of state sequences for the model with resolution R , Y^R represents the outputs for the model with resolution R , ε^R represents the functions of state transition for the model with resolution R , ϕ^R represents the functions of output for the model with resolution R , $i \in \{R\}$, $j \in \{R\}$, F is the objective function of the new network structure optimization model, IC means the investment cost of the new network structure, LC means the loss cost of the new network structure, OC means the outage cost of the new network structure, VII means the voltage improvement income of the new network structure, λ_1 , λ_2 , λ_3 and λ_4 represent the weight coefficients of IC , LC , OC and VII .

- Investment cost (IC)

$$IC = \sum_{i=1}^M (D_{Li} + T_{Li}) + \sum_{j=1}^N (D_{Gj} + T_{Gj}) \quad (2)$$

In equation (2), the cost of investment for the i th new power line is denoted as D_{Li} ; the maintenance and operation cost for the i th new power line is denoted as T_{Li} ; D_{Gj} means the cost of investment for DG which is interconnected with the j th bus; T_{Gj} means the maintenance and operation cost for DG which is interconnected with the j th bus; the number of new power lines is denoted as M ; the number of buses with DG interconnected is denoted as N .

- Power loss cost (LC)

$$LC = \sum_{i=1}^T C_i P_{li} t_i \quad (3)$$

In equation (3), the number of periods in one year is denoted as T ; the length of time during the i th period is denoted as t_i ; the power loss during the i th period is denoted as P_{li} ; the unit of power loss cost during the i th period is denoted as C_i .

- Outage cost (OC)

$$OC = \sum_{j=1}^n [P_j \cdot \sum_{i=1}^m W_j(t_i, \beta_i)] \quad (4)$$

In equation (4), the load for the j th node is denoted as P_j ; the average outage rate is denoted as β_i when the i th kind of fault occurs; the average outage time is denoted as t_i when the i th kind of fault occurs; the cost of outage for the j th node is denoted as $W_j(t_i, \beta_i)$ when the i th kind of fault occurs; the number of nodes is denoted as n ; the fault type number is denoted as m .

- Voltage improvement income (VII)

$$VII = \alpha \cdot \frac{1}{n} \sum_{j=1}^n \frac{U_{jb} - U_{jN}}{U_{ja} - U_{jN}} \quad (5)$$

In equation (5), α represents the coefficient which converts voltage improvement to economic benefit; the normal voltage is denoted as U_{jN} at the j th bus; the voltage at the j th bus is denoted as U_{jb} before new power lines are installed; the voltage at the j th bus is denoted as U_{ja} after new power lines are installed.

In addition, the model of the new distribution network structure must satisfy the constraints as follows:

$$\begin{cases} S_{ij} \leq S_{limit(ij)} \text{ or } I_{ij} \leq I_{limit(ij)} \\ U_{iN} (1 - d_{limit-} \%) \leq U_i - \Delta U_i \leq U_{iN} (1 + d_{limit+} \%) \\ \theta_i^{limit-} \leq \theta_i \leq \theta_i^{limit+} \\ P_{Gi}^{limit-} \leq P_{Gi} \leq P_{Gi}^{limit+} \\ Q_{Gi}^{limit-} \leq Q_{Gi} \leq Q_{Gi}^{limit+} \end{cases} \quad (6)$$

In equation (6), the transmission power is denoted as S_{ij} from the i th bus to the j th bus, and its limit value is denoted as $S_{limit(ij)}$; the electric current is denoted as I_{ij} from the i th bus to the j th bus, and its limit value is denoted as $I_{limit(ij)}$; the normal voltage is denoted as U_{iN} at the i th bus, and its actual voltage is denoted as U_i ; the limit values of voltage deviation are denoted as $d_{limit-} \%$ and $d_{limit+} \%$; θ_i means the actual phase angle at the i th bus, θ_i^{limit-} and θ_i^{limit+} mean their limit values; P_{Gi} means the actual active power at the i th bus, P_{Gi}^{limit-} and P_{Gi}^{limit+} mean their limit values; Q_{Gi} means the actual reactive power at the i th bus, Q_{Gi}^{limit-} and Q_{Gi}^{limit+} mean their limit values.

2.2. Method of the new distribution network structure formation

The aim of building the new distribution network structure is to increase the allowable penetration of distributed energy resource and to allocate various energy resources optimally. According to the proposed model in section 2.1, the method of building the new distribution network structure can be described as follows and shown in figure 1.

- Step1: Choose the key buses in distribution system, for instance, connection buses of distributed energy resource, points of common coupling, overload buses, weak buses and load buses with high reliability requirement of power supply.
- Step2: Build the proposed model of the new distribution network structure in section 2.1. The model is described by multi-dimensional multi-resolution method on the basis of allocating various energy resources optimally and economically. Thus investment cost, power loss cost, outage cost and voltage improvement income are all considered in the objective function of the proposed model. In addition, transmission power, electric current, voltage, phase angle, active and reactive power still need to satisfy the constraints.
- Step3: Construct new flexible power lines and common power lines in the distribution network. According to the model established in Step2, some new flexible power lines could be constructed among key buses chosen in Step1, where various energy resources should be allocated optimally and the penetration of distributed energy resource would be increased. The capacity and position of UPFC installed on the new flexible power lines need to be determined by means of optimization algorithms. Moreover, some new common power lines could be constructed among key buses chosen in Step1, where electric power balance needs to be accomplished further.
- Step4: Check if the new distribution network has been established successfully. Then set appropriate relay protection in the new distribution network. If not, go to Step3.

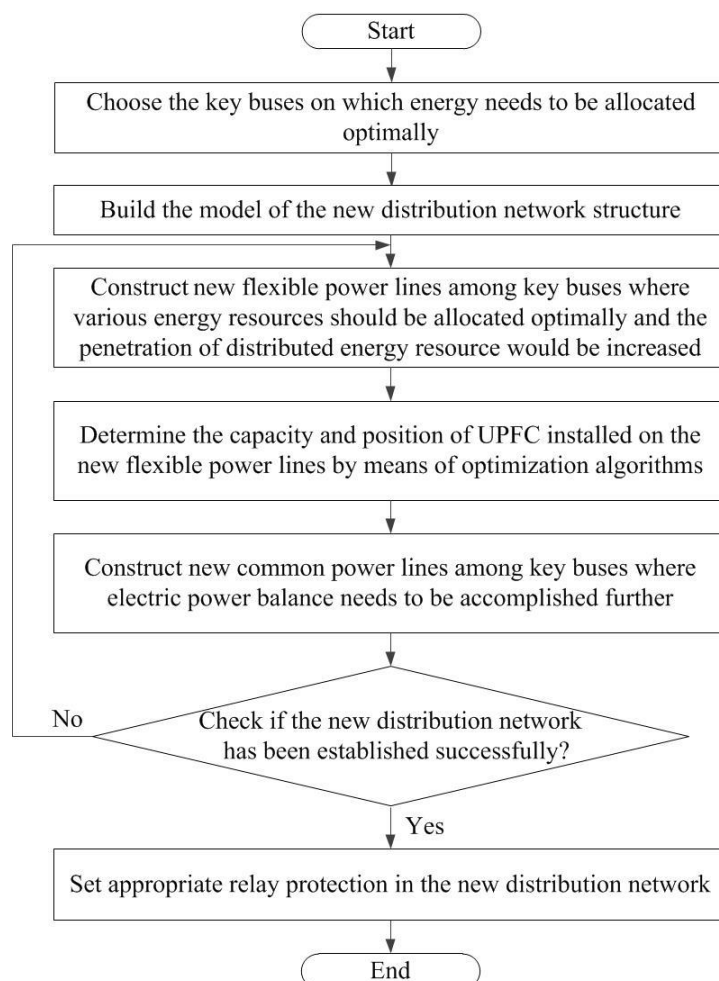


Figure 1. Method of the new distribution network structure formation.

3. Theory basis of increasing the penetration of distributed energy resource by the new structure

The maximum power supply capacity is denoted as S_B in a given distribution network. And choose it as the reference value. The ratio of the DER power output to the reference value is denoted as $a\%$. The power factor of DER is denoted as η_a . The DER is interconnected with the i th bus, and the voltage is $V_i \angle \theta_i$ at the i th bus. The apparent power of each load bus is $P_k + jQ_k$ ($k=1,2,\dots,n$). One of voltage source converters in UPFC can be equivalent to a controlled voltage source in parallel of which the voltage is $V_{sh} \angle \theta_{sh}$, and the other one can be equivalent to a controlled voltage source in series of which the voltage is $V_{se} \angle \theta_{se}$.

3.1. The maximum penetration of DER in the traditional distribution network

The active and reactive power injected by distributed energy resource is as follows:

$$\begin{cases} P_{Gi} = S_B \cdot a\% \cdot \eta_a = \sum_{k=1}^n P_{ik} + \sum_{k=1}^n \Delta P_{ik} \\ Q_{Gi} = S_B \cdot a\% \cdot \sqrt{1 - (\eta_a)^2} = \sum_{k=1}^n Q_{ik} + \sum_{k=1}^n \Delta Q_{ik} \end{cases} \quad (7)$$

In equation (7), P_{Gi} and Q_{Gi} mean the active and reactive power injected by distributed energy resource; P_{ik} and Q_{ik} mean the active and reactive power on the k th line which is interconnected with the i th bus; ΔP_{ik} and ΔQ_{ik} mean the active and reactive power loss on the k th line.

Thus the maximum penetration of DER in the traditional distribution network can be written as:

$$a\% = \frac{\sum_{k=1}^n P_{ik} + \sum_{k=1}^n \Delta P_{ik}}{S_B \cdot \eta_a} \quad (8)$$

In addition, the power loss is given by:

$$\Delta P_i = \sum_{k=1}^n \Delta P_{ik} \quad (9)$$

3.2. The maximum penetration of DER in the new distribution network

The active and reactive power which is exchanged between the voltage source converter of UPFC in parallel and the distribution system can be written as:

$$\begin{cases} P_{sh} = V_i^2 g_{sh} - V_i V_{sh} [g_{sh} \cos(\theta_i - \theta_{sh}) + b_{sh} \sin(\theta_i - \theta_{sh})] \\ Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh} [g_{sh} \sin(\theta_i - \theta_{sh}) - b_{sh} \cos(\theta_i - \theta_{sh})] \end{cases} \quad (10)$$

In equation (10), P_{sh} and Q_{sh} are the active and reactive power which is exchanged between the voltage source converter of UPFC in parallel and the distribution system; g_{sh} and b_{sh} are the conductance and susceptance of the equivalent controlled voltage source in parallel.

The active and reactive power which is exchanged between the voltage source converter of UPFC in series and the distribution system can be written as:

$$\begin{cases} P_{iL} = V_i^2 g_{se} - V_i V_L [g_{se} \cos(\theta_i - \theta_L) + b_{se} \sin(\theta_i - \theta_L)] - V_i V_{se} [g_{se} \cos(\theta_i - \theta_{se}) + b_{se} \sin(\theta_i - \theta_{se})] \\ Q_{iL} = -V_i^2 b_{se} - V_i V_L [g_{se} \sin(\theta_i - \theta_L) - b_{se} \cos(\theta_i - \theta_L)] - V_i V_{se} [g_{se} \sin(\theta_i - \theta_{se}) - b_{se} \cos(\theta_i - \theta_{se})] \end{cases} \quad (11)$$

In equation (11), P_{iL} and Q_{iL} are the active and reactive power which is exchanged between the voltage source converter of UPFC in series and the distribution system; g_{se} and b_{se} are the conductance and susceptance of the equivalent controlled voltage source in series.

The active and reactive power injected by distributed energy resource is as follows:

$$\begin{cases} P_{Gi}' = S_B \cdot a' \% \cdot \eta_a = \sum_{k=1}^n P_{ik} + P_{iL} + \sum_{k=1}^n \Delta P_{ik} + \Delta P_{iL} \\ Q_{Gi}' = S_B \cdot a' \% \cdot \sqrt{1 - (\eta_a)^2} = \sum_{k=1}^n Q_{ik} + Q_{iL} + \sum_{k=1}^n \Delta Q_{ik} + \Delta Q_{iL} \end{cases} \quad (12)$$

In equation (12), P_{Gi}' and Q_{Gi}' mean the active and reactive power injected by distributed energy resource in the new distribution network; ΔP_{iL} and ΔQ_{iL} mean the active and reactive power loss on the new flexible power line L .

Thus the maximum penetration of DER in the new distribution network can be written as:

$$a' \% = \frac{\sum_{k=1}^n P_{ik} + P_{iL} + \sum_{k=1}^n \Delta P_{ik} + \Delta P_{iL}}{S_B \cdot \eta_a} \quad (13)$$

In addition, the power loss is given by:

$$\Delta P_i' = \sum_{k=1}^n \Delta P_{ik} + \Delta P_{iL} \quad (14)$$

Therefore, the penetration of DER can be increased by the new distribution network structure. The various energy resources can be allocated optimally, and high energy efficiency can be realized.

4. Simulation results

The IEEE typical test case is established to verify the practicability of the new distribution network structure, as shown in figure 2. On basis of the test case, four simulation scenes are formed and shown in table 1. The comparisons of simulation results between scene 1 and scene 2 have been shown in figure 3. It indicates that compared with the centralized connection, the maximum allowable penetration of DER has been increased from 20% to 35% by the distributed connection.

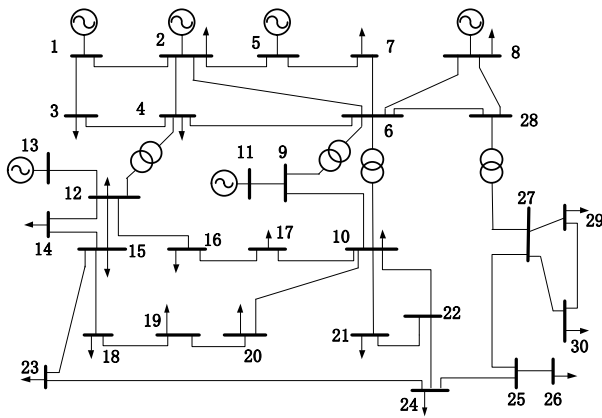


Figure 2. Typical test case of verifying the new distribution network structure.

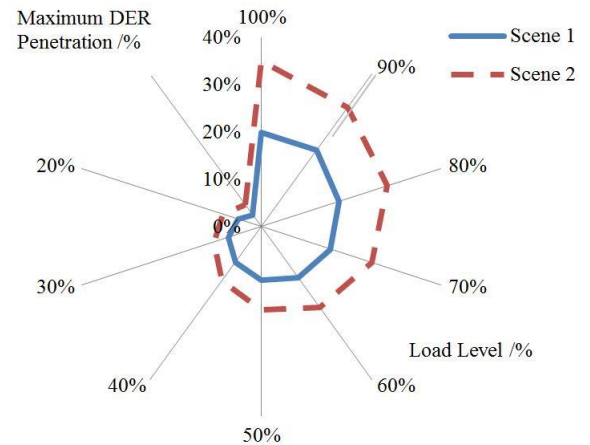


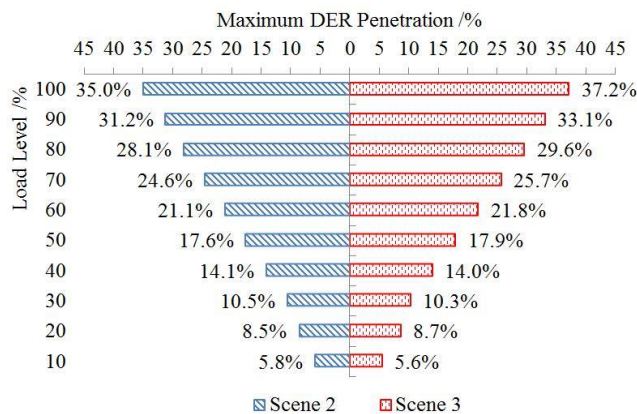
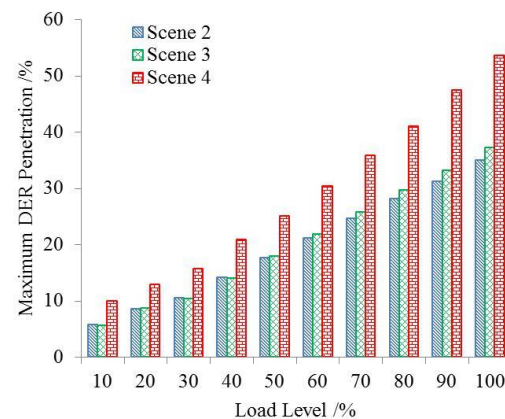
Figure 3. Maximum allowable penetration of DER in scene 1 and scene 2.

Table 1. Placement of four simulation scenes.

Scene number	Distributed energy resource			Model of constructing simple new power lines only without optimization	Model of the new distribution network structure proposed in this paper
	Connection mode	Number of DER	Connection position		
1	Centralized connection	1	12	No	No
2	Distributed connection	3	19, 21, 27	No	No
3	Distributed connection	3	19, 21, 27	Yes	No
4	Distributed connection	3	19, 21, 27	No	Yes

Figure 4 have shown the comparisons of simulation results between scene 2 and scene 3. It can be seen that constructing simple new power lines only without optimization cannot increase the maximum allowable penetration of DER.

The simulation results of scene 2, scene 3 and scene 4 have been shown in Figure 5. Compared with scene 2 and scene 3, the maximum allowable penetration of DER in scene 4 has been increased from 35% to 53.6% by the new distribution network structure proposed in this paper.

**Figure 4.** Maximum allowable penetration of DER in scene 2 and scene 3.**Figure 5.** Maximum allowable penetration of DER in three different scenes.

5. Conclusions

The paper proposes the model and method of the new distribution network structure. Then from the aspect of theoretical analysis, the conclusion that the maximum allowable penetration of distributed energy resource can be increased by the new distribution network structure has been drawn. In addition, the simulation results have also verified the correctness of the proposed model and method. And they have shown that compared with the traditional structure, the new distribution network structure can not only increase the maximum penetration of distributed energy resource greatly, but also realize the high energy efficiency, reliability and sustainability. Therefore, the issue of future distribution network security with high penetration of distributed energy resource can be well solved by the new distribution network structure proposed in the paper.

Acknowledgments

This work was supported by Science and Technology Project of SGCC (PDB17201600020, Research on analysis and evaluation of connection capability of distributed generation in distribution network).

References

- [1] J Rifkin, *The third industrial revolution: how lateral power is transforming energy, the economy, and the world* (New York: Palgrave MacMillan)
- [2] Z Ma, X X Zhou, Y W Shang and L M Zhou, "Form and development trend of future distribution system", *Proc. of the CSEE*, vol 35, pp 1289-98
- [3] G N Koutroumpezis, A S Safigianni, G S Demetzos and J G Kendristakis, "Investigation of the distributed generation capacity in a medium voltage power distribution network", *International Journal of Energy Research*, vol 34, pp 585-593
- [4] M Ettehad, H Ghasemi and S Vaez-Zadeh, "Voltage stability-based DG placement in distribution networks", *IEEE Trans. Power Del.*, vol 28, pp 171-178
- [5] L F Ochoa, A Padilha-Feltrin and G P Harrison, "Evaluating distributed generation impacts with a multi-objective index", *IEEE Trans. Power Del.*, vol 21, pp 1452-58
- [6] S X Zhang, K Li, H Z Cheng, L Z Yao and B Masoad, "Optimal siting and sizing of intermittent distributed generator considering correlations", *Automation of Electric Power Systems*, vol 39, pp 53-58
- [7] K Nekooei, M M Farsangi, H Nezamabadi-pour and K Y Lee. "An improved multi-objective harmony search for optimal placement of DGs in distribution systems", *IEEE Trans. Smart Grid*, vol 4, pp 557-567
- [8] S J Yao, Z Yan, Y Wang, Y X Yan and X Y Song, "Distribution network reconfiguration with distributed power based on genetic algorithm", *Proc. 2011 4th Int. Conf. on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, pp 811-815
- [9] A Keane, L F Ochoa, C L T Borges, G W Ault, A D Alarcon-Rodriguez and R A F Currie. "State-of-the-art techniques and challenges ahead for DG planning and optimization", *IEEE Trans. Power Syst.*, vol 28, pp 1493-1502
- [10] A Q Huang, M L Crow, G T Heydt, J P Zheng and S J Dale. "The future renewable electric energy delivery and management (FREEDM) system: the energy internet", *Proc. of the IEEE*, vol 99, pp 133-148
- [11] W Jia, Y B Feng, W Zheng and S Tang, "Application research on the connection mode of the medium voltage distribution network", *Distribution & Utilization*, vol 30, pp 36-42
- [12] S Georgiopoulos, E Cerqueira, R Johnston, R Currie and C Marantes, "Flexible plug and play low carbon networks: An open and scalable active network management solution for a faster and cheaper distributed generation connection", *22nd Int. Conf. and Exhibition on Electricity Distribution (CIRED 2013, Stockholm, Sweden)*, p 4