Shielding Failure Analysis of 132 kV Transmission Line Shielded by Surge Arresters Associated With Multiple Strokes Lightning

David Caulker[#1], Hussein Ahmad[*2], Zulkurnain Abdul Malek[#3], Sallehhudin Yusof[*4]

[#] Institute of High Voltage and High Current, Universiti Teknologi Malaysia
Skudai, Johor Bahru, Malaysia
[1] dauda9@yahoo.com
[2] hussein@fke.utm.my
[3] zulkurnain@utm.my
[*4] Advanced Power Solutions Sdn. Bhd.
Shah Alam, Malaysia
[4] salleh@aps-my.com

***Abstract*— Analysis of shielding failure is carried out to observe flashover of insulators parallel with phase conductors of a transmission line associated with a lightning strike on phase conductor. Peak current of different magnitude have been used to represent the multiple strokes lightning (MSL). This paper aims to simulate the worst case due to transmission shielding failure with three direct strikes to a line phase conductor of magnitudes 25 kA, 35kA, 50kA, 65 kA and 80kA per strike respectively. Insulators where flashover had occurred with respect to MSL were identified. Installation of an arrester on a phase insulator where a flashover has occurred proven to be useful mitigation technique thatch could prevent flashover of the insulator and also improves lightning performance of the line.**

***Keywords*— Surge Arresters, Multiple strokes, Transmission line, Shielding Failure, Flashover, Insulators, Phase conductors, Strokes**

I. INTRODUCTION

Countries of high isokeraunic activities experience significant amount of line tripping following an occurrence of a lightning terminating an overhead line (OHTL). Lightning is the major cause of power system outage or equipment damage. Many literatures have reported about the overvoltages originating from lightning and their severe damages on installations and apparatus [1-4]. In year 2009, lightning accounted for about 40% of the transmission line trippings in Malaysia [5]. The national utility company Tenaga Nasional Berhad (TNB) has conducted numerous researches to maintain zero tripping of the lines in order to ensure reliability and sustainability of power [5]. Installation of line surge arresters (LSA) for the improvement of lightning performance is more efficient than conventional methods such as double circuit line unbalanced insulation, reduction of tower footing resistance etc. LSA can improve transmission line lightning performance and also avoids double circuit outages [6]. Other applications include; reduction of line insulation level and line compaction, replacement of ground wires, overvoltage control and so on. The residual voltage across the insulators installed parallel to the insulators is lower than the line insulator [7]. Arresters must be capable to withstand the discharged energy from lightning. Economically arresters should not be installed at all phases for better line performance. It is imperative to conduct a thorough study to identify best possible arrangements to install the arresters parallel with the phase insulators. This paper aims to simulate the worst case due to transmission shielding failure by three direct strikes to a line phase conductor of 25 kA, 35kA, 50kA, 65 kA and 80kA per strike respectively. The total energy absorption requirement of the arrester could be determined by multiplying by 3 times the arrester energy due to MSL. Various configurations with respect to the surge arresters parallel with the insulators were examined in order to achieve suitable arrangements that would be economical as well as to improve the lightning performance of the transmission line.

II. LIGHTNING PARAMETERS

A thorough knowledge about the parameters of lightning strokes is necessary in order to forecast the severity of transient overvoltages generated transmission line equipments due to direct and indirect strikes to the power line [8]. Lightning flash parameters which are of primary concern to utilities engineers are: (i) the crest current for the first and subsequent strokes (ii) waveshape of these currents (iii) correlation between the parameters (iv) number of strokes per flash (v) ground flash density. The return stroke and the stroke charge are the most important parameters to assess the severity of the lightning strokes to the lines and apparatus [8]. Transient overvoltages are established by one of the cases as described below.

Shielding Failure

Direct strike to phase conductor results in the associated current splitting into two halves which travel back and forth the struck conductor. The travelling wave generated is given by

$$V(t) = 0.5I(t)Z_p \tag{1}$$

where,

$$Z_p = \sqrt{\frac{L}{C}}$$

Z_p is the surge impedance of the phase conductor, and is given by
and L and C are the series inductance (H/m) and capacitance to ground (F/m) per metre of the phase conductor

respectively. This voltage will be impressed across the insulator at the end of the span [9].

The shielding failure rate (SFR) is the number of strokes that terminate on the phase conductor. If the voltage produced by a stroke to the conductor exceeds the CFO, a flashover occurs. The SFR can be calculated using equation 2

$$SFR = \frac{2N_g L}{10} \int_{I=3}^{I=I_{\max}} D_c(I) f_1(I) dI \qquad (2)$$

where

N_g= Ground Flash Density, flashes/square km/year
L= line length, km
I_{min}= minimum lighnting current, 2-3kA
D_c=Horizontal exposed distance of the phase conductor, m
SFR= Shielding failure rate, per 100 km per year.

The shielding failure flashover rate (SFFOR) is the number of shielding failures that results in flashovers, or Shielding Failure Flashover Rate SFFOR, is

$$SFR = \frac{2N_g L}{10} \int_{I=I_c}^{I=I_{\max}} D_c(I) f_1(I) dI \qquad (3)$$

The total shielding failure rate is the sum of the first stroke failure rate SFFOR and the added rate SFFORs.

SFFORs can be obtained from

$$SFR = \frac{2N_g L}{10} P_s \int_{I=I_{\min}}^{I=I_c} D_c(I) f_1(I) dI \qquad (4)$$

The probability of flashover on a subsequent stroke given that no flashover occurs on the first stroke is given by

$$P_s = \sum_{n=2}^{n=\infty} P_n \frac{2N_g L}{10} P_n \left(1 - [1 - P(I_s > I_c)]^{n-1}\right) \qquad (5)$$

where

P_n= Probability that there are n strokes/flash
I_s= Peak subsequent-stroke current, and

$$P(I_s > I) = \frac{1}{1 + \left(\frac{I}{12kA}\right)^{2.7}} \qquad (6)$$

where,

$I_{\min} < I_s < 30kA$ and I in kA [10].

III. MODELLING APPROACH

To carry out the study, PSCAD/EMTDC version 4.2 is used to model the transmission lines, surge arresters and surge characteristics. The transmission line and towers are modelled as waist towers using the distributed lossless line model.

A Tower and Transmission Line Model

Transmission line model based on standard twin circuit line geometry drawings and conductor information of a typical 132 kV double circuit line geometries is shown in Fig. 1. The followings are used to represent the transmission line: the transmission line conductor comprises of 2 x 300 sq.mm ACSR Batang conductors per phase and 2 x 60 sq.mm ACSR Skunk earth wires. The transmission towers are represented by a multi-storey lattice tower model as shown in Fig. 2. The transmission line is a twin circuit three phase line. The lowest conductor from the ground is 14.01 m. the span length of the line is 300m. A template of the line geometry is given in Fig.3. The surge impedance of the tower is calculated from the tower dimension using equation 6.

$$Zg = 60 \ln\left(\cot\left[0.5 \text{ x } \tan^{-1}\left(\frac{r_{avg}}{H_t}\right)\right]\right) \qquad (7)$$

where

$$r_{avg} = \frac{r_1 h_1 + r_2(h_1 + h_2) + r_3 h_1}{h_1 + h_2}$$

Z_T = the average tower surge impedance,
r_1= the tower top radius, r_2= the tower mid-section radius, r_3= the tower base radius, h_1= the height from base to mid-section, h_2= the height from mid-section to top [7, 10]

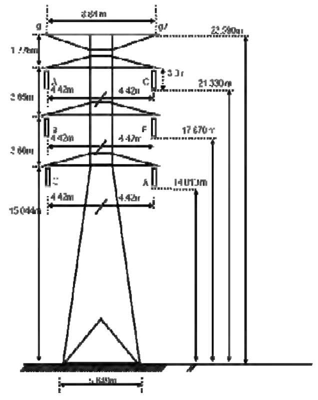


Fig.1. A TNB 132 kV tower model

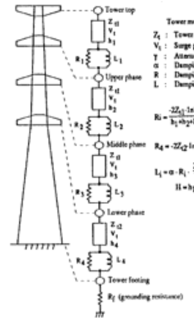
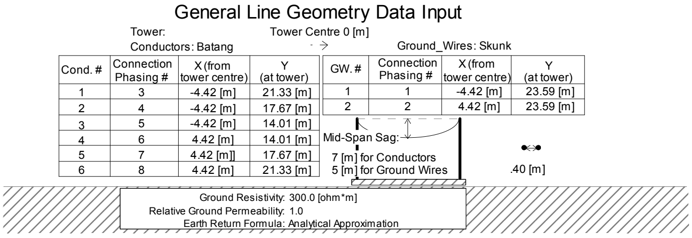


Fig.2. Multi-storey transmission tower model [9]



General Line Geometry Data Input

Tower: Tower Centre 0 [m]

Conductors: Batang

Cond. #	Connection Phasing #	X (from tower centre)	Y (at tower)
1	3	-4.42 [m]	21.33 [m]
2	4	-4.42 [m]	17.67 [m]
3	5	-4.42 [m]	14.01 [m]
4	6	4.42 [m]	14.01 [m]
5	7	4.42 [m]]	17.67 [m]
6	8	4.42 [m]	21.33 [m]

Ground_Wires: Skunk

GW. #	Connection Phasing #	X (from tower centre)	Y (at tower)
1	1	-4.42 [m]	23.59 [m]
2	2	4.42 [m]	23.59 [m]

Mid-Span Sag:
7 [m] for Conductors
5 [m] for Ground Wires

.40 [m]

Ground Resistivity: 300.0 [ohm*m]
Relative Ground Permeability: 1.0
Earth Return Formula: Analytical Approximation

Fig.3. A template of line geometry data input for tower and ground wires

B Insulator Strings

The insulator is modelled based on per string. It is represented by circuit breaker in parallel with capacitor connected between respective phases and the tower. The glass insulators that make up the string contribute to an equivalent capacitor which is used in the model. The flashover will take place along the insulator string when the electric stress between the conductor and the tower cross-arm exceeds the critical withstand voltage of the string. The breakdown performance of the insulators is modelled with the volt-time characteristics curve which leads to back flashover or flashover interpretation. The voltage withstands capability of the insulator voltage can be calculated using the simplified Equation (8) below:

$$V_{flashover} = K_1 + \frac{K_2}{t^{0.75}} \qquad (8)$$

where,

$K_1 = 400{*}L$, $K2 = 710{*}L$

$V_{flashover}$ is Flashover voltage in kV,

L is Insulator length in m,

t is Elapsed time after lightning stroke, µs [10, 11, 12, 13].

C Surge Arrester Model

Surge arrester is modelled as non-linear device suitable to represent its high frequency behavior as recommended by the IEEE working group [14]. The VI characteristics were obtained from the manufacturer data sheet. The parameters used for the model are as follows:

Voltage for 10 kA, 8/20µs, U_{10}=497.6 kV, length of arrester column = 1.436 m, and number of parallel columns of metal-oxide discs= 1.

IV. LIGHTNING

Lightning strokes of 40 kA maximum direct strike to a phase conductor is considered a severe condition. Shielding failures tend to occurs for currents between 10 kA to 20 kA. Over 50% of the lighnting strikes contain more than one stroke [15]. The mean number per flash is three with a time interval of 20 ms to 50 ms. A worse case scenario, is considered were a shielding failure occurred following three direct strikes to the top phase conductor of magnitudes 25kA, 35kA, 50kA, 65kA and 80kA per strike respectively. The arrester energy for one such strike is multiplied 3 times to determine its total energy absorption requirement owing to MSL.

A Surge Arrester Configurations and Analysis

The transmission line is modelled as described above to determine suitable configuration for installing the LSAs when the line is subjected to direct strikes of MSL. Table I summarises the results obtained of the energy dissipated by the arrester. Table II shows that for all currents, top phase A1 of circuit 1 experienced flashover when the line is hit by direct strikes. This could possibly be due to strikes on the top conductor. The same was observed when lightning strokes hit the middle and bottom conductors. Based on this observation, the arrester is placed on the top phase A1 when the strokes terminate on the top conductor.

TABLE I
DISCHARGE ENERGIES OF ARRESTER INSTALLED AT PHASE A1

Config.	Energy A_0 kJ/kV	Energy A_1 kJ/kV	Current kA
A1	212.9	212.9	3×25=75
A1	314.9	110.0	3×35=105
A1	451.0	145.5	3×50=150
A1	568.8	310.4	3×65=195
A1	678.5	438.7	3×80=240

The waveform of the phase conductor associated with lightning stroke on the top conductor is given in Fig.4

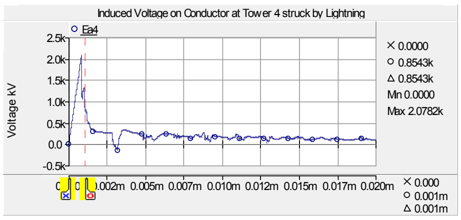


Fig.4 Waveform of the produced voltage on top conductor following multiple strokes

The current and voltage waveshapes of surge arrester subjected to 3 direct strikes of 25 kA each are shown in Fig.5. The current is about 7.2 kA and the arrest voltage is 281.8 kV.

TABLE II
LOCATION OF FLASHOVER OF INSULATORS

Current kA	Direct Stroke on Top Phase Conductor					
	Double Circuit Phase Conductors					
	A1	B1	C1	A2	B2	C2
3×25	✓	×	×	×	×	×
3×35	✓	×	×	×	×	×
3×50	✓	×	×	×	×	×
3×65	✓	×	×	×	×	×
3×80	✓	×	×	×	×	×

Note:

✓ Denotes flashover,

× Signifies no flashover

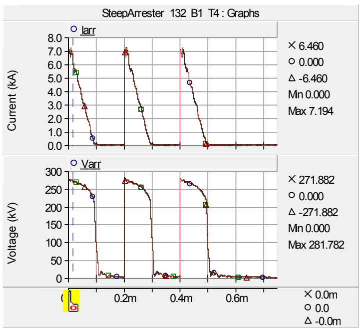


Fig.5 Current and voltage waveforms of IEEE recommended metal-oxide surge arrester installed on Phase A1 during lightning

Plot in Fig. 6 depicts discharged energy by the arrester under the influence of MSL striking the phase conductor. Increase in current result to a corresponding increase in discharge energy.

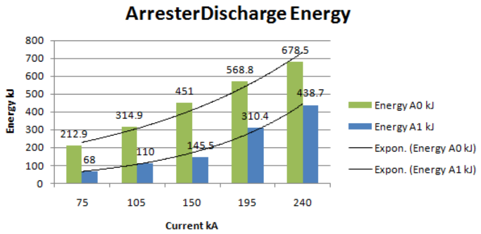


Fig.6 Arrester discharge energy for the surge arrester A_0 and A_1

The waveforms in Fig.7 estimate the maximum energy discharged by the arrester when different peak currents terminate on the top conductor.

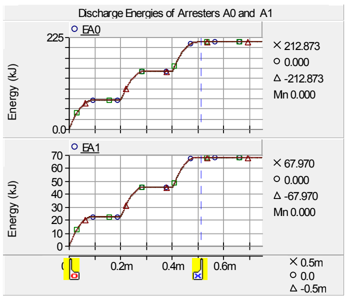


Fig. 7 Plots showing the discharged energies of A_0 and A_1

The results revealed each stroke of MSL causes the arrester to discharge equal amount of energy during an interval of 20 ms. The sum of the two energy gives the arrester energy and when multiply by 3 times result to the total energy absorption requirement due to lightning.

V. Conclusions

This work presents the findings of the study carried out to determine suitable arrangements for installation of surge arresters parallel with phase insulators of transmission towers. It is observed that flashover would occur on an insulator when a lightning strikes a conductor where an insulator is installed. Improvement can be achieved by installing arrester on the phase or phases where the lightning is expected to strike.

This study assumed that the top conductor susceptible to lightning strikes is the main reason why much focus is on the top conductor. Installation of arrester at the upper phase causes no flashover of the insulator. This was also observed during lightning strikes at the middle and bottom conductors of the transmission line. Based on the summarised results of Table II, it is evident that arresters with high energy absorption capability are the preferred choice for selection.

One aspect that would have been worth trying during the study was to assume that lightning hit all of the three phase conductors rather than a single conductor. This would enable to have a clear assessment about the arrester performance and the overall improvement of the line. Future study will be conducted on this assumption during MSL and multiple-simultaneous strokes lightning (MSSL).

Acknowledgment

The authors would like to thank Advanced Power Solutions for their support in carrying out this research in their industry. They would also like to thank the Dean Faculty of Electrical Engineering, Universiti Teknologi Malaysia for his permission to publish this paper. Further thanks are extended to IVAT, Institute of High Voltage and High Current for their assistance during the simulation work.

References

[1] H. M. Suzuki et al, “Rating and Requirement for Externally Gapped Line Surge Arresters,” CIGRE C4 Colloquium on Lighnting and Power System, Kuala Lumpur, Malaysia, May 2010.

[2] B. Richter, “MO Surge Arresters in Emerging Cable Systems” CIGRE C4 Colloquium on Lighning and Power System, Kuala Lumpur, Malaysia, May 2010.

[3] H. Murata et al, “Long Term Study of Line Arrester with External Series Gap Applied to Transmission Lines in Japan”, CIGRE C4 Colloquium on Lighning and Power System, Kuala Lumpur, Malaysia, May 2010.

[4] L. Ekonomou et al, “Lightning Performance Evaluation of Hellenic High Voltage Transmission Lines” International Symposium on High Voltage Engineering”, Rotherdam, Netherlands, 2003.

[5] I. Rawi and N.S. Hudil, “TNB Experience on the Application of Transmission Line Arresters 132 kV Teluk Ewa- Teluk Apau”, CIGRE C4 Colloquium on Lighnting and Power System, Kuala Lumpur, Malaysia, May 2010.

[6] I. Uglesicl, “Application of Line Surge Arresters in Power Distribution and Transmission Systems”, CIGRE SC C4 Colloquium , Cavat, Croatiaa, May 2008

[7] J.A. M-Velascoand F.C-Aranda,” Assessment of the Lightning Flashover Rate of a Shielded Transmission Line Protected by Surge Arrester,” International Conference on Power Systems Transients (IPST) Lyon, France, June 2007

[8] IEEE Task Force, “Parameters of Lighnting Strokes: A Review”, IEEE Transl. On Power Delivery, Vol.20, No.1, 2005.

[9] P. Chowdhuri, “Parameters of Lightning Strokes and Their Effects on Power Systems”, IEEE/PES Transmission and Distribution Conference and Exposition, Atlanta, Georgia 2001.

[10] IEEE WG Report, “Estimating Lightning Performance *of Transmission Lines II” IEEE* Transl. on Power Delivery, Vol.8, No.3, July 1993.

[11] IEEE Modelling and Analysis of Systems Transients Working Group Report, “ Modeling Guidelines for Fast Front Transients ” IEEE Transl. on Power Delivery, Vol.11, No.1, January 1996

[12] P. Yadee and S. Premrudeepreechacharn,” Analysis of Tower Footing Resistance Effected Backflashover across Insulator in a Transmission Line”. International Conference on Power Systems Transients (IPST) Lyon, France, June 2007

[13] IEEE Standard,” IEEE Guide for Improving the Lighting Performance of Transmission Lines”, IEEE Std 1243-1997

[14] IEEE Modeling of Metal Oxide Surge Arresters” IEEE Working Group Report, “ Application of Surge Protective Devices Sub Committee ” ” IEEE Transl. on Power Delivery, Vol.7, No.1, January 1992

[15] PSCAD/EMTDC Manual,” Introduction to PSCAD/EMTDC V3”, Manitoba HVDC Research Centre Inc. 2001