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Investigations on the Influence of D-FACTS Equipment on the Stability of Distribution Network

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Abstract: Distributed generation (DG) with unreasonable location and capacity will adversely affect the network loss, voltage stability and reliability of the distribution network, resulting in the underutilization of distributed energy such as wind energy and solar energy. In this paper, based on the measured wind turbine output data, the distributed flexible AC transmission system (D-FACTS) is used to optimize the power flow of the distribution network to reduce the limitation of DG position and capacity. The double changes of wind turbine output and load at different times are simulated, and the network loss, voltage level and reliability of the system are analyzed. The verification of IEEE36 distribution system shows that the installation of D-FACTS equipment on the distribution network with a large number of DGs plays a role in reducing network loss, stabilizing system voltage and improving reliability.

1. Introduction

With the rapid development of power electronics technology, the structure of distribution network becomes more and more complex. With the increasing types and quantities of power equipment at the user end, more and more nonlinear loads, impact loads and the use of power electronic conversion devices have caused great interference to the power quality of the distribution network[1-3].

Flexible AC transmission technology (FACTS) includes a series of AC transmission equipment. After this equipment are put into the system, the parameters affecting the system power flow (including transmission network node voltage, transmission line impedance and power angle, etc.) are flexibly controlled and adjusted to realize the optimization of system transmission capacity, transmission loss, system power supply reliability and power generation cost. The stability and reliability of the transmission system are greatly improved without changing the network structure of the transmission system. Common FACTS devices include thyristor-controlled series capacitor [4-6] unified power flow controller[7], static synchronous compensator (STATCOM)[8] and so on.

The distributed flexible AC transmission system (D-FACTS) is the extension and application of FACTS technology in distribution system[9]. After the D-FACTS device is put into the distribution network, its power quality is directly adjusted and improved[10].

In the research of DG grid connection, the research of paper [11] shows that when the operation position and capacity of DG play a role in enhancing the power grid, it can reduce the network loss and improve the voltage. [12] describes how to optimize the configuration of DG units in the distribution network. The coordinated control strategy of distribution network with distributed generation and static reactive power compensation is expounded in[13]. In[14][14], an improved non-dominated sorting genetic algorithm is proposed to solve the maximum active power output of DG, so as to optimize the configuration of DG units. In[15][15], a voltage optimization control scheme based on model predictive control is proposed to reduce the impact of DG access. In this paper, it is studied that the location and capacity of distributed generation in distribution network have great influence on the power quality and reliability of the system. The above literature fully shows a series of problems when DG units are connected to the grid, and puts forward some specific solutions. These methods will have better results under certain conditions, but they can not adapt to the randomness of capacity and location when DG is put into operation. Considering the above shortcomings, this paper proposes to use D-FACTS technology to minimize the adverse effects of DG on the distribution system[16].

The purpose of this paper is to use D-FACTS equipment to optimize the power flow of the distribution network, so that some voltage-sensitive node voltages are controlled within a reasonable range, and the blocking degree of the blocking line (DG unit output cannot be sent out) is minimized. Reduce the adverse effects of distributed power access on the system, and ultimately achieve the purpose of making full use of distributed power.

2. The Analysis Method of D-FACTS

2.1. Optimal Configuration Analysis of D-FACTS

In this paper, the objective function is established according to the minimum operating cost of the generator under the condition that the DG unit runs at the maximum output state after the installation of D-FACTS. Therefore, the high-voltage side generator of the distribution network is equivalent to a fixed-capacity generator model, and its operating cost is much larger than the operating cost of the DG unit. The DG unit is equivalent to a generator model, which is lower than the operating cost of the high-voltage side generator to simulate the distributed power priority.

The objective function is based on the optimal power flow model with the minimum operating cost of the generator, and the output change of the DG unit is realized by modifying the output limit of the distributed power supply according to the measured data. Since the operating cost of the distributed power supply is much smaller than the operating cost of the generator on the high-voltage side of the distribution network, and the objective function minimizes the operating cost of the generator, it ensures that the distributed power supply can be in the maximum output state under each operating mode. The objective function is as follows:

$$\min f\left(x\right)=\sum_{i=1}^{ng} a_i P_{Gi}^2 + b_i P_{Gi} + c_i \tag{1}$$

$$\sum_{k\in i} P_{Gk} - P_{Di} - U_i \sum_{j=1}^{n} U_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) = 0 \tag{2}$$

$$\sum_{k\in i} Q_{Gk} + Q_{sng} - Q_{Di} - U_i \sum_{j=1}^{n} U_j \left(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij}\right) = 0 \tag{3}$$

$$-\overline{P}_{ij} - \Delta P_{ijt\,\mathrm{csc}} \le P_{ij} \le \overline{P}_{ij} + \Delta P_{ijt\,\mathrm{csc}} \tag{4}$$

Equation (1) indicates that the objective function is the minimum operating cost of the system, where a_i, b_i and c_i are the quadratic term coefficients of the generator operating cost function, and the linear term coefficient and the constant term are constants. Equation (2) and (3) are node power balance equations; Equation (4) is the line transmission capacity constraint. When ΔP_{ijtcsc} is zero, it indicates that D-FACTS devices are not installed in the system. However, two useful Lagrange multipliers can be obtained by optimal power flow calculation, which are Lagrange multipliers with power flow inequality constraints and D-FACTS capacity inequality constraints.

According to Kuhn-Tucker theorem, the following holds:

$$\nabla f\left(x^*\right) + \sum_{j=1}^{l} \lambda_j \nabla h_j\left(x^*\right) + \sum_{i=1}^{r} \gamma_i \nabla g_i\left(x^*\right) = 0 \tag{5}$$

Where $\gamma_i g_i(x^*)=0$, $\gamma_i \ge 0$, $h(x^*)$ are the equality constraint, $g(x^*)$ is the inequality constraint. By multiplying each term of (9) by dx, the following differential equation can be obtained:

$$df\left(x^*\right) + \sum_{j=1}^{l} \lambda_j dh_j\left(x^*\right) + \sum_{i=1}^{r} \gamma_i dg_i\left(x^*\right) = 0 \tag{6}$$

In equation (6), γ_i (Lagrange multiplier) has important physical meaning, that is, after relaxing the constraint boundary $dg_i(x)$ of the inequality constraint $g(x^*)$, the improvement of the objective function value can be caused by $\gamma_i dg_i(x)$, so it represents the marginal effect on the objective function.

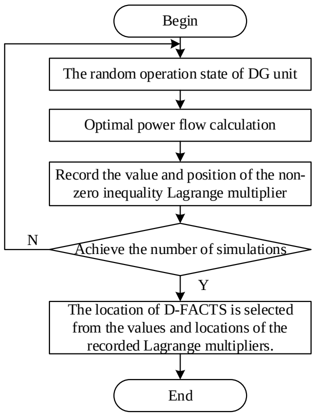

Figure 1: The flow chat of selecting D-FACTS installation position and selection.

Using the γ_i before the inequality, the corresponding D-FACTS equipment is installed on the line or node that has the greatest influence on the objective function. Figure 1 is the flow chart of D-FACTS installation location and type selection.

2.2. The Reliability Evaluation of Distribution Network with DG Units Put Into Operation and D-FACTS

In this paper, the optimal load reduction model is used to evaluate its reliability, in order to better reflect the reliability information of the system. The reliability index is calculated according to the load reduction and the probability of occurrence of the outage state of the system. The model is as follows:

$$\min f(x)=\sum_{i=1}^{nd} c_{Pi} \tag{7}$$

$$\sum_{k\in i} P_{Gk}-(P_{Di}-C_{Pi})-U_i\sum_{j=1}^{n}U_j\left(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij}\right)=0 \tag{8}$$

$$\sum_{k\in i} Q_{Gk}+Q_{sng}-(Q_{Di}-C_{Qi})-U_i\sum_{j=1}^{n}U_j\left(G_{ij}\cos\theta_{ij}-B_{ij}\sin\theta_{ij}\right)=0 \tag{9}$$

$$0\le C_{Pi}\le P_{Di} \tag{10}$$

$$0\le C_{Qi}\le Q_{Di} \tag{11}$$

$$-\bar{P}_{ij}-\Delta P_{ijt\,csc}\le P_{ij}\le \bar{P}_{ij}+\Delta P_{ijt\,csc} \tag{12}$$

Where C_{Pi} is the node active load reduction; C_{Qi} is the node reactive load reduction. The constraint condition increases the constraint of load reduction while ensuring that other constraints do not change. This can ensure that the system constraint violation is eliminated, also avoid load reduction, and ensure that the load reduction is minimized when it cannot be avoided. In this paper, the state sampling method is used to select the system state by Monte Carlo simulation. It is assumed that for a line with fault or excessive load, the line needs to be cut off. At this time, according to the minimum load reduction model, the minimum load reduction in this case is obtained and recorded at the same time. Once the optimal power flow diverges, the system voltage collapse may occur, and the optimal load reduction is the total load. The characteristics of expected energy not supplied (EDNS) and loss of load probability (LOLP) are used as the reliability indexes of the system.

3. Example Analysis

In this paper, the IEEE36 node distribution system is adopted, and the node 17 and node 34 are connected to form a ring network operation. Through the connection to form a ring network operation, it can not only give full play to the flexible control ability of D-FACTS, but also save investment and reduce the installation number of D-FACTS equipment. The example simulates the influence of the installation of D-FACTS equipment on the system network loss, voltage and reliability when the installation position of the system wind turbine is fixed. Table 1 shows the installation location, type and capacity of DG units.

Table 1: The position, selection and capacity for DG.

Access position	Types of DG	Maximum capacity
Node 10	Wind turbine	300kW
Node 14	Wind turbine	300kW
Node 23	Wind turbine	180kW
Node 32	Wind turbine	250kW
Node 35	Wind turbine	100kW

Figure 2 shows the number of out-of-limits when the operating range of the D-FACTS device installed on the system node is zero after simulating 5000 system operating states. Because the transmission capacity constraint range of the example line is wide, there is no line power flow exceeding the limit in the simulation process. The fluctuation of load and the change of wind turbine output are the changes of simulation system.

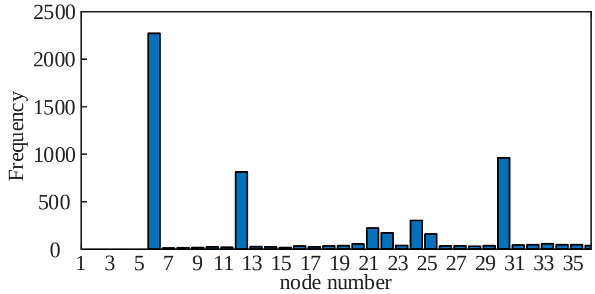

Figure 2: The time of D-FACTS exceed the limit when the limit to be zeros.

According to Figure 2, it can be seen that in the case of load and wind turbine output changes, the number of D-FACTS equipment constraints of nodes 6, 12 and 13 is relatively high, and node 6 is relatively higher. If you want to make the operating state of the system more stable, you can install D-FACTS devices on the corresponding nodes. The location, type, and capacity of D-AFCS devices can be selected, as shown in Table 2.

Table 2: The location, type and size of the need to install D-FACTS.

Position	Type	Capacity
Node 6	SVC or SVG	±100kVA
Node 12	SVC or SVG	±100kVA
Node 30	SVC or SVG	±100kVA

Therefore, the values of Q_{svgmin} and Q_{svgmax} constrained by the corresponding nodes are modified. Then, it is equivalent to installing controllable D-FACTS reactive power compensation devices with adjustable capacity of ±100KVA on nodes 6, 12 and 30 of the system respectively. Re-simulate the system operation status for 5000 times, and the system load, wind turbine output and other conditions are the same as before D-FACTS was installed. The network loss of each running state is analyzed. Figure 3 shows the network loss of 300 running states out of 5000 simulated running states captured at any time. In Figure 3, the black curve represents the network loss rate when the system is installed with D-FACTS, and the gray curve represents the network loss rate when the system is not installed with D-FACTS. It can be seen from Fig 3 that the network loss decreases significantly when the system is installed with D-FACTS, and the installation of D-FACTS can reduce the network loss more effectively when the fluctuation is large. The fluctuation of the network loss is caused by the change of load and the change of wind turbine output. However, it can be seen from the Fig.3 that no matter the network loss increases or decreases, the network loss decreases after the installation of D-FACTS equipment.

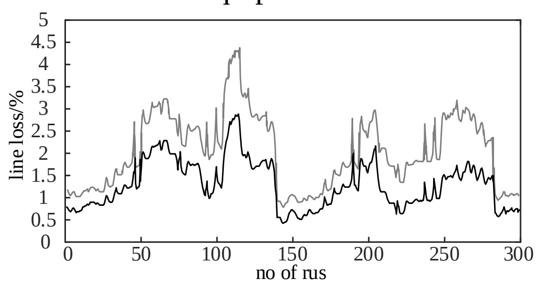

Figure 3: The curve of line loss change.

Figure 4 compares the average voltage of nodes before and after D-FACTS equipment is installed in the system. The gray bar line indicates the node voltage amplitude when D-FACTS is not installed in the system, and the black line indicates the node voltage amplitude when D-FACTS is installed in the system.

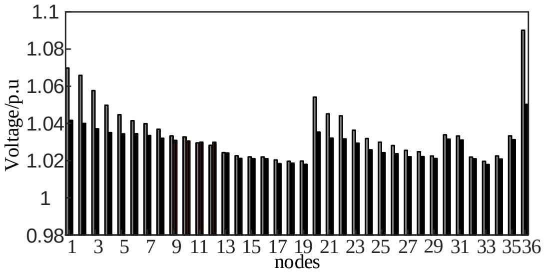

Figure 4: The system node average voltage with D-FACTS and without D-FACTS.

As shown in Figure 4, in the absence of D-FACTS devices in the system, node 36 is the liaison node between the power distribution system and the main network. In order to maintain the voltage of other nodes in the system, the voltage of this node seriously exceeds the limit, and nodes 1 and 2 also exceed the limit, which seriously affects the voltage safety of users connected to these nodes. After installing D-FACTS devices on nodes 6, 12, and 30, all node voltages are within a safe range, reducing load loss due to voltage failures. Due to the access of DG, the operation reliability of the distribution network has been improved to a certain extent. For example, in the area with access to DG, if there is some system failure, the DG in the area can continue to supply power to the important load. This example uses the optimal load reduction model to evaluate the reliability of DG and D-FACTS in the distribution network.

Due to the large fluctuation of DG output, the failure of DG unit will not be considered and it is considered that it does not occur fault except for outage and output change caused by climate, environment and other factors. Table 3 shows the outage rate of system components. The reliability index adopts expected power shortage (EDNS) and expected load cutting probability (LOLP) to reflect the reliability of the system. This paper simulated the system operation for 10,000 times, and its reliability index is shown in Table 4.

Table 3: The outage of system component.

High pressure side contact line	Circuit
0.001	0.003

Table 4: Reliability index.

Reliability index	No DG No D-FACTS	There is DG No DFACTS	There is DG There is D-FACTS
EDNS percentage of load /%	1.22	0.95	0.85
LOLP	0.1099	0.0934	0.1012

It can be seen from Table 4 that when the distributed power supply is connected to the system, the EDNS and expected LOLP are reduced, indicating that the system reliability is improved. namely: If the system fails, the DG can supply power to some important users, or if there is DG in the island after the system is isolated, the island can continue to maintain power supply for some users. The installation of D-FACTS also improved the reliability significantly, and the expected power supply shortage was significantly better than that of the operating DG without D-FACTS. Since the D-FACTS device installed in the system only adjusts the reactive power, it cannot fundamentally reduce the frequency of load cutting, so the expected load cutting probability does not change much. Because the adjustment of reactive power can make some DG units that need to absorb (emit) reactive power continue to provide active power output, the size of the cutting load is reduced, the accident scale is reduced, the EDNS is fundamentally reduced, and the reliability of the system is improved.

4. Conclusions

In this paper, according to load changes and wind turbine output changes, Monte Carlo is used to simulate the operation of the system after connecting to the DG unit. The example of IEEE36-node power distribution system shows that installing D-FACTS equipment on the existing power distribution network plays an important role in stabilizing system voltage, reducing network loss and improving reliability. Especially in improving voltage stability and reducing network loss effect is remarkable. This method makes full use of distributed energy to solve the problems of power supply shortage and unreasonable distribution in some areas.

References

[1] P. S. Georgilakis, N. D. Hatziargyriou, "Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research," in IEEE Transactions on Power Systems, vol. 28, no. 3, pp. 3420-3428, Aug. 2013.

[2] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, N. D. Hatziargyriou, "Distributed and Decentralized Voltage Control of Smart Distribution Networks: Models, Methods, and Future Research," in IEEE Transactions on Smart Grid, vol. 8, no. 6, pp. 2999-3008, Nov. 2017.

[3] V. Terzija et al., "Wide-Area Monitoring, Protection, and Control of Future Electric Power Networks," in Proceedings of the IEEE, vol. 99, no. 1, pp. 80-93, Jan. 2011.

[4] T. U. Okeke, R. G. Zaher, "Flexible AC Transmission Systems (FACTS)," in 2013 International Conference on New Concepts in Smart Cities: Fostering Public and Private Alliances (SmartMILE), Gijon, Spain, 2013, pp. 1-4.

[5] Rathi, A. Sadda, L. Nebhnani and V. M. Maheshwari, "Loss minimization with D-FACTS devices using sensitivity based technique," in 2012 IEEE 5th India International Conference on Power Electronics (IICPE), Delhi, India, 2012, pp. 1-5, doi: 10.1109/IICPE.2012.6450427.

[6] L. D. Colvara, "The influence of the TCSC on power system transient energy," in IEEE Latin America Transactions, vol. 3, no. 3, pp. 284-289, July 2005.

[7] S. An, J. Condren, T. W. Gedra, "An Ideal Transformer UPFC Model, OPF First-Order Sensitivities, and Application to Screening for Optimal UPFC Locations," in IEEE Transactions on Power Systems, vol. 22, no. 1, pp. 68-75, Feb. 2007.

[8] Z. Seddik et al., "Power system stability improvement using shunt FACTS device controller based D-statcom," 2023 Second International Conference on Energy Transition and Security (ICETS), Adrar, Algeria, 2023, pp. 1-5.

[9] Y. Sang, M. Sahraei-Ardakani, "Economic Benefit Comparison of D-FACTS and FACTS in Transmission Networks with Uncertainties," 2018 IEEE Power & Energy Society General Meeting (PESGM), Portland, OR, USA, 2018, pp. 1-5.

[10] D. Zhao, S. Jiang, L. Ma, X. Jin, H. Li, D. Hu, "Research on application of high reliability structure in medium voltage distribution network," 2023 2nd International Conference on Smart Grids and Energy Systems (SGES), Guangzhou, China, 2023, pp. 14-18.

[11] W. Wei, X. Lijie, W. Shidan, K. Jun , G. Jing, "Research on the reactive power optimization of distribution network including DG," 2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Aalborg, Denmark, 2012, pp. 207-210.

[12] C. Ma, Q. Duan, H. Wang, Y. Mu, "Multi-objective Dynamic Network Reconstruction Method for Active Distribution Network Including Distributed Generation and Electric Vehicles," 2022 5th International Conference on Energy, Electrical and Power Engineering (CEEPE), Chongqing, China, 2022, pp. 612-617.

[13] J. Yang et al., "Research on the Mechanism of Affecting the Transmission Capability of HVDC Connected to Weak AC System Considering STATCOM," 2018 International Conference on Power System Technology (POWERCON), Guangzhou, China, 2018, pp. 2524-2532.

[14] L. J. Santander-Hernández and C. Angeles-Camacho, "Implementation of distributed compensation in the transmission lines design (D-FACTS)," 2015 IEEE Thirty Fifth Central American and Panama Convention (CONCAPAN XXXV), Tegucigalpa, Honduras, 2015, pp. 1-4.

[15] L. Ming, W. Yue and W. Zhaoan, "Research on transient performance of D-FACTS," 2011 International Conference on Electrical and Control Engineering, Yichang, China, 2011, pp. 4927-4930.

[16] K. M. Rogers and T. J. Overbye, "Power flow control with Distributed Flexible AC Transmission System (D-FACTS) devices," 41st North American Power Symposium, Starkville, MS, USA, 2009, pp. 1-6.