Investigation of Spark Gap Role in Protection of Distribution Transformer Against Lightning Surges Using ATP-EMT

MUJTABA ALI*, MUHAMMAD YAQOOB JAVED, AND SYED TAHIR HUSSAIN RIZVI*****

* Department of Technology, The University of Lahore, Lahore, Pakistan.

** Department of Electrical & Computer Engineering, COMSATS University, Islamabad, Pakistan.

*** Department of Computer Engineering, University of Lahore, Lahore Campus, Pakistan.

Authors E-Mail: (mujtaba.ali@tech.uol.edu.pk, yaqoob.javed@cuilahore.edu.pk, tahir.hussain@dce.uol.edu.pk)

ABSTRACT

This research implores the capability of the commonly used surge protection device, spark gap, for the protection of distribution transformer in an event of transient over-voltage surge. The spark gap is one of the most valuable protection components because it is small in size, strongly made and capable of withstanding rough handling, has minimal capacitance, and possess the ability to carry transient currents of the order of kiloamperes. However, in some occurrences the spark gaps can be slow to conduct the transient current. This paper investigates the time lag characteristics of the spark gap with respect to the increasing time front of the transient surge. The protective device is installed with a distribution transformer of an 11kV line and the line is energized with a transient source at an adequate distance, and the timely response of the device, for different cases, is recorded with the help of ATP-EMTP (Alternative Transient Program-Electromagnetic Transients Program) simulations. The distribution transformer is faced with transient surges of different parameters, within suitable range, to completely asses the ability of the device to guarantee an effective protection to the distribution. The research aims to lead to an increase in the reliability and performance of the existing spark gap models, and ensure better protection of the distribution transformers. LESCO (Lahore Electric Supply Company) was approached for data regarding the 11kV transmission line for an urban area of Pakistan. The research has been performed on a 630, 11/0.415 kV, distribution transformer installed on 11kV line.

Key Words: Spark Gap, Alternative Transient Program-Electromagnetic Transients Program, Lightning Surge, Distribution Transformer.

1. INTRODUCTION

Lightning is a natural phenomenon and causes transient surges in the transmission system that can lead to the failure of the equipment and the system as well. An 11kV overhead distribution line possesses small insulation level with elevated flashover rate and the distribution transformer is vulnerable to the incidence of lightning strokes [1]. Any incident voltage surge with magnitude greater than the BIL (Basic Insulation Level) value of the transformer can lead to failure of transformer insulation, resulting in severe damage to the equipment. A transformer is expensive equipment in a power system and its failure can lead to loss of revenue and power system reliability. Many countries have reported the outage of distribution transformers owing to lightning surges. The 61% line trip out in Guangdong province of China is caused by lightning [2]. According to the statistical data of 7 years in Brazil, lightning accounts for most of the distribution transformer damages, and was 47% for period between 2003 and 2011, an average of 1140 distribution transformer failure per year [3]. In United States, the lightning surges were responsible for 13% in failure of transformers for a duration of 19 years from 1991-2010 [4]. In researches carried out in Australia by Australia, Norway and US and another in Japan, it was observed that even with the installation of the protection devices , they were able to lower the failure rate but further work is in progress on developing devices to completely safeguard the distribution transformer from lightning [5-6].

Pakistan experiences medium to high thunderstorm activity with northern areas facing the highest lightning activity as shown in the 20 years data of thunderstorm activity in Pakistan in Fig. 1 [7].

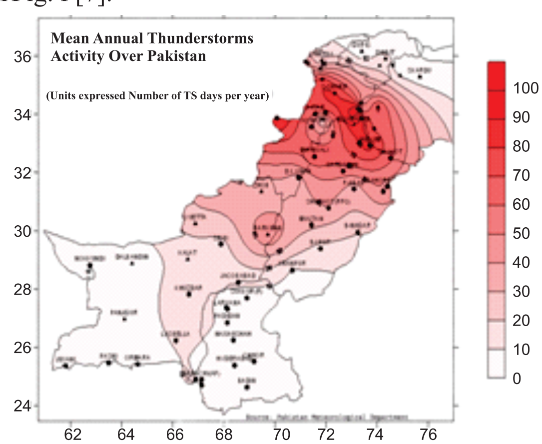

FIG. 1. MEAN ANNUAL THUNDERSTORM ACTIVITY OVER PAKISTAN

A distribution transformer is checked for a standard protection against lightning by a test known as transformer chopped wave test. The procedure of the test is the application of a standard lightning impulse wave shape with crest value exceeding 1.15 times the BIL of transformer. According to the applied voltage, the gap in front of the apparatus flashes over in 1-3 ps. The transformer is supposed to withstand this voltage for the duration and no flashover or the failure should occur [8].

The test intensely verifies the turn-to-turn insulation strength of transformer, as it is checked by the rapid chop to voltage zero. The transformer connections are set up as shown in Fig. 2, where H1, H2 and H3 shows the three windings of primary side of transformer. The transformer experiences many fast front high voltage surges in service, so this is an incumbent test for the transformers. In power system studies, the wavefront time (T_f) and wavetail time (T_t) parameters are employed to define a surge waveform as shown in Fig. 3. The wavefront time (or rise time) is defined as 1.67 times the time taken by the surge to reach 90% of its peak value from 10% i.e. 1.67($T_{0.9}$ - $T_{0.1}$). The wavetail time is the time when the current waveform approaches half of its peak value (i.e. $T_t = T_2$) [9].

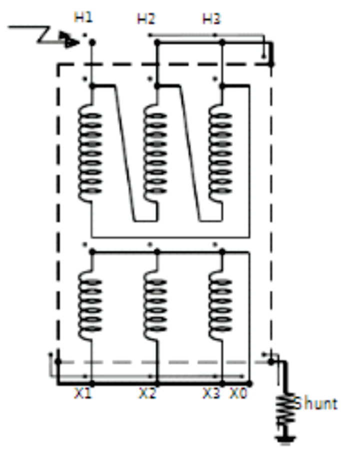

FIG. 2. TEST SCHEME FOR THREE-PHASE DISTRIBUTION TRANSFORMER [8]

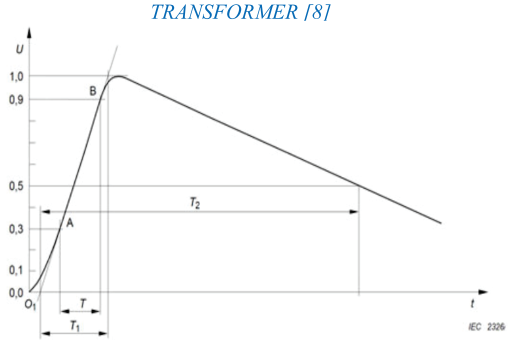

FIG. 3. A TYPICAL SURGE WAVEFORM [9]

2. WORKING OF SPARK GAP

A spark gap device is installed for the protection of the insulation of the windings of the transformer. It is a low-cost device and readily available but is not completely reliable for the purpose of protection against the surges. A spark gap is connected in parallel of the equipment desired to be protected as shown in Fig. 4. The figure shows that one end of the spark gap is connected to the live terminal and the other end is grounded effectively. The gap distance is adjusted such that when the surge appears, it leads to breakdown of air in the gap and an arc is established across the spark gap diverting the surge to the ground, hence protecting the equipment. The normal line voltage is not sufficient to establish an arc, and it only occurs in case of the overvoltage.

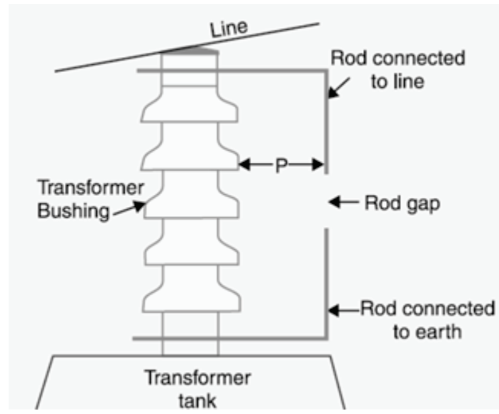

FIG. 4. SPARK GAP CONNECTED ACROSS TRANSFORMER BUSHING [9]

Although the spark gaps are very useful but they have the following drawbacks [9]:

(i) The operation of spark gap creates a short circuit fault leading to operation of protection devices that isolates the circuit.
(ii) The inter turn insulation of the transformer is stressed upon intensely due to the sudden reduction in voltage owing to spark gap operation.
(iii) The equipment insulation breakdown varies according to the overvoltage duration. A spark gap demonstrates a slow response to overvoltage surges which have a high-rise time gradient. In other words, the protection provided by the spark gap is dependent on the steepness of the gradient of overvoltage surge.
(iv) The flashover voltage of the spark gap is affected by the environmental conditions such as presence of dust particles, humidity level, foreign particles etc. This badly influences the performance of the spark gap.
(v) The birds and the debris brought by the wind are a deadlock to the operation of spark gap and leads to its maloperation.

The Fig. 5 shows that as the overvoltage magnitude of the incident wave increases, the spark gap takes longer time to reach the arcing point.

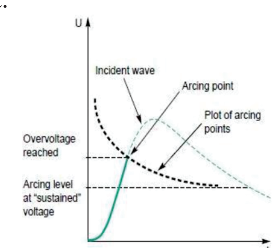

FIG. 5. SPARK GAP PROTECTION RELATIVE TO STEEP GRADIENT [10]

3. MODELING IN ATP-EMTP

ATP does not possess any model regarding the transmission system; however, it subjugates the authority to users to construct their own models with the help of library tools. Fig. 6 shows the block diagram of the ATP model. The voltage source model is used which transmits power to the transmission line, and it conducts power to the distribution transformer, protected by spark gap, across the transmission tower. The Fig. 6 shows the block diagram of the model where the voltage source energizes the transformer, across the transmission line and transmission tower. The distribution transformer is protected by the spark gap.

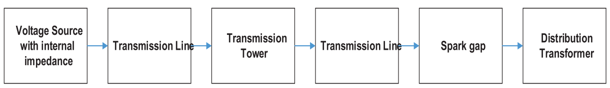

FIG. 6. BLOCK DIAGRAM OF THE ATP-EMTP MODEL

Lightning Surge Model: A lightning surge magnitude and parameters are affected by the climatic conditions, resistivity of the soil, geological conditions and the location. The Heidler type current source is used from ATP library that possess the required capability of energizing the transmission line with lightning strike.

Transmission Line Model: The analysis up to a frequency of 500 kHz was carried out using the LCC module type JMARTI, representing the transmission line as shown in Fig. 7 [11-13]. The data regarding the conductors was collected from LESCO [14]. The length of the line was set to be 0.61km from substation to the transformer, with ten connecting transmission towers. A 3 km line section has been included at both ends of the transmission line to circumvent the reflections and accurately study the transient response. It is modeled by the component LINEZT_3. [15-17].

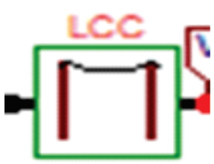

FIG. 7. LCC MODULE FOR TRANSMISSION LINE MODELING

Tower Model: The modeling of steel lattice tower, as shown in Fig. 8, was achieved in three sections: Firstly, the voltage-controlled switches were used to model the pin type insulators and the component LINEZT_1 modeled the tower impedance. Secondly, the tower resistance was computed as Equation (1):

$$Z_T = 60\left[\ln\left(\sqrt{2}\,\frac{2h}{r}\right) - 1\right] \quad (1)$$

where h corresponds to the height and r is the pole radius [18-19].

Thirdly a linear resistance was used to model the foot resistance [20-21].

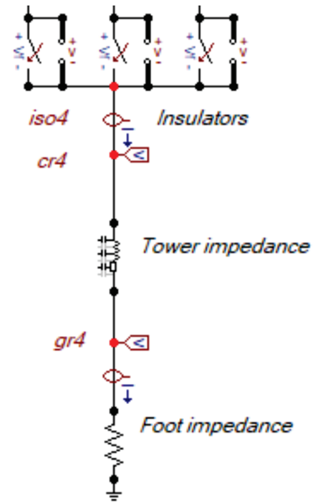

FIG. 8. THE TRANSMISSION TOWER MODEL

Spark Gap Model: The voltage-controlled switch is used to model the spark gap, which is set to operate at the required voltage level. For an 11kV line, it is set to operate at 70 kV. Table 1 shows the parameters of the spark gap used for 11 kV line, and ideal upper and lower limits of the spark gap flashover are used in this simulation [22].

TABLE 1. SPARK GAP PARAMETERS FOR 11 KV LINE

Parameter of 11 kV Line	Voltage Level (kV)
Transformer BIL	95
Ideal upper limit of Spark gap flashover	76
Ideal lower limit of Spark gap flashover	63
Max. arrester residual voltage	53

Transformer Model: We have used 630kVA distribution transformer and the data for its windings was obtained from a transformer manufacturer PEL (Pak Elektron Limited). Fig. 9 shows the labelled model of the distribution transformer used in ATP. Fig. 9 shows the equivalent transformer resistances, inductance and capacitance, with end line model.

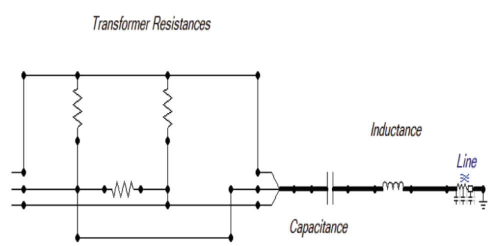

FIG. 9. THE DISTRIBUTION TRANSFORMER MODEL

4. TRANSIENT ANALYSIS IN ATP-EMTP

The lightning parameters used are: peak amplitude 5kA, stroke duration of 20 µs, 3.7 growth factor 3.7, surge rise time varied from 0.5-5 µs [23]. The over voltages faced by the transformer windings is recorded and then it is investigated if the level and duration of exposure can damage the transformer insulation. Six cases were developed for the 11kV transmission line with the surge rise time varying from 0.5-5 µs, which is the normal range of time front duration of the lightning surge waveform. The remaining parameters were all kept constant as discussed in the modeling section. Now for each case we will investigate if the spark gap is able to respond quickly to avoid over voltage from being stressed upon the windings of transformer. Many latest researches regarding the transient analysis with the help of ATP-EMTP have employed the same strategy [24-27].

In Fig. 10, the x-axis shows the time in µs, and y-axis shows the over voltage magnitude. We can see a transient surge waveform, where it reaches its peak value of 170 kV, time front of 1.5µs. Now we will see the impact of this surge on the distribution transformer and will measure the response of spark gap. The lightning surge parameters are set as the stroke duration 10 µs, growth factor 3.7, peak amplitude set to 5 kA.

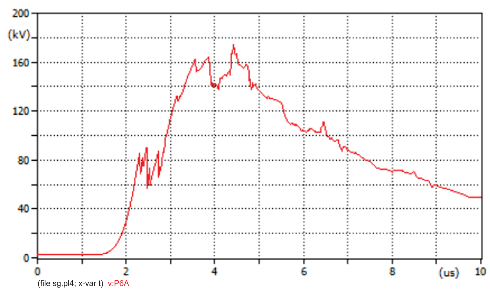

FIG. 10. TRANSIENT SURGE WAVEFORM

Case-1: The lightning surge time front duration was set to 0.5 µs. It can be observed in Fig. 11 that over voltages reached above 95 kV at the transformer terminals for duration of about 1 µs which is sufficient enough to lead to the failure of transformer. Hence in this case the spark gap failure is prominent.

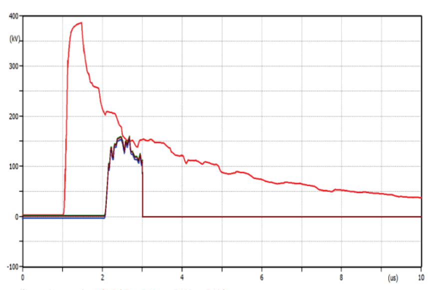

FIG. 11. ATP-EMTP SIMULATION FOR LIGHTNING TIME FRONT 0.5 µS

In Fig. 11, the red line shows the transient surge as it reaches its peak value in 1.6 µsecs. The green line shows the voltage across the terminals of the transformer, and it can be obeserved that from 2-3 µs, the transformer windings were exposed to the transient surge reaching above its BIL value of 95 kV for 1 usec, before the spark gap completes its operation and saves the transformer from the overvoltage surge. This is sufficient to damage the insulation windings of the transformr and hence it can be seen that for a transient surge of 0.5 µs time front, spark gap was unable to completely protect the transformer in a timely manner.

Case-2: The lightning surge time front duration was set to 1 µs. It can be observed in Figs. 12-13 that over voltages reached above 95 kV at the transformer terminals for duration of about 0.8 µs which is sufficient enough to lead to the failure of transformer. Hence in this case the spark gap failure is prominent.In Fig. 12, the red line shows that the surge voltage applied has a peak value of 380 kV, and a time front of 1 µs. The other waveforms, that show the overvoltage magnitude across the transformer windings, have been focused in next Fig. 13, where the time and magnitude can be clearly observed

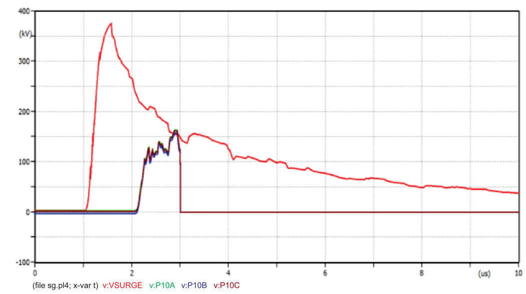

FIG. 12. ATP-EMTP SIMULATION FOR LIGHTNING TIME FRONT 1 µS

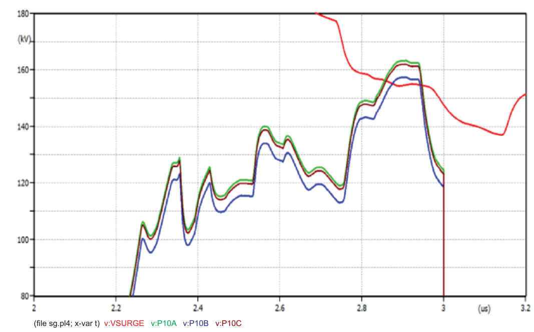

FIG. 13. ATP-EMTP SIMULATION SHOWING OVER VOLTAGE ACROSS THE TRANSFORMER WINDINGS FOR LIGHTNING TIME FRONT 1 µS

In Figs.12-13, the green line shows the voltage across the phase A terminals of the transformer, and it can be obeserved that from 2.22-3 µs, the transformer windings were exposed to the transient surge reaching above its BIL value of 95 kV for 0.88 us, before the spark gap completes its operation and saves the transformer from the overvoltage surge. This is sufficient to damage the insulation windings of the transformr and hence it can be seen that for a transient surge of 1 µs time front, spark gap was unable to completely protect the transformer in a timely manner.

Case-3: The lightning surge time front duration was set to 2 µs. In Fig. 14, the green line shows the voltage across the terminals of the transformer.It shows that the over voltages across the terminal of the transformer reached above 95 kV for duration of about 0.6 µs, from 2.38-3 µs, before the spark gap completes its operation and saves the transformer from the overvoltage surge. This overvoltage of 130 kV for this short duration is sufficient enough to lead to the failure of transformer. Hence in this case the spark gap failure is prominent.

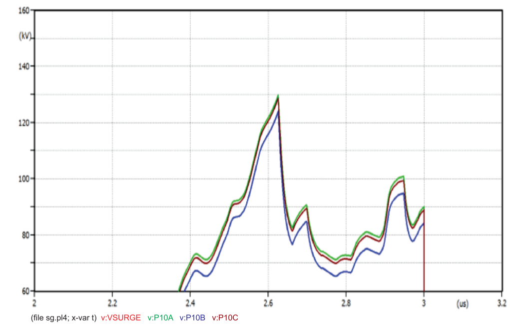

FIG. 14. ATP-EMTP SIMULATION SHOWING OVER VOLTAGE ACROSS THE TRANSFORMER WINDINGS FOR LIGHTNING TIME FRONT 2 µS

Case-4: The lightning surge time front duration was set to 3 µs. In Fig. 15, the green line shows the voltage across the terminals of the transformer. It shows that the over voltages across the terminal of the transformer reached above 95 kV for duration of about 0.1 µs, from 2.8-2.9 µs, before the spark gap completes its operation and saves the transformer from the overvoltage surge. This overvoltage of 100 kV for this short duration is sufficient enough to lead to the failure of transformer. Hence in this case the spark gap failure is prominent.

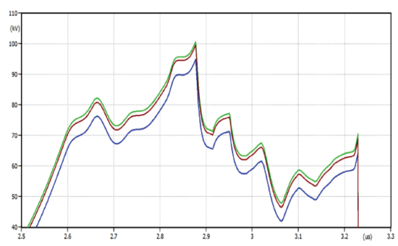

FIG. 15. ATP-EMTP SIMULATION SHOWING OVER VOLTAGE ACROSS THE TRANSFORMER WINDINGS FOR LIGHTNING TIME FRONT 3 µS

Case-5: The lightning surge time front duration was set to 4 µs. In Fig. 16, the green line shows the voltage across the terminals of the transformer. It shows that the over voltages across the terminal of the transformer reached about 92 kV, before the spark gap completes its operation and saves the transformer from the overvoltage surge. Hence in this case the spark gap timely completes its operation and it is observed that spark gap was successfully able to protect against the fast rise time surge for a transient surge of 4 µs time front.

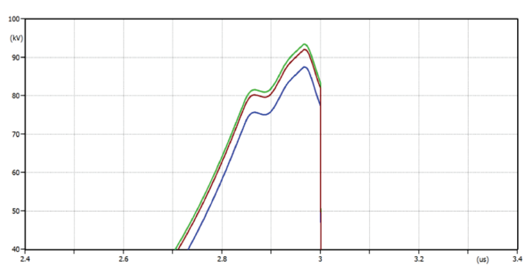

FIG. 16. ATP-EMTP SIMULATION SHOWING OVER VOLTAGE ACROSS THE TRANSFORMER WINDINGS FOR LIGHTNING TIME FRONT 4 µS

Case-6: The lightning surge time front duration was set to 5 µs. It can be seen in Fig. 17 that spark gap effectively operated as soon as the over voltage surged beyond 70 kV. The spark gap operated timely to protect the transformer windings and did not allow over voltages at the terminals to exceed the BIL value. Hence in this case the spark gap success is prominent and it is observed that spark gap was able to protect against the fast rise time surge.

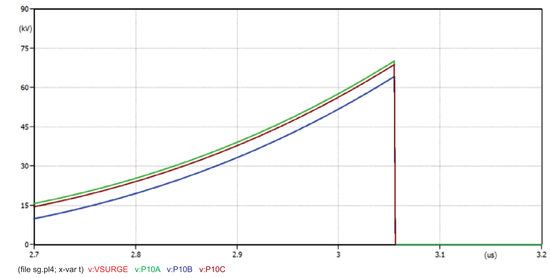

FIG. 17. ATP-EMTP SIMULATION SHOWING OVER VOLTAGE ACROSS THE TRANSFORMER WINDINGS FOR LIGHTNING TIME FRONT 5 µS

The Table 2 collectively shows the results of the simulations and concludes that the spark gap provides adequate protection for slow rise time lightning surges, but in an event of fast lightning surge, its ability gets compromised.

TABLE 2. RESULTS OF USING SPARK GAP FOR PROTECTION OF DISTRIBUTION TRANSFORMER

Case	Lightning Surge Time Front (µs)	Spark Gap Operation
1	0.5	Fail
2	1	
3	2	
4	3	
5	4	Successful
6	5	

5. CONCLUSION

It has been observed that the spark gap was able to protect the transformer windings against transient voltages for slow rise time surges i.e. above 3 µs, but is unable to protect against the very fast rise time transient surges with rise time less than 3 µs. It does not offer satisfactory protection for all the cases, and hence spark gap alone is not a reliable device for the protection of distribution transformer. It must be used in combination with other devices such as surge absorber or surge arrestor that first reduces the steepness of the transient surge and enables spark gap to effectively operate, as shown in the cases with low steepness of surge, and hence provide enhanced protection against lightning.

ACKNOWLEDGEMENT

The assistance provided by Prof. Dr. Mustafa Kizilcay, European Regional Coordinator, ATP-EMTP, regarding the coding and analysis for components of the software, has been of immense support.

REFERENCES

[1] Zejun, L., Shanqiang, G., and Chun, Z., "Calculation of Lightning Trip-Out Rates for 10 kV Overhead Distribution Line", IEEE International Conference on Lightning Protection, pp. 667–670, 2014.

[2] He, Y., Fu, Z., Jiang, A., Wu, A., and Wang, G., "Impact of Distribution Line Insulated Tower Head and Cross Arms on Lightning Surges in 10 kV Substations", IEEE International Conference on Lightning Protection, pp. 936–941, 2014.

[3] DeCarvalho, T.O., Piantini, A. Obase, P.F., and Bastista, J.M.,"Lightning-Caused Transformer Failures in Distribution Systems", IEEE International Conference on Lightning Protection, pp. 955–960, 2014.

[4] Hoffman, P., and Bryan, W., "Large Power Transformers and the US Electric Grid", Infrastructure Security and Energy Restoration, Office of Electricity Delivery and Energy Reliability, US Department of Energy, April, 2014.

[5] Ishii, S.,Yokoyama, S., Imai, Y., Sugimoto, H., and Morooka, Y.,"Lightning Protection of Pole-Mounted Transformer Japanese mV Lines", Harmonics and Quality of Power, New York, USA, September, 2004.

[6] Darveniza, M., and Mercer, D.R., "Lightning Protection of Pole Mounted Transformers", IEEE Transactions on Power Delivery, Volume 4, No. 2, pp. 1087–1095, 1989.

[7] Meer, H., Hussain, A., and Babar, A.Z.,"Analysis of Thunderstorms Activity Over Pakistan During (1961-2000)", Pakistan Journal of Meteorology, Volume 3, Issue 5, June, 2006.

[8] Hileman, R., "Insulation Coordination for Power Systems", CRC Press, Taylor & Francis Group, 1999.

[9] Bayliss, C., and Hardy, B., "Transmission and Distribution Electrical Engineering", Newnes Elsevier Publications, 2012.

[10] Futchiron, D., "Schneider Cahier Technique no. 192, Protection of MV/LV Substation Transformers", 1998.

[11] Martinez, J.A., and Castro-Aranda, F., "Lightning Performance Analysis of Overhead Transmission Lines Using the EMTP", IEEE Transactions on Power Delivery, pp. 2200–2210, June, 2013.

[12] Chu, J., and Vaddeboina, V., "Probabilistic Determination of the Impact of Lightning Surges on 145kV GIS Equipment - A Comprehensive ATP/EMTP Study", Proceedings of Universities Power Engineering Conference, 2012.

[13] Chatterjee, T., and Mukherjee, A., "Study of Lightning Overvoltage Transients Using ATP", IEEE International Conference on Circuit, Power and Computing Technologies, 2015.

[14] "LESCO Power Distribution Planning Guideline", General Manager (Operation), WAPDA, September, 2003.

[15] Cabral, R.J., Gazzana, D.S., Leborgne, R.C., and Bretas, A., "Improved Distribution Feeder Topology Against Lightning", IEEE International Symposium on Lightning Protection, Computer Society, pp. 267–272, 2013.

[16] Cabrai, R.J., Gazzana, D.S.,Leborgne, R.C., and Bretas, A., "Efficiency of Rural Distribution Feeders Against Lightning: A Case Study", Proceedings of IEEE Conference on Power Systems Computation, 2014.

[17] Dawalibi, F.P., Ruan, W., Fortin, S., and Ma, J.,"Computation of Power Line Structure Surge Impedances Using the Electromagnetic Field Method", Proceedings of IEEE Conference on Power Engineering Society Transmission and Distribution, Volume 2, pp. 663–668, 2001.

[18] LESCO "Power Distribution System for Construction Design", General Manager (Operation), WAPDA, May, 2016.

[19] Heidler, F., Cvetić, J.M., and Stanić, B.V., "Calculation of Lightning Current Parameters", IEEE Transactions on Power Delivery, Volume 14, No. 2, pp. 399–404, 1999.

[20] IEEE Standard 1410-2010, "IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines", 2010.

[21] Chowdhuri, P., Anderson, J.G., Chisholm, W.A., Field, T.E., Ishii, M., Martinez, J.A., Marz, M.B., and McDaniel, J., "Parameters of Lightning Strokes: A Review", IEEE Transactions on Power Delivery, pp. 346–358, 2005.

[22] Seitshokelo, K.V., Beutel, A., Cebekulu, J., and Gekdenhuys, H., "Auxiliary Spark Gaps For Transformer Protection", South African Institute of Electrical Engineers, Johannesburg, 2009.

[23] IEEE-TF on Parameters of Lightning Strokes, "Parameters of Lightning Strokes: A Review," IEEE Transanctions on Power Delivery, Volume 20, No. 1, pp. 346–358, January, 2005.

[24] Ali, M., and Saqib, M. A., "Transient Analysis of a Distribution Transformer Using ATP-EMTP",Proceedings ofIEEE 1st International Conference on Power, Energy and Smart Grid, pp. 1–6, 2018.

[25] Kopp, T.H., Runge, T., and Kurrat, M., "Analysis of Arc Behavior in a Model Spark Gap After Surge Currents", IEEE Transactions on Components, Packaging and Manufacturing Technology, Volume 8, No. 6, pp. 958–965, 2018.

[26] Omidiora, M., and Lehtonen, M., "Mitigation of Lightning Flashover from Tree to Medium Voltage Aerial Cable Using Shield Wire", IEEE Transactions on Power Delivery, Voolume 32, No. 4, pp. 1924–1934, 2017.

[27] Lu, W., Xu, J., Hao, S., Chen, H., Ma, S., and Zhai, W., "Study on Lightning Overvoltage Protection Methods for UHV GIS Substation with Different Lightning", IEEE 4th International Conference on Electric Power Equipment- Switching Technology, pp. 808–812, 2017.