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A Review of Lightning Protection System - Risk Assessment and Application

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Abstract

A lightning strike could bring thousands mega-ampere of current in a blink of eyes. As a result, a failure of grounding the strike may cause serious damage to the home and industrial appliances and gadgets. Hence, a lightning protection system is essential to the current transmission system. Lighting is a natural phenomenon that is unavoidable. Hence, the study of the properties and characteristics of lightning is a must in designing lighting protection system. Every application has different criteria to be fulfilled. The type of lighting protection system is categorized based on the location and user. The different of location is a public area, transportation system, power system transmission and generation system which include renewable energy source. Each area can conclude different level of protection. This paper is assessing the possibility and probability of transient impact on all applications including, public area, power system line, and generating system. The review includes countermeasure which addressed few steps to determine the effect of lightning and countermeasure of protection.

Keywords*: lightning protection system, Surge protection devices*

1. Introduction

A deadly but beautiful natural sky phenomena are lightning. As the name implies, lightning is a sparkling flash of light that emitted due to electrical discharged that occur all around the world, whether the urban area, rural or even on space of fields. In theory, lightning is happening due to the disproportion of charges between thunderclouds to ground or clouds themselves [1]. Most lightning strikes occur between clouds and sometimes happen to be the lightning to the ground which is small possibility occur. A lightning strike could bring thousands mega-ampere of current in a blink of eyes [2]. Mostly, likely lightning targeting at the nearest point on earth to it which with high potential of positive charges. In another word means the closest point is referred to tall building, structure, electrical tower or even trees as long as they can discharge the electricity to the ground.

Globally know that human activity equipped with electrical and electronic devices whether used at home or work, which indeed are exposed highly to a lightning strike. When lightning struck, the overcurrent of lightning would create a huge transient onto the circuit line. Transient or surge is one of the major contributors for the electrical equipment to be damage, failure to operate and destruction. Therefore, it is essential to be equipped with protection system to prevail the effect of the lightning strike. To minimise damage may cause by a lightning strike, a lightning protection system (LPS) commonly is installed [3-5]. The primary function of LPS is to protect the building structure and all invaluable equipment in or on the structure. LPS act as a Faraday Cage protects defendless equipment from the threat of external electric field by diverting the electricity and its contents around the cage to the earth. Apparently, a good LPS provides lowest resistance path for a surge to flow to the ground for dispersing the transient.

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Various characteristics have been taken into account to consider a single installation of a protective measure such the probability of occurrence, the probability of maximum current of a lightning strike and last but not least the economical aspect. The economic aspect played a significant role since it will contribute to preinstallation and post-installation of any protective measure. However, typical fuses and circuit breaker are not ample to suppress the high conductivity of transient induced by lightning. Thus, an alternative such mounting a surge protection device on a conduction link become crucial. Surge protection devices (SPD) are used to assist the whole protection system for a vulnerable threat of transient either voltage or current that comes from lightning or switching. There are many types of SPD available in the market according to the usage, functionality, and location [6]. However, the main functional aspect of SPD is to divert and protect the equipment as well as the safety of the surrounding.Various types had been researching over decades from small and economically like varistor to the bulky based intelligent systems. Many studies had been investigated for a suitable method to reduce the effect of the surge due to a lightning strike. Recently, researchers employed a new technology to minimise the effect of the transient by applying spark gap system in SPD [7].

Therefore, for further understanding of SPD in the case of lightning protection, this paper reviewed all SPD available commercially to analyze the characteristics of each SPD. This study is also investigating the suitable protection method for each application in the electrical link for a generation to a distribution system.

2. Lightning Protection System

In the present, as stated in IEC 62305, lightning protection system (LPS) is considered an obligation for every structure to be installed to protect the structure itself and also the content in it [3]. It includes the equipment and the safety of the people inside the building.As stated previously, every aspect must be taken care for mounting the LPS, comprising safety, the architecture of LPS and cost for installation. The economic influence play on of major role for LPS since the lightning strike is unpredictable. Almost 5% probability of lightning to ground occurrence compared to overall lightning worldwide. This paper categorized the LPS according to location and application of the area. The category area is public area, transportation system, power system transmission and generation system which include renewable energy source.

2.1. Public Areas

In modern day, most of the lightning protection in new design building related to electronic devices appliances and equipment such closed circuit television (CCTV), computer network, etc. Since the electronic devices are so vulnerable to lightning surge and impacts. For the building with a well equipped electronic system, besides of lightning terminals installation to diverting direct stroke to earth ground, a lightning countermeasure also must be embedded. A lighting countermeasure covers diversion and balancing of transient, shielding and grounding. Normally, surge protection devices (SPD) was mounted to assist the protection of the whole system by diverting the overcurrent in short period as well preventing the electronic equipment from surge damage.At the beginning of growth electronic devices equipped with modern structures. A metal oxide varistor was proposed by M. Abdel-Salam et al. to be installed as a part of lightning protection system (LPS) [5]. A simulation model with the series arrangement was tested with different level of voltage. The result pointed out that the load level voltage never exceeds the maximum safe value.

In 2008, a model was constructed to simulate the surge effects onto the electronic equipment in a building [8]. The equivalent circuit of equipment was varied from normal resistive load, inductive, capacitive and combination of them. Still, the topology of the circuit was by cascading all the loads, but with an SPD was placed in between circuit to direct the transient to the ground. The result showed that for a different type of total equipment used in a building require a different level of the protection system. From the result, type of cable installed for a building also plays a key role in the appearance of the surge oscillation.H. Shin et al. was investigating the effect of a surge by varying coordination of SPD [9]. The tested was conducted by different type of voltage and arrangement of SPD. The outcome of the experiment indicated that distances between SPD installed could react differently to the variation of the surge. In short distance, during microsecond of time, SPD could not react as it supposed to set time for a small surge of current. However, the coordination of SPD was effective in the longer distance.In

the same year, 2014, H. Li et al. introduced spark gap technology SPD for building [10]. The reason behind the method was because of the increment of sensitive electronic equipment as well as appliances in a building. Spark gap technology had been available in the market, but the usage was limited to power system line that required a higher voltage level compared to an ordinary building. Spark gap SPD is considered type I SPD, and the result of the experiment showed that the coordination of the SPD was not only the reason to minimise the damage due to surge transient.

While differently T. Kisielewicz et al. had a different approached for building protection [11]. The researchers tend to suppress the surge before entering the building by installing the SPD at the overhead line of low voltage (LV). The model build was by considering all the overhead line was in series of load, but with different weight of resistance. The simulation result indicated that type I SPD must be installed near to equipment that wants to be protected. The distance is so close only in few centimeter.Again the same group of researchers continues to study [12], but now with indirect flash on the lightning strike. In the model developed, they considered various of level of an indirect surge.The simulation verification that the shape of transient was still similar with direct strike surge, but the indirect surge is more depending to the ground, either the soil resistance and type for earthing.Table 1 summarises the studies that have been done by previous experts. From stated studies, a typical arrangement of a load for a building was in series with different weight of resistances. Type of SPD chosen for building protection demonstrates a vital part for determining the safety of the apparatuses. For power system line whether high voltage or low voltage transmission, SPD installation was a common practice and up to the standard stipulated in IEEE or IEC regulation. A. Pinto et al. had investigated characteristics that must account for surge protection system at transmission line [13].

Table 1. Summarisation of lightning protection of building at low voltage level

Year	Author Reference	Surge Protection Devices	
		Ordinary Metal Oxide Varistor (MOV)	Spark gap Technology (MOV)
2004	[5]	√	
2008	[6]	√	
2014	[7]	√	
2014	[8]	√	√
2014	[9]	√	
2015	[10]	√	

The researchers also model the SPD arrangement by using considering the load was formed by parallel resistance and inductor. The connection of SPD was referred to IEEE standard model, which SPD is connected in between load, in parallel with a capacitor, representing dielectric between the line to ground. The connection configuration is shown in Figure 1. The nominal voltage used for the installation was 462kV. Type of SPD mounted on the transmission line was MOV with zinc oxide materials.

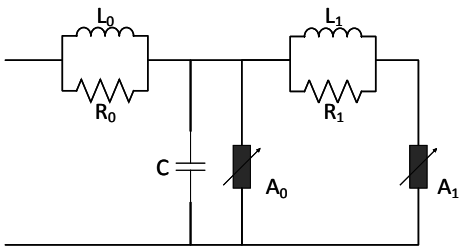

Figure 1. IEEE model for SPD arrangement at transmission line

A simulation model of protection system with MOV surge arrester modeled by M. Araújo et al. covering almost 9km of distribution line [14]. The proposed model was introduced Pinceti and Giannettoni in 1999. Since they acclaimed that the model highlighted was dynamic and fulfill the criteria that were pre-assigned by them. As illustrated in Figure 2, by dividing the distribution line into eight sections, with three surge arrester model connected to it. The typical MOV ZnO was selected for the installation. The tested conducted with various voltage level to determine the suppression of surge by lightning. Even five sets showed a better capability for protection, they said that three sets of surge arresters were enough to cope for that length. The conclusion was made by considering on economic angle point of view.

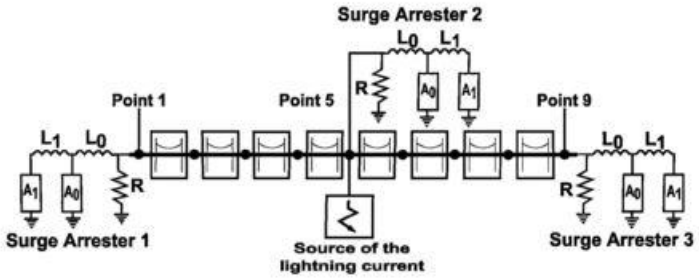

Figure 2. Surge arrester arrangement as model by Pinceti and Giannettoni

2.2. Power System Transmission

In 2016, C. Weijang et al. proposed a controllable ultra-high voltage (UHV) surge arrester [15]. The UHV controllable arrester had tested on a field with rated equal to 828kV similar to conventional MOV surge arrester. The arrangement of controllable UHV arrester was in series with fixed arrester. As shown in Figure 3, the controllable UHV arrester is represented by MOV2, connected below the fixed arrester, MOV1 with rated voltage 124.2kV, which 15% of total rated voltage for arrester. The controllable UHV arrester was connected in parallel with the control unit. An experiment was carried out by a group of researchers with collaboration with the energy supplier to determine the short circuit occurrence in air switch on distribution line [14]. Even from the result, at an open position the air switch could induced spark that may cause the short circuit failure depending on the gap. But for lightning protection, the surge arrester at the air switch cannot be un-mounted.

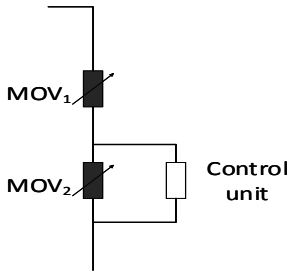

Figure 3. Controllable UHV AC arrester structure

A detail of study was conducted in Malaysia to analyze the suitability of surge arrester for a 500kV transmission line. Since, for high voltage level, a double circuit trip cannot be allowed. So, I. Rawi et al. [16] conclude that the installation of surge arrester was a must and with ground resistance improvement to avoid any unnecessary unexpected event of occurrence due to a lightning strike. Again, I. Rawi et al. experimented with the energy supply provider to test the performance of gapless surge arrester on 132kV overhead line [17]. Gapless type surge arrester is consisting a block that apparently connected to the phase conductor. It was built with

the same material, zinc oxide, ZnO, the blocks can suppress the transient voltage. After a year of observation, gapless type surge arrester had an equal ground to gap type surge arrester. However, the transmission line still exposes to failure even after numerous installation of SPD, which called shielding failure. A typical occurrence of tripping at high voltage transmission line was because the presence of transient in the line causing a direct lightning stroke. In essence, it can be divided into two categories, back flash and shielding failure. However, shielding failure attracts more attention since the modeling back-flash investigation near to the point of saturation.

Shielding failure effect on transmission line was modeled since 1960 with electro geometric model. The model was undergone much modification until now, even combining the old model with leader progression model (LPM). LPM is sideliner accepted since the structural model almost equal to lightning physical process. But, the exact solution of the criterion due to shielding failure still full with uncertainties. A huge of previous studies proposed various inception characteristics to leader progression model. A probability method was introduced in 2009, by C. Christodoulou et al. [18] to assessed the failure rate of SPD at transmission line. The probability was by considering calculating the previous failure occurrence. The result showed a significant difference between typical estimation and the probability calculation. The method also was tested on real field transmission line, with selected areas for measuring purposes.

Overvoltage was the main reason behind the failure in substation and distribution line. Many previous studies investigated the both simulation and experimentally to understand the characteristics of induced overvoltage and the invasion that come from it. Z. Wang et al. [19] experimenting an induced overvoltage by creating an artificial rocket triggering lightning strike, even the experiment had gone through some minor error, but it can be simplified the data still within the range of numerical method calculation. While X. Zhang et al. [20] had experimented to visualize the transient and electric field distribution due to flash over lightning strike. A setup for the experiment was conducted at ultra high voltage direct current (UHVDC) converter station. They tested transient on a DC line at 800kV at few point, the result indicated that the distance of lightning strike point to the substation influence the characteristic of the transient and electric field distribution. So, the construction and selection of SPD on power system line must be followed as stipulated in international standard such IEC or IEEE. But even so, the probability of lightning occurrence must be taken into consideration for selection and installation. One most important aspect to compromise is the countermeasure protection when an un-expectable situation like SPD failure which results in shielding failure. In previous research showed the main risk at transmission line was shielding failure, resulting in more than one tripping that would cause a major catastrophe economically.

Table 2, tabulated the previous study record and data that was carried out either in simulation or experiment. As for the model arrangement, two major model was adopted that is from IEEE standard and the dynamic model proposed by Pinceti and Giannettoni. Both models having respective advantages, but the preference of installation still depend on the standard measurement applied worldwide.

Table 2. Modelled of SPD Arrangement chosen for typical power system line

Year	Reference Author	Type of Surge Arrester	Model		Rated Voltage
			IEEE	1999	
2014	[11]	Gap	✓		426kV
2014	[16]	Gapless	✓		
2015	[12]	Gap		✓	
2016	[13]	Controllable Gap	✓		828kV

2.3. Generation System

The development of renewable energy increases rapidly nowadays, and become one of major power supply for certain area. The wind turbine as one of renewable energy source also grown steadily attracted many researchers to deepen the knowledge on it. On the country, wind

turbine also attracted natural phenomena such lightning to strike since the structure is tall and build from low resistance and conductive materials.

Therefore, the protection on wind turbines from lightning strike recently draw expert to study and become sensational news. The construction of wind turbine involving vast plain area or open sea. Wind turbine seems to be the only structure that 70m tall compared to another thing that was relatively smaller. An observation at wind turbine at Japan showed that the lightning not only on downward stream, cloud to the ground by also in the opposite way, ground to clouds [21].From the experiment showed that the pollution level at certain area also contributes to the significance of the possible lightning strike. This was supported by few researcher that highlighted tall building or structure attract more attention of lightning compared to short structure [22]. H. Wu et al. analyze the effect of the transient when directly stroke by lightning [23]. By using available data, a simulation process was conducted. From the outcome, they stated that for offshore wind turbine must be selected with a high resistivity of grounding and facilitated with good earthing construction.

Meanwhile, the exposure risk was higher at the offshore side, side the grounding and the environment were not favorable to the wind turbine tall structure. Y. Hernández et al. were studied the effect of the lightning stoke onto wind turbine blade [24]. The study was carried out in simulation but based on real data. Experiment purposed was to detect the normal overvoltage characteristics that touched onto the wind blade. While simulation more toward the distribution of electric field onto the blade. From both results, even installation of SPD at the wind farm is an obligation, but additional criteria that caused by lightning stoke must have been taken into consideration. Even not contribute to complete destruction, but a single wind blade is costly. A monitoring study was conducted to analyze the behavior of lightning transient on the wind turbine. The case tested at about 16kA of current [25]. But the lightning strike carries out far greater of amperes. The polarity of lightning tested was negative with theoretically lowest the capability of damage. They stated that a high protective measure must be installed to avoid large damage since the polarity of lightning is a totally different level which can be bipolar or positive.

Later, a SPD was introduced by T. Zhang et al [26] to be mounted at wind turbine to reduce the damage inflicted due to direct lightning strike. The proposed method was by connecting SPD to the signal line into wind tower construction. A simulation was tested on the model build, and the result showed the installed SPD to the signal line improve the quality of signal. The effect of overvoltage was far less than unmounted SPD to the signal line. Figure 4 illustrated the tower model with SPD connected to signal line as investigated by them. So, N. Malcolm et al. proposed a gapless metal oxide varistor (MOV) to wind turbine structure [27]. By considering the severe surroundings and nonlinear characteristic. A simulation was tested to analyze that SPD installed onto the turbine minimize the effect of direct lightning strike compared to SPD installed adjacent to the structure. As shown in Figure 5, the model that had been introducing to the wind turbine. The model was based on the dynamic model proposed in 1999. In 2015, SPD was proposed to be installed at hydropower plant [28]. The system used to protect the equipment as well as uninterruptible power supply. The system was tested with standard surge transient, and the result showed that not only gave the UPS guarding but also cost effective compare to normal installation and lightning occurrence. The system promoted on SPD arrangement suitable to the energy flow principle.

As illustrated in table 3, the timeline of researches conducted by experts to investigate the lightning behavior at generation system, mostly on a wind turbine. Today, wind turbine become an important part for certain countries to cope the electrical supply. The wind turbine rapidly popular since the energy generated is renewable, unlike typical supply, using fuel that comes out from fossil which will not everlasting. However, to construct a windmill for producing electricity. The location is one of the major aspects, and wind turbine requires a windy but plain field, for bettering the construction is taking place on top of the high place, either hill, mountain or offshores. Those locations and environment is risky and exposed to the possibility of a lightning strike. Therefore, a high protective measure must be taken into account to estimate the probability and possibility of the transient effect. Since the construction of a single wind turbine is costly, then the estimation must compromise the life expectancy of the construction as well as economic value.

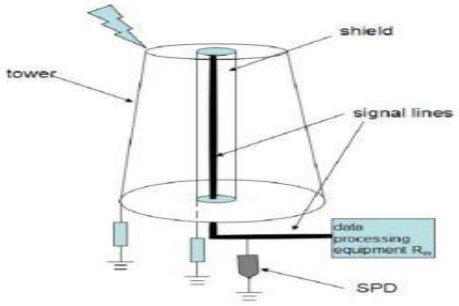

Figure 2. Wind Turbine tower construction with SPD installed

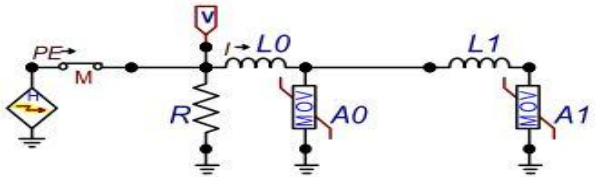

Figure 3. SPD model proposed on wind turbine

Table 3. Timeline of research on generation plant

Power Plant	Year	Author	Description
Wind Turbine	2010	[21]	Characteristic of lightning strike on upward stream
	2013	[20]	Characteristic of plant that attracts lightning
	2014	[23]	Electric distribution due to overvoltage
	2014	[25]	Impact of overcurrent on wind turbine
	2015	[22]	System protection on wind turbine
	2016	[26]	Gapless MOV directly installed at wind turbine
Hydro	2016	[27]	Uninterruptable Power Supply

3. Discussion

In the modern age, a lightning protection system is essential and obligation for building to comply with the standard that had been published. So this paper uncovers the steps to be taken to see the needs of any LPS particularly to install any surge protection device. From the reviewed paper, few key points were a highlight as was arrange for any structure especially the public with encompassing the safety of the public.

At initial stage is the probability and likelihood of a lightning event. The numerous events of lightning are on the intersection of equator line. So any building that can be considered tall at equator line for instance Malaysia, the safety protection should be improved and add suitably. Apart from installing air terminal for dispersing the lightning to the ground, an SPD also needs to be installed mainly when the grounding full with high resistivity soils. Then the second part is by considering the equipment, especially electronic and computerized devices. Since, previously in the reviewed paper [28], showed that electrified cables attract more lightning to strike. So any electrified equipment in present or in future installment must be approximately calculated. The calculation is likely the requirement for SPD installation. Lastly, the location of the electronic devices equipped within the building, so that any SPD need be installed is mounted at the correct location point. The distance of SPD plays an important aspect to determine the protection all equipment around it. The nearest apparatus to SPD receive the highest protection over the rest.

4. Conclusion

This paper address few and recent development of progress in lightning protection system (LPS) on normal applications. The applications divided into for category which is public area, power system line, generating system and transportation. Each application is consisting

location and any lightning research related to it. For the public area, which comprises the safety of people, the LPS is a must even sometimes people like to careless. For power system line, the standard practice followed expect certain cases. However, the protection still installed where there also a probability of facing lighting strike failure. So if there is a need for a new type or additional installment thus, implement it. The same thing goes to generating system. The requirement depends on the environment of the renewable source.

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