Analysis of Short-circuit Current Calculation Method in Wind Power Plant Design

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Abstract—Due to the differences between wind power plant and normal power plant in mathematical model and network structure, it will lead to great discrepancy between the results worked respectively by the practical method of normal short-circuit current calculation and the international popular IEC60909 method in engineering design. Therefore this paper analyzes the differences between the two methods and put forward an improved practical method. Finally with the simplified modeling of collection lines, the effectiveness and feasibility of this method is verified by the actual wind power plant data and simulation results with ETAP. This method offers some ideas to the establishment of uniform standards of short-circuit current calculation method of wind power plant in our country.

Index Terms—Short-circuit calculation, practical calculation method, IEC60909, wind power plant.

1. I NTRODUCTION

At present, the clean energy has been paid great attention by the countries all over the world. And with the continuous innovation of technology, the development of wind power has attracted worldwide attention [1][2]. However there are many differences between wind power plant and normal power plant in the unit arrangement, system composition, system configuration and equipment selection [3], therefore the practice of normal power plant cannot be completely copied, in the design of the wind power plant, to avoid large design errors.

In electric power engineering design, short-circuit current calculation is the foundation for electrical equipment selection, conductor selection, relay protection setting and checking, and the results will directly affect the electrical system safety, reliability and cost of the project. [4-6] analyzed the effects of different wind turbine models on short-circuit current, and derived the corresponding expressions which was cumbersome in the actual engineering application. However there are not a unified standard to analysis or calculate the short-circuit current of wind power plant at home and abroad. In foreign countries, the short-circuit current calculation method based on IEC60909 standard (IEC60909 method) is usually used [7-9], while the short-circuit current calculation method in national standard (practical method) is adopted in our country [10]. Due to the different models and methods of calculation, the results of short-circuit calculation of wind power plant are quite different. Therefore the similarities and differences of the two methods were analyzed, then an improved engineering practical

calculation method was proposed in this paper, and the efficiency of this method was verified by using actual wind power data and ETAP.

II. SHORT-CIRCUIT CURRENT CALCULATION METHOD IN WIND POWER PLANT DESIGN

The structure of collector system and generator is the main difference between wind power plant and normal power plant. At present, the mainstream models of wind power plant are doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG), which are different from the traditional turbine, such as steam turbine and hydro-turbine, in the unit structure and calculation model. And the generator wiring is generally in a chain structure inside the wind power plant, while it is unit wiring type inside the traditional power plant. Therefore, this paper analyzed the calculation method of short-circuit current of wind power plant, and proposed a improved practical calculation method which is more suitable for engineering practice. This section focused on the model analysis of the power supply and the wind power generator.

A. The Practical method

When calculating the short-circuit current of the power system by the practical method, the impedance of all the equipment (the reactance instead of the impedance is used in the calculation to simplify the calculation) in the network is calculated as the corresponding per-unit value according to the unified power reference value, regardless of the load in the network. Then draw the equivalent system network, simplify the network, obtain the transfer reactance, achieve the short-circuit current of each power supply to the fault point, and the total value of short-circuit current could be obtained by the summation.

In the practical method, the short-circuit current is supplied by the two kinds of power supply, the infinite system power supply and the limited power supply.

For the system with infinite capacity of power supply, the power supply voltage is kept constant during the short circuit, and the per-unit value of the voltage is 1.0. The short-circuit current and short-circuit impulse current are given as follows:

$$I_k^* = \frac{1}{x_*} \cdot \frac{S_d}{\sqrt{3}U_d} \tag{1}$$

$$i_{sh} = k_{sh}\sqrt{2}I_k^* \tag{2}$$

$$\kappa = 1 + e^{-0.01/T_a} \tag{3}$$

where $I_k^{''}$ is the initial symmetrical short-circuit current; $x*$ is the short-circuit reactance (the subscript * indicates that the variable is the per-unit value); S_d is the reference capacity; U_d is the reference voltage at fault point; i_{sh} is the short-circuit impulse current; k_{sh} is the impact factor; $T_a = X_\Sigma / \omega R_\Sigma$ is the time constant; X_Σ and R_Σ are short-circuit reactance and resistance respectively.

For the convenience of calculation in engineering, k_{sh} takes different values directly according to different short-circuit points, instead of using (3). When the short circuit point is the exit of the generator, k_{sh}=1.9; When the short circuit point is the high voltage side of transformer in the power plant, k_{sh}=1.85; When the short circuit point is other location of the high voltage power grid, k_{sh}=1.8.

For the system with limited capacity of power supply, generally using the calculation curve method. Since there are a lot of resources describing the method, they won't be covered in this paper. In particularly, limited capacity of power supply can be treated as the infinite capacity of power supply when $x* > 3.45$.

In the practical method, the equivalent reactance of the feeder system is estimated based on (4), which is also present in [10].

$$x_{s*} = S_d / S_k \qquad (4)$$

where S_k is short circuit capacity of the dividing bus of the feeder system.

The wind power generator is processed by the high voltage motor, and the short-circuit current and the short-circuit impact current can be estimated based on (5) and (6).

$$I_{kM}^{''} = \frac{1}{x_{M*}} \cdot I_{MN} \qquad (5)$$

$$i_{shM} = k_{shM} \sqrt{2} I_{kM}^{''} \qquad (6)$$

Where x_{M*} is per-unit value of the motor subtransient reactance, which is equal to the reciprocal of the starting current ratio; I_{MN} is the motor rated current; generally the impact factor is equal to 1.4-1.6, which is estimated as 1.5 in this paper.

The model and formula of other electric equipments, such as transformers, cables and overhead lines, etc, could be found in national standard. And this paper won't repeat them because of the limited space.

B. The IEC60909 Method

In the International Electrical Commission (IEC) the latest promulgated standards (IEC60909), an equivalent voltage source at the short-circuit location is used for calculation. The equivalent voltage source ($c U_N / \sqrt{3}$) is the only active voltage of the system. All network feeders, synchronous and asynchronous machines are replaced by their internal impedances. The impedances of all the equipment in the network are calculated as their actual values instead of the corresponding per-unit value. Then draw and simplify the network to obtain the short-circuit impedances, and the short-circuit current and short-circuit impulse current are given as shown in (7)-(10).

$$I_k^{''} = \frac{c U_N}{\sqrt{3} Z_k} \qquad (7)$$

$$Z_k = \sqrt{R_k^2 + X_k^2} \qquad (8)$$

$$i_{sh} = \kappa \sqrt{2} I_k^{''} \qquad (9)$$

$$\kappa = 1.02 + 0.98 e^{-3R_k / X_k} \qquad (10)$$

where U_N is the rated voltage of the fault point; c is the voltage factor corresponding to U_N; Z_k is the short-circuit impedance; κ is the impact factor, which can be estimated based on (10); X_k and R_k are short-circuit reactance and resistance respectively.

In the IEC60909 method, at the moment of calculating the maximum short circuit current, c is equal to 1.05 or 1.1 in low voltage systems (100V~1000V), and 1.1 in medium and high voltage systems (>1kV).

The correction factor and different calculation formulas are used to calculate the impedances of the electrical equipments. Only the feeder system and wind power generator are described in this paper, other equipments could be found in the literature [7].

The equivalent impedance of the feeder system is estimated based on (11).

$$Z_Q = \frac{c U_{nQ}}{\sqrt{3} I_{kQ}^{''}} \qquad (11)$$

where Z_Q is the modified equivalent impedance of the feeder system; U_{nQ} is the rated voltage of the point Q; $I_{kQ}^{''}$ is the short circuit current of the point Q. Generally if R_Q/X_Q is unknown, $Z_Q=0+jX_Q$ when $U_{nQ}>35kV$, while $R_Q=0.1_{X_Q}$ and $X_Q=0.995R_Q$ are used to estimate the resistance and reactance when $U_{nQ}<35kV$.

The wind power generator is processed by the high voltage motor, and its short circuit impedance can be estimated based on (12).

$$Z_M = \frac{1}{I_{LR} / I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} I_{rM}} \qquad (12)$$

where Z_M is the impedance of the motor; U_{rM} is the rated voltage of the motor; IrM is the rated current of the motor; I_{LR}/I_{rM} is the ratio of the locked-rotor current to the rated current of the motor.

If R_M/X_M is unknown, the resistance and reactance of the motor could be estimated based on (13).

$$\begin{cases} R_M = 0.1 X_M, U > 1kV, P_{rM} \geq 1MW \\ R_M = 0.15 X_M, U > 1kV, P_{rM} < 1MW \\ R_M = 0.42 X_M, U < 1kV \end{cases} \qquad (13)$$

where R_M and X_M are the motor resistance and reactance respectively; P_{rM} is the motor rated power per pair of poles.

The model and formula of other electric equipments, such as transformers, cables and overhead lines, etc, could be found in IEC60909 standard. And this paper won't repeat them because of the limited space.

C. The improved calculation method

The influence of resistance on the result and the calculation of short circuit impact factor are neglected in the practical method, the accuracy of the calculation results will be greatly influenced although the calculation process is simplified. So the practical method with faster computing speed is more suitable for the rough and rapid calculation.

Compared to the practical method, the voltage correction factor c, the resistance, the correction coefficient and the modified calculation formula are considered in the IEC60909 method. Obviously the calculation results will be more comprehensive and accurate with the more complicated calculation process. Therefore calculation speed of the IEC60909 method is more slow, however the detailed and accurate calculation is more suitable for it.

For engineering calculation, the calculation accuracy of the

practical method is not high, calculation process of the IEC60909 method is complicated, so an improved short-circuit current calculation method (improved method) is proposed in this paper, based on the index of the calculation accuracy and the goal of the fast and convenient calculation.

The equivalent voltage source method used in IEC60909 method is similarly used in the improved method. The source is the only active voltage of the system. The electric potential of other power supplies are regarded as zero and replaced by their own internal impedance. After modified the impedance of all the equipment in the network, they will be calculated as the corresponding per-unit value according to the unified power reference value. Then draw and simplify the network to obtain the short-circuit impedances, and the short-circuit current and short-circuit impulse current are given as shown in (14)-(15).

$$I_{impk}'' = \frac{1}{Z_{k*}} \cdot \frac{cS_d}{\sqrt{3}U_d} \qquad (14)$$

$$i_{impsh} = k_{impsh}\sqrt{2}I_{impk}'' \qquad (15)$$

where I_{impk}'' is the initial symmetrical short-circuit current (the subscript imp means the improved method); c is the voltage factor, its value is the same as the IEC60909 method; Z_{k*} is the short-circuit impedance; S_d is the reference capacity; U_d is the reference voltage at fault point; i_{impsh} is the short-circuit impulse current; k_{impsh} is the impact factor.

It is important to note that the ratio of the short-circuit resistance and reactance is equal to 9999 similarly. In this way, there is no complex number in the calculation so that the calculation process is simplified; on the other hand, the reactance and the impedance are approximately equal in value according to the relationship shown in $|Z_{k*}| = \sqrt{R_{k*}^2 + X_{k*}^2} \approx |X_{k*}|$, therefore the calculation accuracy of the results is trustworthy.

With the analysis of the two methods on the short-circuit impact current calculation formulas, it was not difficult to find that the main influencing factor to calculate the short-circuit current between the practical method and the IEC60909 method was the impact factor. Therefore this paper tried to deduce the value of the impact factor in the improved method, which is as shown in Table I, to improve calculation speed. The way is similar to the practical method.

TABLE I. Impact Factors of The Improved Method

Short circuit point	The exit point of the generator	The high voltage side of package transformer	Other point
k_{impsh}	1.53	1.86	1.81

In the improved method, the equivalent impedance of the feeder system is estimated based on (16).

$$Z_{imps*} = c \cdot S_d / S_k \qquad (16)$$

where Z_{imps*} is the impedance of the feeder system; S_k is short circuit capacity of the dividing bus of the feeder system.

The wind power generator is processed by the high voltage motor, and its short circuit impedance is given as shown in (17).

$$Z_{impM*} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{S_d}{S_{rM}} \qquad (17)$$

where Z_{impM*} is the impedance of the wind power generator; S_{rM} is the rated capacity of the generator; I_{rM} is the rated current of the generator; I_{LR}/I_{rM} is the ratio of the locked-rotor current to the rated current of the generator.

The model and formula of other electric equipments could be estimated as the corresponding modified per-unit value according to the unified power reference value, the same as above method in principle.

III. SIMULATION AND RESULTS

The data of an actual wind power plant was taken to carry out the verification of the improved method with ETAP. The wind power plant contains 38 DFIGs with stand-alone capacity of 4MW, and the output voltage of the wind generator is 0.69kV. With the connection form, "one generator and one transformer", each wind power generator is configured with a 4500kVA package transformer. The 38 DFIGs are divided into 6 groups, and connected to the 35kV bus of the offshore substation of the wind power plant with 6 collection lines, then connected to the 110kV bus of the onshore substation of the wind power plant with 2 marine cables, and connected to external power grid at last. In order to simplify the calculation, only one set of generating units was retained and the other groups are simplified by the equivalent method proposed by [11]. The wiring diagram of the simplified system is as shown in Figure 1.
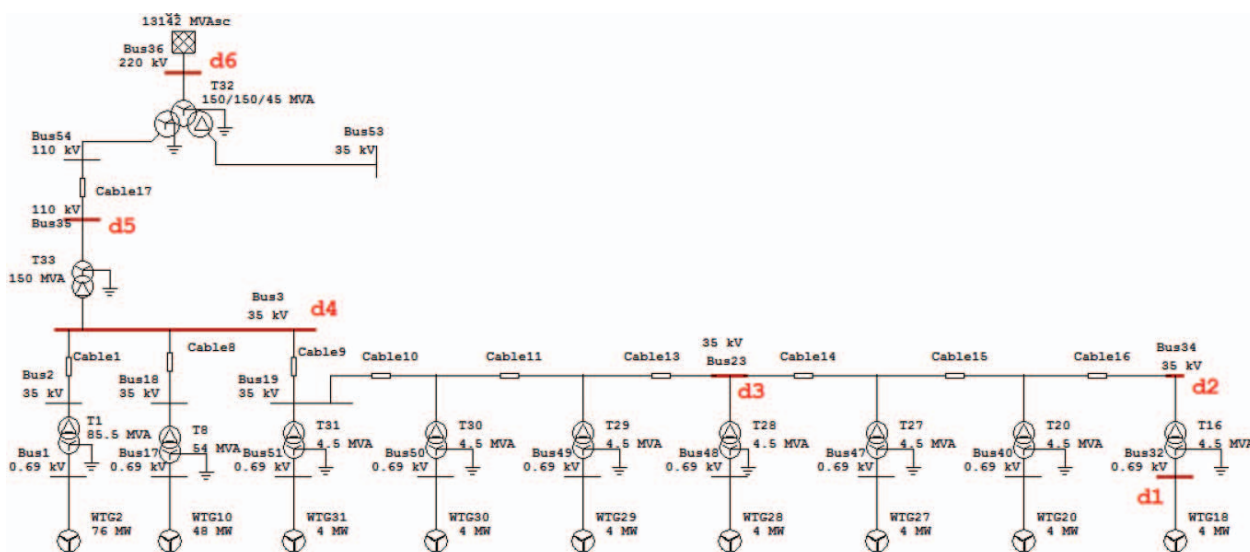
Fig.1 The main wiring diagram of the equivalent wind power plant

In Fig.1, the red lines are the short circuit points, which are shown as follows:

Point d1 is Bus32, the exit point of the wind power generator, 0.69kV;

Point d2 is Bus34, the terminal point of the single collection line, 35kV;

Point d3 is Bus23, the middle point of the single collection line, 35kV;

Point d4 is Bus3, the low pressure side of the offshore substation, 35kV;

Point d5 is Bus35, the high pressure side of the offshore substation, 110kV;

Point d6 is Bus36, the high pressure side of the onshore substation (the point connected to external power grid), 220kV;

Symmetrical short-circuit current of above points were calculated using the practical method (PM), the improved method (IM) and the method in ETAP (the IEC60909 method) respectively,

TABLE II. Results of Short-circuit Current Calculation

Short circuit point	Calculation method	short-circuit current (kA)	short-circuit impulse current (kA)
d1 0.69kV	PM	72.41	173.83
	IM	76.01	184.10
	ETAP	77.62	179.98
d2 35kV	PM	6.57	16.926
	IM	6.80	17.448
	ETAP	7.249	12.10
d3 35kV	PM	9.07	23.49
	IM	9.48	24.285
	ETAP	10.02	17.94
d4 35kV	PM	20.49	52.16
	IM	22.58	57.79
	ETAP	22.87	56.84
d5 110kV	PM	6.92	17.605
	IM	7.67	19.525
	ETAP	7.76	19.53
d6 220kV	PM	35.30	89.86
	IM	35.38	90.06
	ETAP	35.39	94.42

After analyzing the results of calculation in Table II, the two points are given as follows:

a) The practical method simplifies the calculation process, and it is simple and convenient, however the value of calculation is smaller, so the practical method is more suitable for rough and rapid calculation. The IEC60909 method has detailed calculation, however, its process is cumbersome and complex and the calculation values are bigger, so the IEC60909 method is more suitable for precise and detailed calculation. The calculation results of the improved method proposed in this paper are more closed to the simulation results, while the method is more simple than the IEC60909 method and more accurate than the practical method. The effectiveness and feasibility of this method is verified.

b) The structure of the collection network in the wind plant had great influence on the result of short circuit impulse current. Especially when short-circuit faults occur in d2 or d3 point, there would be a considerable error in the impulse current obtained by different methods, which demand particular attention, and a more appropriate impact factor may be obtained in the further research.

IV. CONCLUSION

The similarities and differences between the two methods are analyzed in this paper firstly, and then put forward an

improved practical method based on the index of the calculation accuracy and the goal of the fast and convenient calculation. Finally with the comparison and analysis to the results calculated using the three methods, the effectiveness and feasibility of the improved method is verified. This method offers some ideas to the establishment of uniform standards of short-circuit current calculation method of wind power plant in our country.

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