Simulation Analysis on Overvoltage of Wind Turbines by Lightning Stroke

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Abstract- With the large-scale exploitation and use of fossil fuels, the reserves of fossil fuels are decreasing. Therefore, people are looking for new energy sources that could replace non-renewable emery. Wind power technology develop, under such circumstance. The selected wind farm in the paper is located in northern Shaanxi, with high transmission voltage level and large installed capacity. Wind turbines work in the natural environment, and it often use high-tower structure, installed in open, low-altitude mountains or above sea in order to obtain abundance wind energy resources, which makes it vulnerable to lightning. In the paper the lightning overvoltage characteristics under lightning stroke are studied by simulation, and the effective lightning protection measures are put forward. When lightening stroke, the higher amplitude of the lightning current is, the higher overvoltage of components will be. And when the phase number of incoming wave increase, the overvoltage of transformer will increase but thyristors' will decrease. After installing arrester, the overvoltage will be limited, but there is still a certain distance that cannot be exceed.

Keywords- Wind turbine; lightning overvoltage; arrester; transformer; thyristor

I. INTRODUCTION

The development of electric power system depends on the primary energy, such as oil, coal, natural gas which belongs to non-renewable energy[1]. The reserves of non-renewable energy is decreasing with the development of electric power system. As a kind of clean and renewable energy, wind power technology is the most mature one, and it would reduce environmental pollution and make great contribution to relieve energy shortage[2],which make it become the focus of country's attention. And also wind power is also the world's fastest growing energy, the installed capacity of which keep a continue growing at more than 20% a year[3].

In order to obtain the best wind resources, the wind turbines are generally installed in open areas, and the height of wind turbines increase with the increasing height of impeller diameter, which results in its vulnerable to be struck by lightning[4]. Wind turbines are the most valuable equipment in wind farms, whose price accounts for more than 60% of the entire wind power project investment[5]. Due to the weak electromagnetic compatibility and the low insulation strength of wind turbines, the damage caused by lightning occurs frequently. Lightning has become the greatest harm to the safe and stable operation of wind power system. Therefore, it would have great significance to study the characteristics of lightning overvoltage and find out the effective protection measures to ensure proper and reliable operation of wind power generation system.

A 330kV wind farm simulation model was established in this paper. Lightning overvoltage in the internal rectifier inverters, filter elements and transformer was studied, and arresters were used to restrain this lightning overvoltage. Results show that the lightning overvoltage in transformer would increase with the increase number of phases that lightening coming into the system, while the regular of thyristor is opposite, and the protective effect of arresters decreases with the increase distance from the protected original.

II. SIMULATION MODEL OF 330kV WIND FARM

A. Principle of wind farm

The 330kV wind farm is a wind farm gathering station in the north of Shaanxi. This wind farm differs from the past small-capacity, low-voltage wind farm. It has the features of high power transmission level, large capacity and fewer incoming and outgoing lines. Non-boosting gearbox and variable speed constant frequency technology are used in this wind turbines. The main circuit includes generator, rectifier inverter unit, filter and transformer, which is shown in Fig.1.

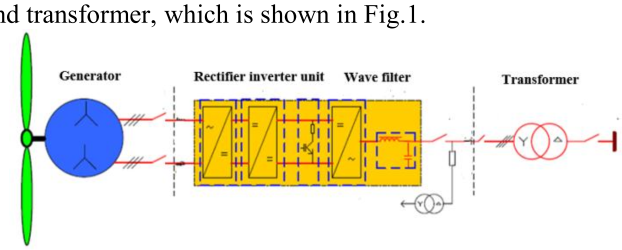


Fig.1.Main circuit schematic diagram of the wind turbines[6]

The wind farm consists of 50 sets 1.5MW doubly-fed wind turbines. The voltage of the transformer is 690V/35kV. The collector line sent the electric energy to 35kV bus, which is connected to the 330kV bus station by 35 / 330kV transformer. The electrical connections are shown in Fig.2. Y connection is used on the low voltage side of 690V/35kV transformer, and delta connection is used on high voltage side. The main transformer of 330 kV side use Y0 connection, while 35 kV side with delta connection.

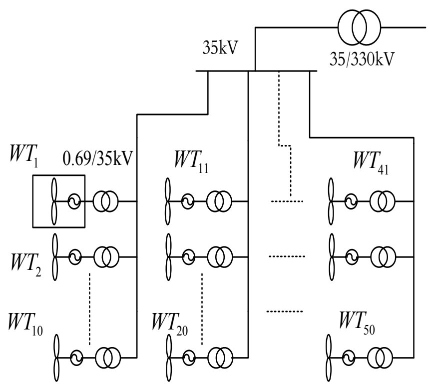


Fig.2.Electric circuit of wind farm

B. Simulation model

The rated voltage of the wind turbine is 690V, and the neutral point is not directly connected to the ground. Therefore, the neutral point in Simulation is grounded through the large resistance (105Ω)[7]. Experiences show that voltage of distribution network is not considered during lightning strike[8]. The circuit of double-fed wind generator is shown in Fig. 3, and the parameters are shown in Table I.

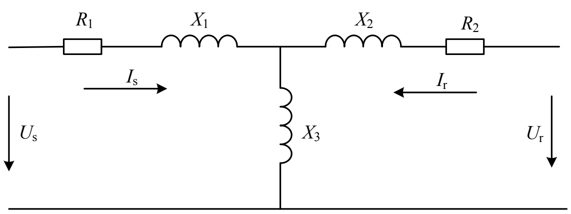


Fig.3. The circuit of double-fed wind generator[9]

TABLE I
THE PARAMETERS OF GENERATOR

Component	Element symbol	Value
Stator resistance	R_1	0.00205Ω
Stator reactance	X_1	0.0748mH
Rotor resistance to stator side	R_2	0.00182Ω
Rotor reactance to stator side	X_2	0.0614338mH
Magnetizing reactance	X_m	3.915212mH

The rectifier inverter unit is installed inside the wind turbines. The thyristor has a much lower tolerant voltage level than other devices. Back-to-back six-pulse rectifiers inverter circuit was used for the consideration of cabin size and economy reason. When thyristor is conducted, it is equal to resistance-capacitance series-parallel circuit; it is equal to a capacitor while it is cut-off[10]. The thyristor equivalent circuit is shown in Fig.4, and the parameters are shown in Table II.

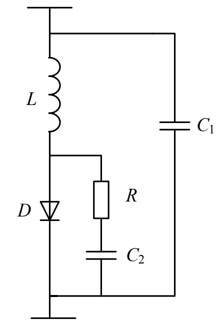


Fig.4.The thyristor equivalent circuit

TABLE II
PARAMETERS OF THYRISTOR EQUIVALENT

Component	Element symbol	Value
Series inductance of saturated reactor	L	0.0557mH
Resistance of resistance capacitance loop	R	0.567Ω
Series capacitor	C_1	0.0096μF
Capacitor of resistance capacitance loop	C_2	0.927μF

The underground cable sent electricity to 690V/35kV transformer, and it could be equal to π-type circuit under normal operation for analysis and calculation. The equivalent model of transformer under transient circumstance is shown in Fig. 4, and the parameters are shown in Table II.

When the lightning wave invade from the fan side, the voltage of transformer high side is shown as below(considering the magnetic component and field components)[11]:

$$U=\frac{C_{12}}{C_{12}+C_{20}}\cdot U_0+U_0\cdot k \quad (1)$$

$$U_1=\frac{C_{12}}{C_{12}+C_{20}}\cdot U_0 \quad (2)$$

The voltage coupling of the field component are taken in consideration in the above formula. While $U_2=U_0\cdot k$ when the voltage coupling of the magnetic component (k=50.72)is taken in consideration. According to the data given in Table II, $U_1=0.193U_0$, $U_2=50.72U_0$.

When the lightning wave invade from overhead line side, the voltage of transformer high side is shown below (considering the magnetic component and field components):

$$U=\frac{C_{12}}{C_{12}+C_{10}}\cdot U_0+\frac{U_0}{k} \quad (3)$$

$$U_1=\frac{C_{12}}{C_{12}+C_{10}}\cdot U_0 \quad (4)$$

The voltage coupling of the field component are taken in consideration in the above formula. While $U_2=U_0/k$ when the voltage coupling of the magnetic component (k=50.72) is taken in consideration.

It's easy to figure out that when the lightning invade from the fan side, the field component part of the voltage proportion is very small, the impact on the overvoltage could be ignored, so that only the magnetic component of voltage is needed to be considered. When the lightning wave invade from overhead line side, only the field component of voltage is needed to be considered.

III. SIMULATION STUDYOF OVERVOLTAGEUNDERDIFFERENT LIGHTNING SITUATION

The study of incoming wave overvoltage is divided into single-phase and multi-phase. The operating mode is the most rigorous when there is only one wind turbine, and the simulation results were based on this most rigorous situation. The amplitude of lightning overvoltage on different devices was shown in Table III.

TABLE III
OVERVOLTAGE AMPLITUDE OF EACH DEVICE IN SINGLE-PHASE INCOMING WAVE

cur rent (kA)	Th yristor(k V)	ilter (kV)	6 90V s ide (kV)	N eutral point (kV)	3 5kV side (kV)	vol tage gradient (k V/age
5	14 5.8	1.3	1 3.2	1 2.9	6 50.1	10 6
10	27 5.6	1.2	2 5.9	2 5.7	1 240	20 5
Inc rease ratio	89 %	3%	9 6%	9 8%	9 1%	93 %

It could be seen from Table III, the overvoltage of thyristor would exceed its own maximum reverse voltage of 2650V, and the thyristor would break down in a short time. It could be known by the standard that the insulation level of low side in 690V/35kV transformer is 2.5kV, while high side is 200kV. When the single-phase lightning invade, the overvoltage of transformer would exceed its insulation level, which would threatened the safety operation of the transformers. When lightning stroke blades, the lightening wave may invade in two or even three-phase, and the voltage amplitude of different devices was shown in Table IV.

TABLEIV
THE OVERVOLTAGE AMPLITUDE OF EACH DEVICE IN MULTI PHASE

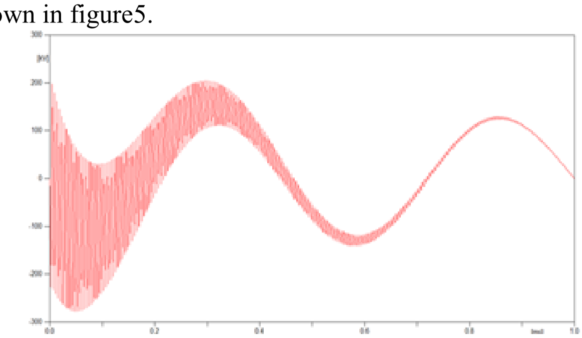
Number of phases	Thyristor voltage (kV)	Transformer voltage of 690Vside (kV)	Transformer voltage of neutral point (kV)	Transformer voltage of 35kVside (kV)
1	150kV	13.2	12.9	650
2	80kV	25.7	25.7	1350
3	14kV	48.9	38.9	2803

It could be seen from Table III and IV that the voltage of thyristor shows a significant downward trend with the lightning current amplitude increases. When the lightning wave comes from single-phase, the other two phases equivalent to paralleled load, and the equivalent load impedance of blades decreases. When the wave coming from two-phases, the left phase equivalent to the load, so the equivalent load of blades is larger, since lightning wave have a superposed effect on the thyristor, the voltage amplitude of it would be lower. With the increase of the amplitude of the lightning current and phase number of incoming waves, the overvoltage amplitude of transformer increases obviously.

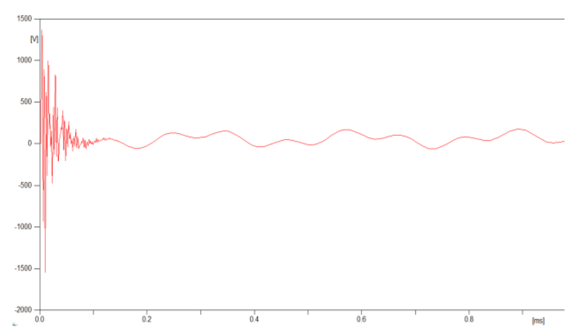
IV. MEASURES TO RESTRAIN LIGHTNING OVERVOLTAGE

Under the lightning stroke, the overvoltage is far beyond the withstand voltage of the devices. So the arresters should be installed near the devices to limit this overvoltage.Y0.5W-1.2/2.1 and 0.5W-51/132 arresters are selected according to the insulation level of thyristor and transformer. 2800pF and 147pF capacitor are paralleled with arresters respectively to realize the purpose of protection.

According to the matched lightning arrester, the lightning arrester should connected in parallel with each thyristor in the rectifier inverter circuit as well as transformer. After installing arresters, the overvoltage could be restrainedbelow1260V at the thyristor when the lightning current is 10kA. As long as lightning current is less than 100kA, it could achieve good protection. The voltage of thyristor with and without arrester is shown in figure5.



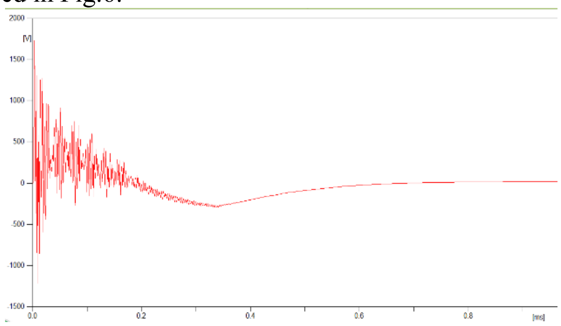
(a) without arrester



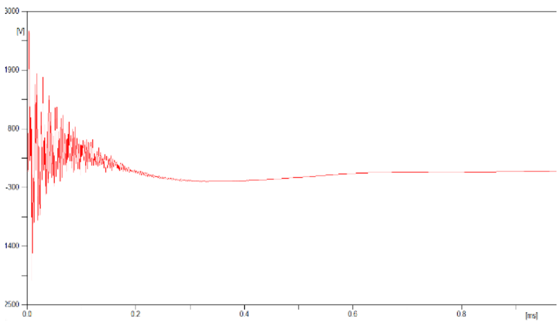
(b) with arrester

Fig. 5Voltage of thyristor when lightning current is 10kA

The voltage at the low side of transformer could be limited to about 1490V when lightning current is 10kA, this value is below than the withstand voltage, as long as the low side could withstand the voltage, high side could withstand as well. The previous simulation analysis show that, the voltage of thyristor would reduce when the wave coming from two phases. If it could realize the protection when lightning wave coming from one phase, then two-phase incoming wave is easier to achieve the protection purpose. At actual situation, there is a certain distance between arrester and the protected elements, when distance changed, the voltage at low side of transformer is showed in Fig.6.



(a) The arrester is 30m away from transformer



(b) The arrester is 80m away from transformer

Fig.6Voltage at low voltage side of the transformer with different installation location of arrester

As is shown in Figure 6, the overvoltage is limited to about 2kVwhen the distance between arrester and transformer is 30m,this value is less than the withstand voltage which is 2.5kV.But when the distance is 80m, the overvoltage amplitude is about 2.7kV, which make arrester failed in protecting transformer. The difference between the maximum voltage of the transformer and the voltage of the arrester could be obtained by the following formula:

$$\Delta u = 2a\tau = 2a \cdot \frac{L}{v} \quad (5)$$

In the above formula, Δu is the difference between the maximum voltage of the transformer and the arrester voltage; a is gradient of the voltage; τ is time constant; v is wave velocity; L is the maximum electrical distance between the transformer and the arrester. It could be calculated from the above formula that L=66m.

When the blades are stroked by lightning, the overvoltage amplitude and steepness would increase with the increase of lightning current amplitude. For example: the overvoltage at the low side of transformer is 13.2kVlightning current is 5kA, and steepness of the filter is106kV/us; while the amplitude is 25.88kV, and steepness is 250kV/us when lightning current is 10kA. When the wave coming from multi-phase, the voltage of thyristor would decrease with the increase number of phase. For example: when 5kA single-phase wave incoming, the voltage of thyristor is about 140kV, while this value is 80kV and 14kV when the lightning wave came from two-phase and three-phase.

V. Conclusions

The electromagnetic transient simulation model, based on the 330kV wind farm model, is established by using EMTP-ATP software, and the characteristics of lightning overvoltage as well as its protection are studied. Conclusion are got as follows:

(1)When the Wind turbines and High voltage overhead lines are struck by lightning, the overvoltage would be very high, without protection, fan internal components and transformer windings would be damaged.

(2)When fan side struck by lightning, the higher amplitude of the lightning current is, the greater overvoltage amplitude and gradient would be. When polyphase wave coming into the transformer, the overvoltage amplitude increases with the increase of the incoming wave number, While the overvoltage of the thyristor decrease with the increase of the incoming wave number.

(3)After installing arresters, the restrictions on overvoltage effect is obvious, and the effect would decline with the increase of distance between the arrester and protected. The greater distance is, the more obvious decline of the effect would be. And the arrester from the transformer installation distance should be less than 66m.

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