FACTORS AFFECTING TO TRANSIENT OVERVOLTAGE DUE TO DIRECT LIGHTNING STRIKES ON WIND TURBINE BLADE IN WIND FARM

MỘT SỐ YẾU TỐ ẢNH HƯỞNG TỚI QUÁ ĐIỆN ÁP QUÁ ĐỘ DO SÉT ĐÁNH TRỰC TIẾP VÀO CÁNH TUA BIN TRONG TRANG TRẠI ĐIỆN GIÓ

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ABSTRACT

Wind power is one of the growing renewable energy sources to meet the rapidly increasing demand for loads, in the context that traditional energy sources are increasingly limited and discouraged for development. However, wind power also has many disadvantages, one of which is frequently lightning strikes to the wind turbine blades, causing economic damage and disrupting power supply. There are many factors affecting to transient overvoltage when lightning strike to in wind power farms that have not been studied, in Vietnam, few published works. This paper analyzes some factors affecting lightning overvoltage in wind farm such as parameters of lightning current, grounding system of turbine, application of lightning surge arrester (LSA) installation solution, identifying the over voltages at the low-voltage and high-voltage side of the transformer. The results show that applying this solution can reduce the overvoltage value caused by lightning on the low voltage side by 60 times and the medium voltage side by 3 times. From these analysis results will be the basis for choosing effective lightning protection solutions for wind turbines. Research results are carried out using The Electromagnetic Transient Program Alternative Transient Program (EMTP/ATP).

Keywords: *Overvoltage, wind turbine, line surge arrester, EMTP/ATP*

TÓM TẮT

Điện gió là một trong các nguồn năng lượng tái tạo ngày càng phát triển để đáp ứng nhu cầu tăng nhanh của phụ tải, trong bối cảnh các nguồn năng lượng truyền thống ngày một hạn chế và không được khuyến khích phát triển. Tuy vậy, điện gió cũng có nhiều nhược điểm, một trong các nhược điểm đó là thường xuyên bị sét đánh gây thiệt hại về kinh tế và làm gián đoạn cung cấp điện. Có rất nhiều các yếu tố ảnh hưởng đến quá điện áp khi xảy ra sét đánh trong trang trại điện gió chưa được quan tâm nghiên cứu, đặc biệt tại Việt Nam rất ít các công trình công bố. Bài báo này sẽ phân tích một số yếu tố ảnh hưởng đến quá điện áp sét trong trang trại điện gió như tham số của dòng điện sét, hệ thống nối đất của tua bin, ứng dụng giải pháp lắp đặt chống sét van (CSV) phía hạ áp và phía cao áp của máy biến áp nối với máy phát tua bin điện gió. Kết quả cho thấy áp dụng giải pháp lắp đặt CSV có thể giảm 60 lần trị số quá áp do sét gây ra ở phía hạ áp và 3 lần ở phía trung áp. Từ những kết quả phân tích này sẽ là cơ sở để lựa chọn giải pháp chống sét hiệu quả cho tuabin gió. Các kết quả nghiên cứu dựa trên cơ sở lý thuyết quá trình quá độ và phần mềm quá độ điện từ EMPT/ATP.

Từ khóa: *Quá điện áp, Tua bin gió, chống sét van, phần mềm EMTP/ATP.*

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1. INTRODUCTION

Wind power is one of the growing renewable energy sources in the world as well as in Vietnam. According to [1] and forecast of changes in power structure capacity over time (base load scenario), wind power is a priority for Vietnam's energy strategy, wind power in Vietnam is increasingly developing. In 2020 wind power capacity only accounts for 1%, but it is forecasted to increase to 13% in 2030 and up to 22% of total capacity of power sources in 2045 (Fig.1). Wind power technology develop, modern turbines are increasingly designed with a height including the height of the tower and the length blade of the wind turbine is getting larger and larger to optimize the energy extracted from the wind, so the turbine height can be more than 100m [2]. However, such tall turbines pose great concern for lightning protection. Because, the larger the turbine, the higher the height, so it is more susceptible to lightning, the number of times lightning strikes the turbine depends on the height of turbine, length of the blade and the ground flash density at the turbine installation area [2].

Vietnam is located in an area with a fairly high ground flash density [3], with ground flash density of 1.4 - 14.9 times/km^2.year, so the number of times lightning strikes the turbines is very large, the number of times lightning strikes the turbines can be up to 30 times/year [3] and cause damage to turbine equipment. Therefore, problem of lightning protection for turbines must be studied specifically and find out the effective protection, comprehensively in order to improve reliability and reduce damage caused by lightning.

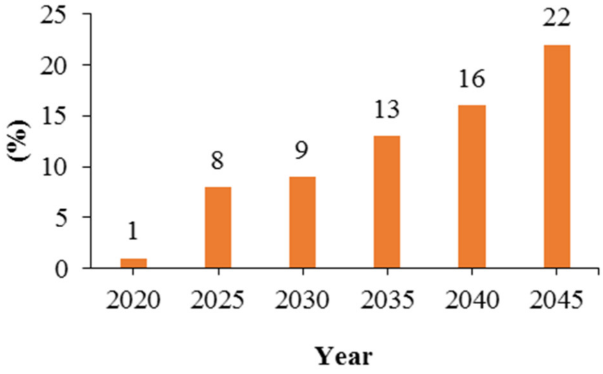


Figure 1. Proportion of wind power capacity forecast to 2045 in Vietnam [1]

When lightning strikes direct to the blades of a turbine, the lightning current passes through the air-terminations installed on the blades of the turbine, then the lightning current flows through the down-conductors installed in the blades and on the down-conductors installed placed in the pylon of the turbine down to the grounding system (Fig. 2)

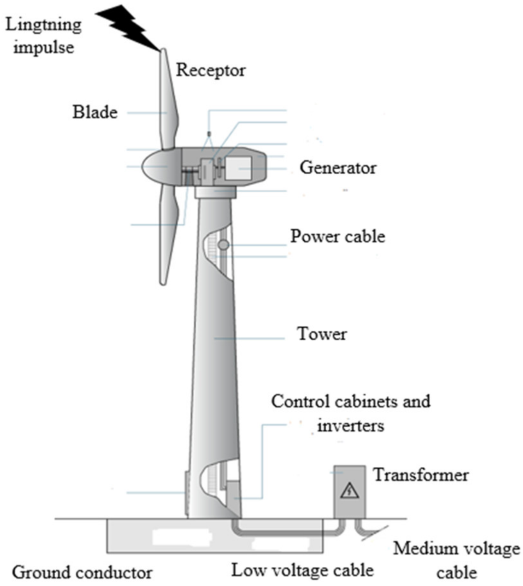


Figure 2. Components of a wind turbine

This lightning current when running in the down-conductor will be induced to the power cable lines causing overvoltage. In a wind farm, there are turbines connected to each other to generate power to the system, so the overvoltage will also affect the neighbouring turbines. The magnitude of this transient overvoltage depends on many factors such as lightning current parameters, the resistance value of the turbine grounding system, the arrangement of conductors in the turbine tower [4]. According to IEC 61400-24 [5], the most frequent failures, more than 50%, in wind turbine equipment are those occurring in low-voltage, control and communication circuits. Indeed, many dielectric breakdowns of low voltage circuits and burnout accidents of surge arresters in wind turbines are reported. Such frequent problems in the low-voltage circuits may cause a deterioration of the utilization rate and consequently cause increases in the cost of power generation [6]. The events on low-voltage circuits are not triggered by only direct lightning strikes but also induced lightning and back-flow surges propagating around wind farms just after lightning strikes on other wind turbine [7]. Usually, converter units and boost transformers are installed very close to wind turbines or inside windmill towers. In addition, LSAs are often installed on the high-voltage side (power grid side) and grounded jointly with the low-voltage side in order to decrease the grounding resistance of wind turbine tower. Therefore, when the grounding potential rises around transformers due to lightning strikes to wind turbine blade, LSAs may operate in the opposite direction from ground to line, causing a lightning surge that flows toward the distribution line. In actual lightning accidents at wind farms, insulation breakdown often occurs not only in lightning-stricken wind turbines but also in adjacent wind turbines or even relatively distant ones [8]. Such reverse surges flowing from the low-voltage side to the high-voltage side should be studied in the case of lightning strikes on wind turbine blades and wind farm.

Therefore, this paper we present a case study analyse the factors affecting to the transient overvoltage of the turbine struck by lightning and neighbouring turbines in wind power farm, to assess the danger of the transient overvoltage caused by lightning as a basis for proposing and studying mitigation measures. Computer simulations obtained by using the EMTP/ATP are presented, and conclusions are duly drawn. In this paper, the configuration of an operating wind turbine in Vietnam is the subject of research.

2. LIGHTNING STROKE PARAMETERS

Lightning is a natural physical phenomenon, which occurs randomly in the atmosphere between clouds or between clouds and ground [8]. The lightning stroke is considered as a current source in parallel with lightning channel impedance. The strokes are comprised of both first and subsequent return strokes. The first stroke has the greatest current peak with subsequent strokes have reduced current peaks. Approximately 90% of lightning strikes have negative polarity and the other 10% having positive polarity [8]. The lightning stroke is represented by a double ramp waveform, with four principal parameters: the peak current, which ranges from about 3kA to about 300kA [5]; the front time t_f defined as the time taken to reach the peak current; the tail time, t_h defined as the time taken to decay to 50% of the peak value and the polarity of which is either negative or positive [9]. The tail time is significantly greater than the front time. The parameters of the lightning stroke are not uniformly distributed across the globe; they are dependent on different geographical and orographic areas and influenced by weather and climatic variations [10, 11]. The lightning-path impedance was assumed to be 400Ω [12]; in this paper. Lightning stroke parameters can be statistically represented by the general log-normal distribution, which has probability density function given by (1) [10]:

$$f(I)=\frac{1}{\sqrt{2\pi}\sigma I}\exp\left[-\frac{1}{2}\left(\frac{\ln(I/I_M)}{\sigma}\right)^2\right] \quad (1)$$

where I_M is the median and σ is the log standard deviation, according to [13], the parameters are presented in table 1.

Table 1. The Median and the Log Standard Deviation

Parameters	General Log-Normal Distribution	
	Median	Log Standard Deviation
$I_{M,}$ (kA)	31.1	0.48
t_f (μs)	2	0.494
t_h (μs)	77.5	0.577

3. WIND FARM LAYOUT AND PARAMETERS

Figure 3 shows a layout of wind power farm composed of five identical wind turbines. Wind turbines with a capacity of 2MW, generating voltage of 690V. The turbine pillar has a height of H_T = 80m, a blade length of H_b = 40m. The top outside diameter of the grab post is 5.4m while the outside diameter of the base is 8.6m. Each turbine has 2MVA-0.69/24kV transformer located at the base of each turbine tower. The average soil resistivity of the location was estimated at 1500Ωm. The wind farm is connected to the grid by XLPE underground cables and then through a 16MVA, 24/110kV transformer. The turbines are located approximately 300m from each other to minimize on the wake effects. The substation is located about 50m from the turbine. The wind power farm is connected to the grid via a 3km overhead line.

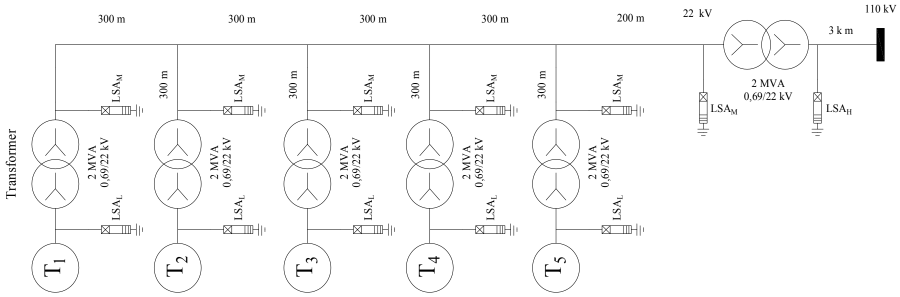


Figure 3. Wind power farm model

4. DESCRIPTION OF THE EMTP/ATP MODEL

In order to calculate the lightning overvoltage in a wind power farm when lightning strikes to the blades of a turbine, it is necessary to model the elements in the path of the lightning current, including blades, tower and cables and grounding system. In addition, the lightning power source, the LSAs is also needed to be modeled. The following describes the basic elements of a turbine in this paper the most recent version, the EMTP/ATP, is applied. The following explains briefly the most important models used in this paper:

4.1. Blade and tower model

The blade and a tower of wind turbines: described by a surge impedances of a blade and a tower were approximated from conical and cylindrical equations established from electromagnetic field theory as follows [14]:

$$Z_b = 60\ln\frac{2H_b}{r_b},\Omega \quad (2)$$

$$Z_T = 60\ln\frac{\sqrt{2}H_T}{r_T},\Omega \quad (3)$$

where H_b and r_b represent the length and radius of the blade, and T_H and r_T represent the height and radius of the base of the tower.

4.2. Grounding resistance of tower model

A detailed model of the wind turbine grounding should include both time-dependent nonlinear soil ionization and the frequency dependent impedance. The soil ionization improves the grounding performance and the frequency dependent inductive behavior, which is rather complex to model [15], hinders it. Because of the opposing effects of mentioned phenomena, the grounding was modeled simply as a resistance. The grounding resistance in the simulations was varied from 1Ω, to 3Ω, 5Ω and 10Ω.

4.3. Transformer model

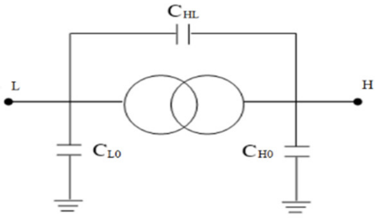


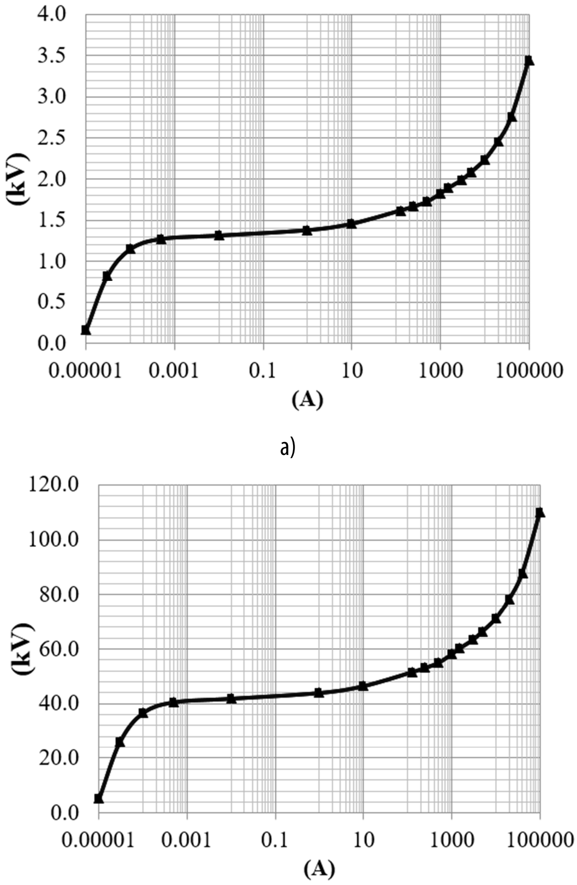
Figure 4. High frequency transformer model

In order to study the transient, involve frequencies up to a few kHz, stray capacitance of transformer coils must be added to the transformer model. Transformer capacitance is represented by C_{H0}, C_{L0} and C_{HL} as shown in Fig. 4. Where, C_{H0}: capacitance of high winding to ground, C_{L0}: capacitance of low winding to ground and C_{HL}: capacitance between high and low windings. Normally the C_{L0} and C_{HL} are greater than C_{H0}. This is because the fact that the high voltage calls for more separation between windings and between windings and core [16]. In this paper C_H = 15nF, C_L = 17nF, C_{HL} = 18nF [17].

4.4. Conductor System

Modern wind turbines' blades and towers are equipped with receptors and internal down-conductor, which goes from the receptors, embedded in the blades, down the tower and connected to the grounded system at the base of the tower and underground cable sent electricity to 0,69V/22kV transformer [6]. The down-conductors are generally made from aluminium or copper wires with suitable cross-sectional area to safely conduct the fault currents. The minimum cross-sectional area of the down-conductor has been recommended as 50mm^2 for both aluminium and copper conductors [6]. In this analysis, the ground wire was modelled as single-phase π-model, with each pi-model cascaded in 20 m per section as outlined in [7].

4.5. Low voltage and Medium voltage LSAs



a)

b)

Figure 5. V-S characteristics of LSA (a) low voltage 0.69kV, (b) medium voltage 22kV

The lightning surge arresters used in this paper are the gapless MOV type. The typical low voltage surge arresters (LSA$_L$) have maximum continuous operating voltage (MCOV) of 440V and voltage protection level of 2700V for a 40kA (8/20µs) lightning impulse and 1800V for 10kA (8/20µs) lightning impulse. The typical medium voltage surge arresters (LSA$_M$) have MCOV of 15.3kV and rated voltage of 18 kV. Fig. 5 shows the surge arresters' characteristics V-A. The arresters were modeled according to the frequency-dependent model proposed in [18]. The arresters' lead lengths impact the overvoltage significantly. The lead lengths were modeled as lumped inductances with value of 1µH/m [19].

4.6. Lightning Current Source

The lightning current source is modeled by a time-varying ideal current source connected in parallel with the surge impedance of the lightning channel Z$_s$ were presented in session 2. This paper uses a Slope- Ramp type lightning source, Z$_s$ =400 (Ω) [5].

The simulation model in EMTP/ATP of a wind turbine is shown in Fig.6.

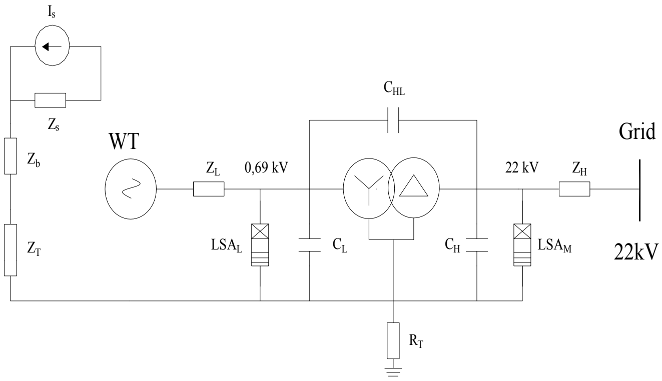


Figure 6. Simulation model of each turbine in EMTP/ATP

5. SIMULATION RESULTS

5.1. Effect of lightning current parameter

Figure 7 illustrates the transient voltages at the top of wind wind turbine (T1) when the tip of the blade was struck by lightning with amplitude 31kA and the front time of the lightning current, the footing resistance of turbine tower R$_T$ is 10Ω, it can be clearly seen that the steepest lightning wave front (1/70µs) produces the greatest overvoltage. The transient voltages decrease drastically as the steepness of the front time decreases. The 5/70µs gives a much lower voltage than 1/70µs. While 10/230µs generates the least transient voltage. The results show that when the front time of lightning current decreases, the overvoltage caused by lightning on the turbine also decreases.

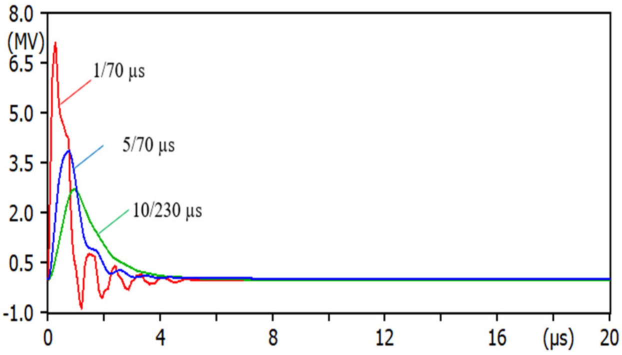
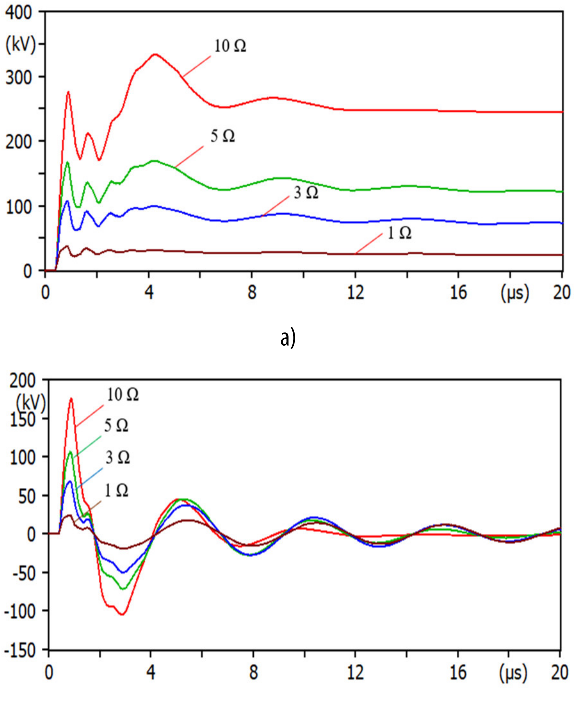


Figure 7. Turbine blade tip voltage hit by lightning with different lightning waveforms

5.2. Effect of turbine grounding resistance

Simulation when lightning strikes to the wind turbine blade with lightning current is 31kA (1/70μs), the footing resistance of wind turbine tower is 1, 3, 5, 10Ω, respectively, the simulation results of transient voltage wave on the ground and the phase voltage on the side the low voltage of turbine T_1 is shown in Fig.8. The results show that reduce the R_T value further reduce the transient voltage level on footing resistance of turbine tower and in phase voltage the low voltage side, the transient voltage reduction is linear with the decrease R_T. When R_T is 10Ω, the transient voltage on footing resistance of turbine tower is 350kV, while R_T is 5Ω, the transient voltage reduces to 150kV (Fig.8.a). The transient voltage of in phase voltage the low voltage side reduce from 170kV to 100kV when the footing resistance of turbine tower reduce from 10Ω to 5Ω (Fig.8.b). Therefore, the solution of reducing R_T will reduce the transient overvoltage when lightning strikes to the turbine.



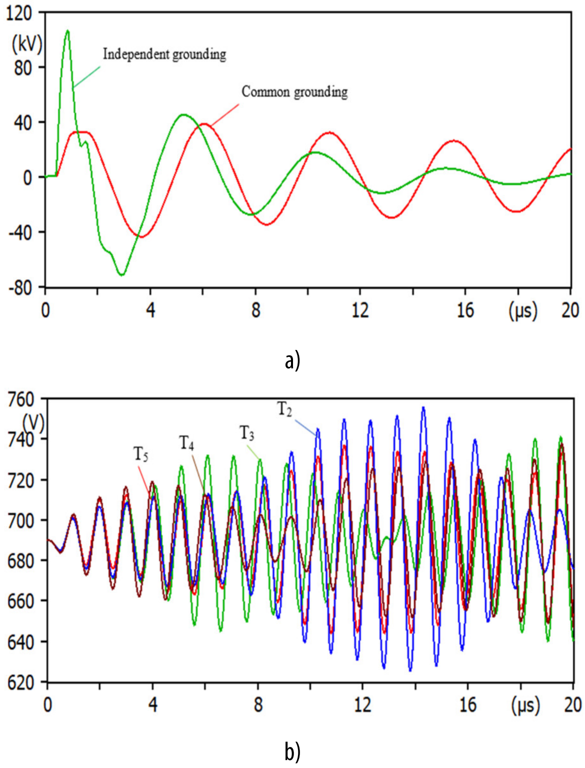
a)

b)

Figure 8. The transient voltage at footing resistance of turbine tower (a) and phase voltage the low voltage side (b) of the T_1 is struck by lightning according to different ground resistance values

5.3. Effect of grounding configuration

This case considers the influence of independent grounding (there is no connection between the grounding systems for wind turbines) and common grounding of turbines (there is connection between the grounding systems for wind turbines) to the transient overvoltage propagated in the wind farm. Comparison the transient overvoltage in wind farm in case of using independent grounding form and common grounding form with lightning current is 31kA (1/70μs). The footing resistance of each turbine tower has a resistance value of 5Ω. Horizontal steel electrode with zinc coating outside, diameter is 22mm, buried at depth is 0.8m in soil with resistivity ρ = 1500Ωm. The horizontal electrode connects two adjacent turbines 300m long, divided into 30 segments, 10m each and replaced with an equivalent circuit model as shown in [4]. The simulation results comparison the transient overvoltage waveform appearing on the low voltage side of T_1 to T_5 in the wind farm in two grounding forms (independent and common ground) are presented in Fig. 9. The simulation results show that, the grounding system has a great influence on the transient overvoltage spread in the wind farm. When using the common grounding system, the amplitude of lightning transient overvoltage propagated in the wind farm is significantly reduced. For a turbine struck by lightning that uses common grounding, the transient overvoltage amplitude at this turbine is reduced by more than 3 times compared to the case of independent grounding (Fig. 9a). In neighboring turbines, common grounding does not significantly reduce the value of transient overvoltage propagated on the low-voltage side (Fig. 9b).



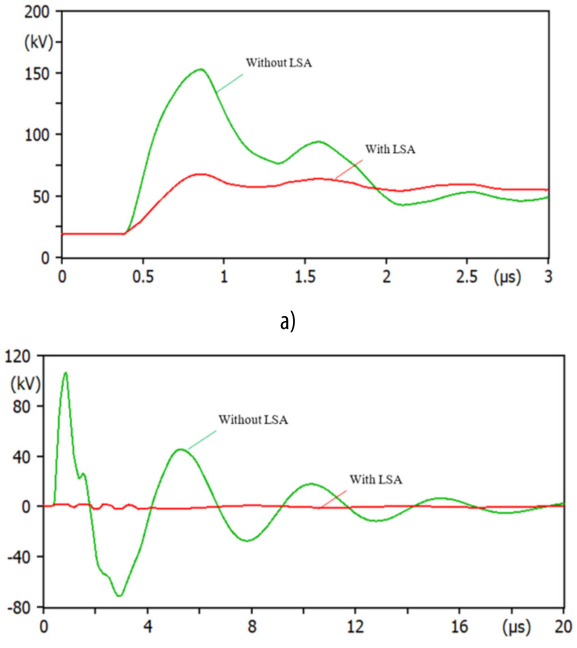
a)

b)

Figure 9. The transient overvoltage low-voltage side of T_2 to T_5 when the common grounding (a) and the transient overvoltage low-voltage side of T_2 to T_5 when the common grounding (b)

5.4. LSA Installation Application

Install LSA has the effect of reduce the transient overvoltage used a lot in the power grid. In this paper, simulation for the case of direct lightning strikes to wind turbine blade T1, the high and low voltage side of the turbines installed LSAs has the characteristics as shown in Fig. 5. Simulation when lightning strikes to the wind turbine blade with lightning current is 31kA (1/70µs), the footing resistance of wind turbine tower is 10Ω. The simulation results in Fig.10 show that, it is clear that when installing LSA, the induced lightning transient overvoltage is degraded very significantly reduced. The loss of transient overvoltage at the high voltage side when installed compared to not install LSA is reduced by 3 times, the low voltage side is reduced up to 60 times.



a)

b)

Figure 10. Compare the transient overvoltage a) high -voltage side and b) low -voltage side of the turbine being struck by lightning, without LSA and with LSA

6. CONCLUSION

The paper used the electromagnetic transient simulation program EMTP/ATP to simulate the phenomenon of lightning strikes to wind turbine blade in the wind farm. The main conclusions obtained from the results are. The Result was clearly shown that the steeper the lightning impulse, the larger the generated transient overvoltage across the wind turbine components; when the turbine's blade was struck by lightning first-return stroke. The stricken turbine endures the greatest overvoltage and then the transient decreases progressively throughout the adjacent wind turbines network.

The footing resistance of turbine tower is small, the lower the transient overvoltage level for the turbine that is struck by lightning and the turbines next to it. If economic conditions allow, the turbines should be grounded in common, however, measures must be combined another to avoid the influence of the transient overvoltage wave propagation in the wind farm.

Although the cost of LSA is high, the installation of LSA on both the high and low voltage side of all turbines is the necessary solution to best reduce the transient overvoltage.

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