Case Study on the Failure of 400kv XLPE Cables Termination of Tala Hydropower Plant through Electromagnetic Transient Analysis Using Mipower Software

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Abstracts

This paper presents an investigation into the failure of 400kV XLPE (Crossed-Link Polyethylene) cable terminations at the Tala Hydropower Plant (THP) using Electromagnetic Transient (EMT) analysis in MiPower software. Four XLPE cables connect the underground Gas Insulated Switchgears (GIS) to the outdoor switchyard, from where twin moose transmission lines link to the Indian grid via Siliguri Substation. There have been frequent issues with cable terminations. Noteworthy incidents include a flashover in the outdoor cable terminations of Y phase feeder 1 on June 4, 2021 and another flashover in the indoor cable termination of B phase feeder 2 on March 17, 2022. Despite these recurring failures, the root causes remain inconclusive. EMT analysis was employed to examine the Temporary Over-Voltages (TOV), during various operations. The THP-Siliguri network was modelled in MiPower, and two case studies were analyzed, considering the impact of lightning arrestors (LAs). In the first case, a three-phase to earth fault was simulated at a distance of 0.5km from Tala on transmission line 1. In the second case, a simulation was conducted to replicate conditions during the energization of feeder 2 when circuit breakers (CBs) were closed sequentially at Siliguri and THP ends. Both cases indicated that TOVs occurred during fault but were effectively suppressed by LAs. The study confirms that the LAs at THP are functioning reliably, as simulations show TOVs suppression at cable terminations. With LAs in place, TOV levels remain within safe operational limits, validating their effectiveness. With TOV eliminated, the study suggests other degradations such as thermal aging, improper termination practices, or moisture ingress as potential contributors to the failure. As the first known EMT based study of such failures at THP, the findings offer broader insights for similar HV cable termination of hydropower plants in Bhutan with comparable configurations.

Key Words: *THP, MiPower, EMT, TOV, LA, XLPE Cable*

1. INTRODUCTION

THP is Bhutan's largest underground powerhouse, with an installed capacity of 1020 MW. THP evacuates its power to India through four twin-moose transmission lines, one of which is looped in and out at Malbase Substation, Bhutan. Before reaching these lines, power from the underground GIS is evacuated via 400kV XLPE cables to the outdoor POTHEAD yard. However, frequent failures have been observed at both ends of the cable termination. Noteworthy incidents include a flashover in the outdoor cable terminations of Y phase feeder 1 on June 4, 2021, during heavy rain and thunder, and another flashover in the indoor cable termination of B phase feeder 2 on March 17, 2022. Despite these recurring failures, the root causes remain inconclusive, necessitating further investigation to prevent future occurrences.

To address this issue, the Tala-Siliguri network was modelled in MiPower software to study the effects of TOV on cable terminations. Overvoltage in a power system is caused by many factors, broadly internal and external factors. The internal factors are phase to earth fault, and switching activities, while the external factors are such as lightning, etc. One of the common overvoltage causes due to internal factors is TOV. TOV is defined as an oscillating phase to ground and phase to phase overvoltage, which can last for seconds or minutes (Othman et al., 2019).

Using EMT analysis capabilities in MiPower, two case studies were conducted based on historical failure data and operational assumptions as recorded in the shift logbook. In the first case, a three-phase-to-earth fault was simulated at a distance of 0.5km from Tala on transmission line 1. EMT simulations revealed elevated overvoltage at the termination point under fault conditions, even with lightning arrestors (LAs) in place. In the second case, a simulation was conducted to replicate conditions during the energization of feeder 2 when circuit breakers (CBs) were closed sequentially at Siliguri and THP ends. The analysis indicated that TOVs occurred during energization but were effectively suppressed by LAs.

The study confirms that the LAs at THP are functioning reliably, as EMT simulations show significant overvoltage suppression at 400kV XLPE cable terminations. With LAs in place, TOV levels remain within safe operational limits, validating their effectiveness.

2. LITERATURE REVIEW

During power system operation, XLPE cables and their accessories are constantly subjected to various stresses, leading to insulation degradation, which results in defects and often causes cable breakdown (Gugulothu et al., 2024). THP has four outgoing feeders of GIS connected to the outdoor POTHEAD yard through 400 kV XLPE cables.

The XLPE cables of the THP have a history of incidents of failure of cable termination and its components, therefore, it has become vital to study the system behaviour. Dhiman & Shingne (2023) stated that the cable terminations are crucial components which, most of the time, are subjected to various stress which caused the cable to fail. The causes can be imbalanced electrical stress which must be must be controlled through good design, proper materials, and skilled installation. Over 50% of cable terminations are caused by installation errors. Other causes include poor design and defective materials. Improper stress control can lead to partial discharge and insulation breakdown

Other than THP, hydropower plants in Bhutan such as Mangdechhu Hydropower plant, Dagachhu Hydropower Plant, Tangsibji Hydropower Plants and upcoming plants like Punatsangchhu Hydropower Plant I and II has also XLPE cables interconnecting the GIS and outdoor POTHEAD yard. Nevertheless, only the THP experienced such cable termination failures. On 4th June 2021, the Y phase of feeder 1 failed due to the failure of the outdoor cable termination. On 17th March 2022, the B phase of feeder 2 failed due to the failure of the indoor GIS cable termination.

Given the history of failure, the root cause of failure cannot be conclusive and may likely to be repeated. Nevertheless, a detailed study is carried out to examine the system behaviour during normal operation, the different faults that occur in power system networks, and the impact of operating with and without LA. Conducting such a study would help maintain the system balance thereby improving the system's reliability and avoiding any unnecessary outages.

3. MODELLING IN MIPOWER

Conducting EMT analysis requires precise modelling and simulation of the real power system network. MiPower provides robust tools and modules to achieve this. To represent the actual system, the real-time data from THP is used to model the system network. THP has 6 generating units of 170 MW of each, totaling 1020 MW, 6 Generator Transformers and 4 outgoing feeders from the GIS to the POTHEAD yard. From there, the power is evacuated to Siliguri Substation, India through twin moose transmission lines.

The network model for studying the failure of the 400kV XLPE cable is as follows:

- All six units of THP station load are represented with individual generators with a capacity of 170 MW each.
- Since the length of XLPE cables is short i.e. around 0.7kM, they are represented in terms of pi-network (delta). The length of the twin moose transmission lines are about 156 km and are modelled as T-network.
- The bus at Siliguri end is treated as a slack bus.
- Circuit breakers are connected to study surges due to switching actions.
- Additional buses are created somewhere on the mid of the lines so as to allow user to create faults on lines.
- Other elements such as shunt reactor and lightning arresters are shown for easy reference of the location of the installation of those elements.

Since the main components of the developed model are XLPE cables and the twin moose transmission lines, the important specifications and parameters of these lines are provided in the Table 1. Fig.1 shows model of Tala-Siliguri network develop in MiPower software.

***Table 1**: Parameters of Lines, termination and LA*

XLPE Cables	
Manufacturer's name & country of origin	ABB Energiekabel GmbH, Germany
Type	400 kV, single phase, single core, copper conductor
Highest system voltage	420 kV
Impulse withstand voltage	1425 kV_{peak}
Switching impulse withstand	1020 kV_{peak}
Material Cross-sectional area	1200 mm^2
Positive Sequence Resistance	0.0000161 Ω/meter
Positive Sequence Reactance	0.000182 Ω/meter
Outdoor XLPE Cable Termination	
Name and country of manufacturer	ABB Energiekabel GmbH, Germany
Type	EHFV 420
Insulating medium	Polyisobutene (Insulating Oil)
Lightning impulse withstand voltage	1425 kV_{peak}
Switching impulse withstand voltage	1050 kV_{peak}
Indoor XLPE Cable Termination	
Name and country of manufacturer	ABB Energiekabel GmbH, Germany
Type	EHSV 420
Insulating medium	Polyisobutene (Insulating Oil)
Lightning impulse withstand voltage	1425 kV_{peak}
Switching impulse withstand voltage	1050 kV_{peak}
Lightning Arrestor	
Rated arrestor voltage	390kV
Maximum continuous operating voltage at design ambient temperature	303kV
Maximum equivalent front of wave protection level	1050kVp
Impulse withstand test voltage of arrestor housing with 1.2/50 micro second wave	1425kVp
Twin Moose Transmission Line	
Positive Sequence Resistance	0.02936 Ω/km
Positive Sequence Reactance	0.30716 Ω/km
Zero Sequence Resistance	0.27566 Ω/km
Zero Sequence Reactance	1.0715 Ω/km

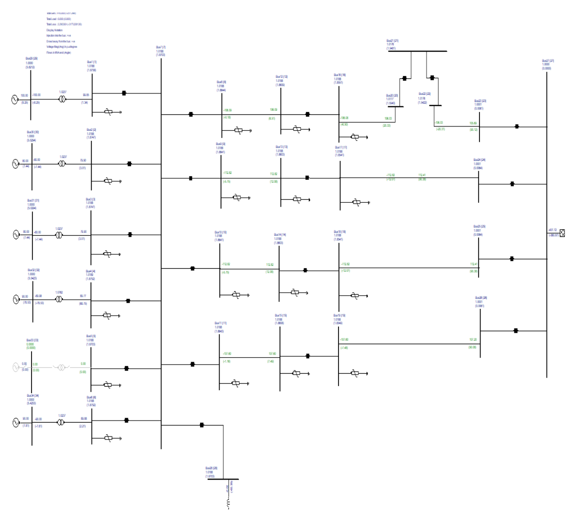

***Fig.1:** THP-Siliguri Model*

4. VALIDATION OF MODEL

The developed model is validated with the THP's operational data. Load Flow Analysis (LFA) was performed to establish the initial steady state of the balance system before conducting EMTP studies. Conducting an LFA is essential before undertaking other studies, such as short circuit studies or dynamic stability studies, as it serves the same foundational purpose outlined earlier (Dubey, 2016). MiPower software provides an option to perform LFA involving various methods like Gauss-Seidel, Newton-Raphson, or Fast Decoupled with a plot option as well. However, the interest of the EMT study is just to achieve its convergence and initial steady state of the system; the Fast Decoupled method has generally been adopted due to its nature of faster convergence.

As the system's initial steady state with convergence of load flow is successfully achieved, the overvoltage study through EMTP is executed.

Under the EMTP solve option, we can create different faults on a bus/line and study the corresponding degree of surges due to these faults. There is also an option for studying switching surges by closing or opening a breaker(s) with/without fault existence on the system.

Upon execution of the EMT analysis, the result obtained can be interpreted both in a graphical and text form. In the graphical platform, different waveforms like bus voltages, phase voltages, etc are obtained. The results obtained in this study could be used to study system behaviour during the occurrence of disturbances like switching actions, etc.

The Tala-Siliguri model developed in Mi-Power software is validated by comparing the simulation results with the real-time data to ensure that the model accurately represents the behaviour of the actual Tala-Siliguri system. The power generation data of THP on 20th March 2023 were compared with the simulation results. The key parameters, like voltage profile, power flow, and line loading, were considered for the comprehensive model validation. There were no significant discrepancies in voltage magnitude and phase angle when compared between the simulated results and the real-time operational data.

The active power flows on the XLPE cables and transmission lines were observed to be similar to the actual operational data. It was therefore validated that the model THP-Siliguri networks were accurately represented in MiPower.

5. CASE STUDIES

5.1 Case study 1

On 4th June 2021 at 23:40 hrs (BTT), Tala-Siliguri 400 kV feeder 1 Y phase outdoor cable termination experienced a flashover. There was heavy rain with severe thunder around the powerhouse premises from the evening throughout that night. During the trip, security personnel stationed outside the powerhouse reported hearing abnormal noises and sparks at the POTHEAD yard. The feeder was shut down for further inspection.

Based on the shift logbook recorded by the Operation Division, THP, pre-conditions, and certain assumptions are made for the failure studies of the XLPE cables:

- Unit 1 was generating 100 MW, Unit 2 and Unit 3 with 80 MW, Unit 4 and Unit 6 with 90 MW, and Unit 5 as a standby.
- All the feeders were in service. Therefore, there was a mutual coupling effect between the circuits.
- The Tala-Siliguri feeder 1 tripped, and the outdoor Y-phase cable termination experienced a flashover. There was 3 phase-earth faults at a distance of 0.5 km, zone 1.
- For the study purposes, the three-phase earth fault is introduced at 0.5 km on the Tala-Siliguri Transmission line 1, and the different cases were considered.

5.2 Case study 2

On 17th March 2022 at 16:43 hrs (BTT), Tala-Siliguri 400 kV feeder 2 B phase indoor cable termination experienced a flashover. Based on the shift logbook recorded by Operation Division, THP, pre-conditions, and certain assumptions are made for the failure studies of the XLPE cables

- Unit 4 and Unit 6 were generating 140 MW and other Units were not in service.
- Only feeder 3 was in charged condition. Therefore, there was no mutual coupling effect between the circuits initially.
- Feeder 2 was brought to charged condition by closing the circuit breaker at the Siliguri end at 16:25 BTT and closing the circuit breaker at the THP end at 16:27 BTT.
- At 16:43 BTT, feeder 2 tripped as there was flashover in the indoor cable termination of feeder 2 B phase.
- The feeder has tripped with the actuation of XLPE cable differential protection. There was a fault on the B phase indoor termination.
- For the study purpose, a fault was created at the B-phase indoor termination. The circuit breaker at the Siliguri end was keep in first closed at 0.1 seconds, and then the circuit breaker at THP was in open condition initially and closed at 0.15 seconds.

6. RESULT & ANALYSIS

EMTP simulation in the Mi-Power software gives voltage and current waveforms on various buses and lines in the modelled system. Nevertheless, for this particular study, the main focus is to study the overvoltage at the termination side of 400 kV XLPE cables. Therefore, the output voltage waveform of the XLPE cable at the termination location is interpreted. In all the waveform graphs, the x-axis represents the time series in seconds and the y-axis represents the voltage in kV.

The simulated TOV values experienced at the cable terminations were also compared with the switching impulse withstand voltages. The Table 2 and Table 3 show the comparison of these voltages.

6.1 Case study 1

For this case study, the TOVs experienced at the outdoor cable termination of XLPE feeder 1 are thoroughly analyzed. Fig. 2 illustrates the graphical representation of TOV across all the phases. Since the Y-phase outdoor cable termination failed, the TOV at this particular cable termination is shown in Fig 3. To further analyze the TOVs in the absence of LAs at the cable termination, the LAs at the particular termination are deliberately taken out of service, and the corresponding TOVs are analyzed and shown in Fig. 4 and Fig.5. In the Fig. 2 and 4 all the three phases of the voltage are shown, R, Y and B phases are represented by red, green and blue colour respectively. Table 2 shows the simulated values of TOVs experienced at the Y phase outdoor cable termination.

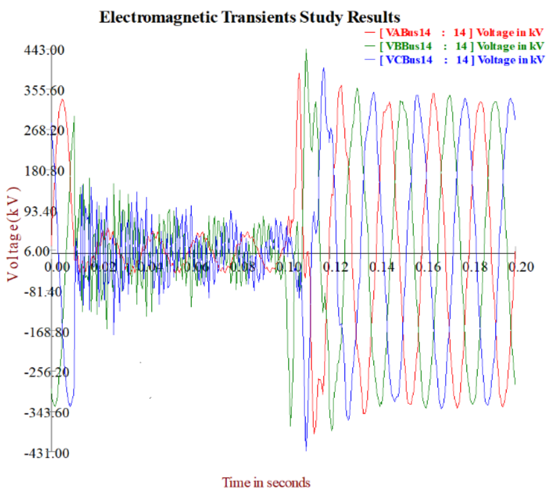

Fig.2: *Voltages at outdoor termination with LA*

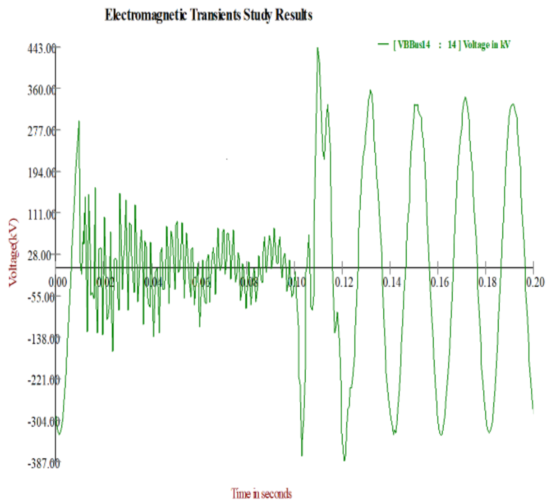

Fig. 3: *Voltage at outdoor termination of Y phase with LA*

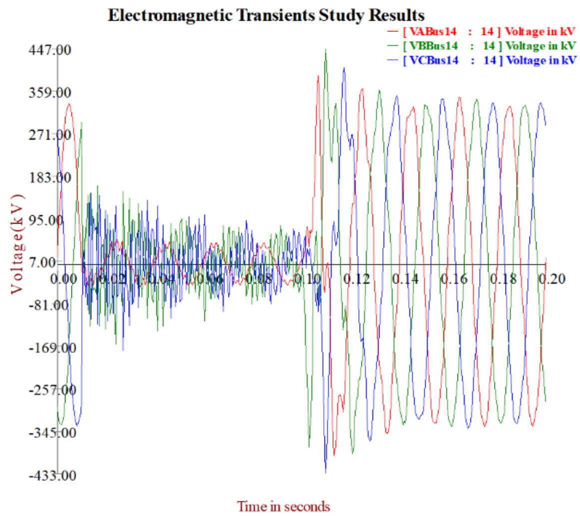

Fig.4: *Voltages at outdoor termination without LA*

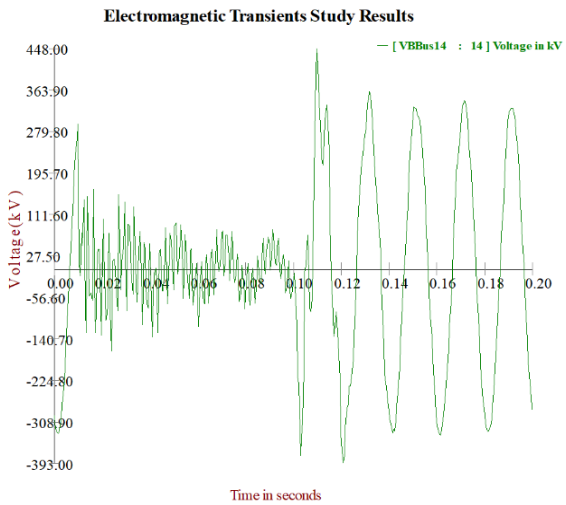

Fig.5: *Voltage at outdoor termination of Y phase without LA*

***Table 2** TOV values with and without LA-Case 1*

Event	TOV Without LA (kV_{peak})	TOV With LA (kV_{peak})
Three phase to earth fault on transmission line 1	445	439

6.2 Case study 2

Similar to case study 1, in this case study, the TOVs experienced at the indoor cable termination of XLPE feeder 2 are thoroughly analyzed. Fig. 6 illustrates the graphical representation of TOV across all the phases, with

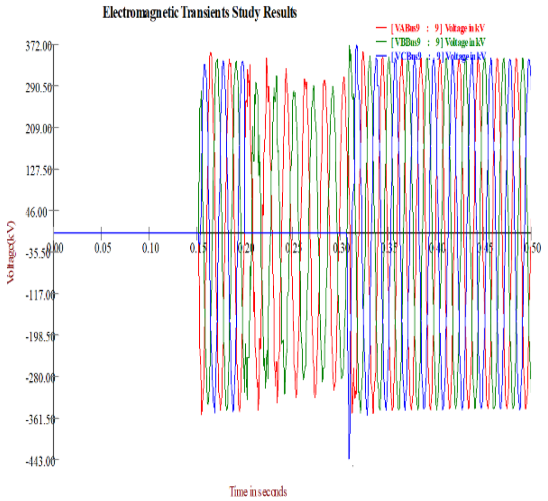

***Fig.6:** Voltages at indoor termination with LA*

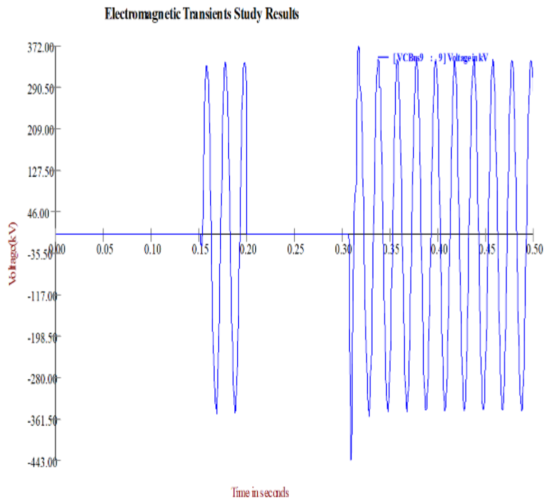

***Fig.7:** Voltage at the indoor termination of B phase with LA*

Fig 7. Focusing on the B-phase in indoor cable termination, where the failure has occurred. TOVs analyzed and shown in the Fig. 8 and Fig.9 are used to study the impact of LAs on the affected termination. Same as in case study 1, in the Fig. 6 and 8 all the three phases of the voltage are shown, R, Y and B phases are represented by red, green and blue colour respectively. Table 3 summarizes the simulated values of TOVs experienced at Y phase indoor cable termination.

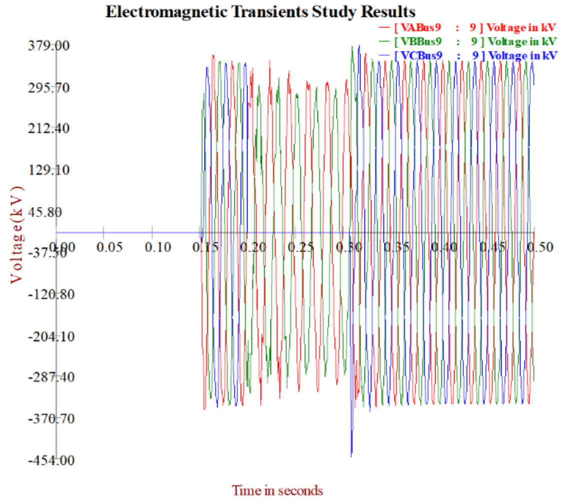

***Fig.8:** Voltages at indoor termination without LA*

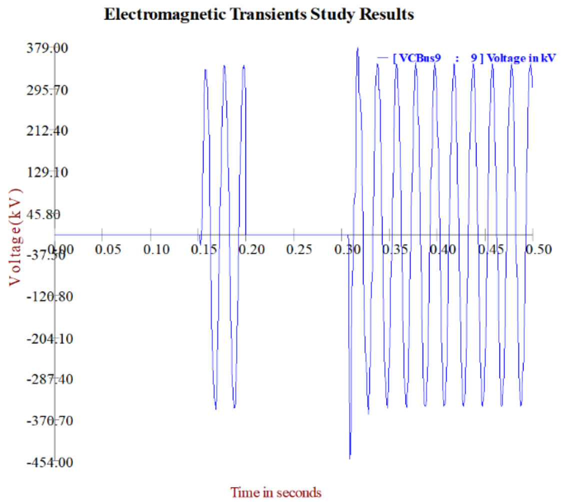

***Fig.9:** Voltage at indoor termination of B phase without LA*

***Table 3.** TOV values with and without LA-Case 2*

Event	TOV Without LA (kV_{peak})	TOV With LA (kV_{peak})
B phase to earth fault on indoor cable termination of XLPE cable 2	453	438

From the number of above-mentioned observations and results, the cause of the failure of the 400kV cable termination based on the two case scenarios is theoretically eliminated. At the same time, the LAs in the cable termination are also functioning effectively, as evidenced by their response on the TOV. The peak values of all simulated TOVs are within the limit compared to that of LAs rating. Hence, other potential degradation mechanisms, such as insulation ageing, moisture ingress, thermal cycling, etc., should be further explored as probable contributors to failure.

7. RECOMMENDATIONS

Based on this study, the recommendations are made. For a double circuit line, there is a mutual coupling effect when both circuits running on the same tower are under the charged condition, which contributes to a change in sequence impedances which in turn causes the voltage fluctuation in the system. As far as possible, it is therefore recommended to always charge the feeder running on a different tower if only two feeders are required to be in service.

Infrared thermography is one of the best techniques to detect fault in cable terminations since the HV cables generate a large amount of heat (Li et al., 2023). It is recommended that thermal imaging be conducted on all the XLPE cable terminations regularly. The obtained results and the thermal images should be analyzed by trending the results.

Online partial discharge monitoring system. Partial discharge measurement is also one of the best insulation diagnostics techniques for the condition assessment of HV equipment. For the online PD monitoring system, the ultrawideband PD (UHF PD) can detect the partial discharge activities (Hoek et al., 2007). Nevertheless, CoEACaP has an ICMcompact kit for PD measurement, which can be used to measure the PD interval.

8. CONCLUSION

This study investigated the failure of 400kV XLPE cable terminations at the THP through EMT simulations conducted in MiPower software. The model replicated the THP-Siliguri network to study the impact of TOVs during fault conditions and switching events. Two historical failure events, outdoor cable termination failure in Y phase of feeder 1 and indoor cable termination failure in B phase of feeder 2, were thoroughly analyzed using EMT analysis to evaluate the TOVs experienced at cable terminations.

The EMT simulation results confirmed that although significant TOVs were observed during both fault and energization events, the magnitude of these surges remained within the protective limits of the installed LAs. The comparative analysis of TOVs with and without LA revealed the effective performance of LAs, thereby validating their critical role in transient overvoltage suppression. This theoretically eliminates the possibility of LA failure or inadequacy as the root cause of the termination failures. Hence, other potential degradations should be further explored as probable contributors to failure.

As a way forward, the same model can be used to study detailed insulation coordination of the cable termination. The same methodology can be also employed for the similar study for the other hydropower plants in Bhutan.

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