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Analysis of Transient Overvoltages within a 345kV Korean Thermal Plant

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Abstract – This paper presents the simulation results for the analysis of a lightning surge, switching transients and very fast transients within a thermal plant. The modeling of gas insulated substations (GIS) makes use of electrical equivalent circuits that are composed of lumped elements and distributed parameter lines. The system model also includes some generators, transformers, and low voltage circuits such as 24V DC rectifiers and control circuits. This paper shows the simulation results, via EMTP (Electro-Magnetic Transients Program), for three overvoltage types, such as transient overvoltages, switching transients, very fast transients and a lightning surge.

Keywords: Surge, Transient Overvoltages, Switching, Lightning, Gas Insulated Switchgear, EMTP

1. Introduction

Power systems consist of various facilities such as power stations, substations, transmission lines and various loads, etc. Transient overvoltages may occur within a power system when a system status change occurs due to an event such as a fault, lightning or even normal operation.

Generally, modeling of switching devices, such as circuit breakers and disconnector switches, are implemented by ideal switches for analysis within a switching transient simulation. However, the contacts of a disconnector switch move slowly during opening and closing operations, which causes numerous pre-strikes between the contacts. Pre-strikes occur when the dielectric strength between the contacts of the disconnector switch are exceeded by overvoltages. Therefore, the effects of pre-strikes due to disconnector switching continue for a relatively long time compared to the time in a circuit breaker [1-5].

Specifically, in gas insulated switchgear (GIS), a large number of restrikes across the switching contacts will occur when disconnector switches or circuit breaker operation occurs. Each restrike generates very fast transient overvoltages (VFTO), which enter the substation and may propagate inside depending on the substation layout. VFTOs typically have a very short rise time, in the range of 4 to 100 ns, and are followed by high frequency oscillations, in the range of 1 to 50 MHz. Therefore, the analysis of switching transients and very fast transients in GIS is extremely important [6-11]. Also, when lightning hits a nearby tower or the shield wire of an incoming line, this can cause a backflashover, which is when the resultant lightning surge enters the substation and may propagate inside depending on the substation layout. Hence, as in the case of switching transients, the transients caused by a lightning surge also need to be analyzed.

In 2005, when a disconnector closed within a 345kV Korean thermal plant, the circuit breakers for the exciter protection of two generators tripped except the operation of any protective relay. The tripping of the circuit breakers caused inoperation to occur for two generators, which then caused a productivity decrease for the entire plant. Thus, analysis is required in order to discover the trip cause for the circuit breakers due to disconnector switching. In this paper, the authors analyze the VFTOs due to disconnector switching, including the switching transient and lightning overvoltages.

This paper shows the simulation results of transient overvoltages within a GIS. Also, both a 345kV thermal plant and a pre-strike model of a disconnector switch are modeled by EMTP and then it is further simulated to analyze the transient overvoltages via various transients.

2. Background Theory

The components in a GIS have already been previously modeled by the authors via several transient simulations [12, 13]. The previous papers include more details about modeling as follows, except for in the case of lightning surges. Therefore, these factors are described briefly within this paper.

2.1 Very fast transients

VFTs may occur within a GIS at any time and will cause an instantaneous voltage change, one example being the change caused by disconnector switching. These transient over-voltages are generally below the basic insulation level (BIL) of the GIS and are connected to equipment with

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lower voltage classes. However, they frequently contribute to the life reduction of the insulation within the system [9].

The propagation of VFT through the GIS can be analyzed by representing GIS sections as low-loss distributed parameter transmission lines. The main frequencies depend on the length of the GIS sections affected by the disconnector operation and are in the range of 1 to 50MHz. Also, an internally generated VFT will propagate throughout the GIS and reach the bushing where it will cause both a transient enclosure voltage and a traveling wave that will propagate along the overhead transmission line.

2.2 Pre-strike

The pre-strike phenomena of the switches are considered in order to simulate the switching transients. In this paper, the authors refer to references 4 and 5 for modeling the pre-strike, which consists of a calculation for the withstand voltage (Vw), a comparison of the withstand voltage, the switch voltage, a controlled switch, and a probe for measuring the switch terminal voltage. Fig. 1 shows the model of a pre-strike in EMTP [14].

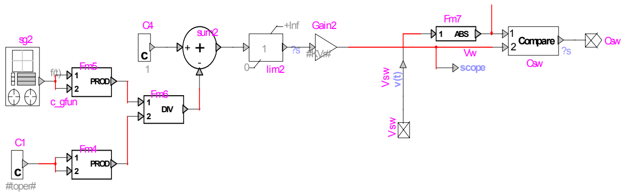


Fig. 1. Model of a pre-strike by EMTP

It is confirmed via the simulation results that the verification of the pre-strike model is properly implemented.

2.3 Grounding system

The operational safety and proper functioning of electric systems are influenced by their earth terminations.

Local inequalities of reference potential for a grounding system are sources of malfunction and may cause the destruction of components that are electrically connected to the grounding system. Therefore, ground system modeling is necessary in order to analyze the effects of reference potential disturbances during various operation abnormalities.

The presented methodology extends the validity range of well-known grounding system models towards higher frequencies, in the range of a few MHz. The approach is based on the three basic concepts that have been developed [15, 17].

This paper uses a grounding system model via the circuit approach method, as mentioned in [18] and shown in Fig. 2.

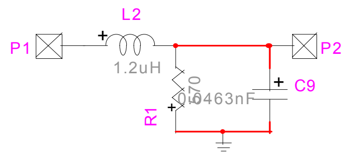


Fig. 2. Equivalent model of the grounding system per unit length

2.4 Lightning surge

Generally, lightning strikes that occur directly on a substation are ignored because it is safely assumed that the substation is shielded appropriately. On the contrary, lightning strikes to the tower or shield wire can cause backflashover due to line insulation flashover between the tower and the phase conductor, and can enter the substation and propagate inside according to the substation layout [9].

In this paper, the standard 1.2x50us impulse waveform is used for the lightning surge model, as shown in Fig. 3.

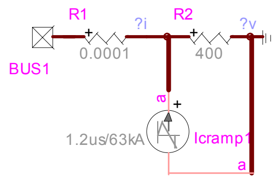


Fig. 3. Lightning surge model

3. Simulation and Results

3.1 System Model

This paper models a 345kV thermal plant via EMTP. The modeled system, as shown in Fig. 4, is comprised of six generators and six transformers, and connects to other systems via six transmission lines.

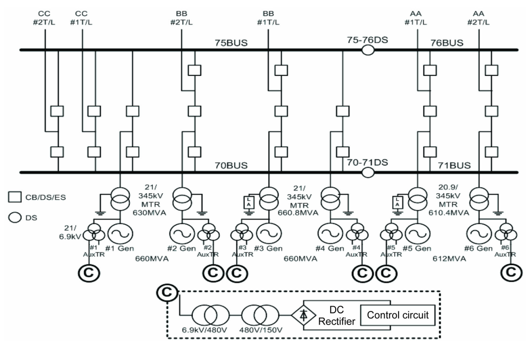


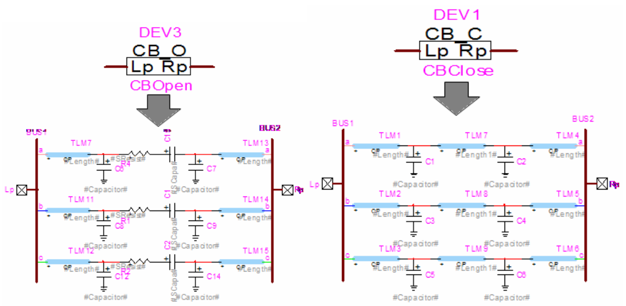
Fig. 4. System Model

3.1.1 Very fast transients and lightning surge section

In order to successfully simulate VFT overvoltage, accurate models are needed for various equipment devices in the range of zero hertz to a few megahertz. However, component modeling within all frequency ranges is very difficult and impracticable. Thus, for reasons of practicality, the modeling of frequency-dependent power system components is implemented within a specific frequency range [9]. The equivalent GIS model consists of various pieces of equipment that function differently for varying frequency ranges. Therefore, equivalent typical equipment models for very fast transients are used [6-8, 10-13, 17].

For the simulation of the lightning surges, the system model is derived from plant layout drawings and should include the lightning surge characteristics. For this reason, the modeling method is similar to the method used for the case of VFT. Though the plant modeling for VFT is more complicated rather than typical modeling for a lightning surge, when the lightning surge is simulated the authors use the modeled system for the VFT in order to reduce effort and time due to repeated modeling.

Fig. 5 shows the equivalent model of the circuit breaker from the equivalent model of GIS components. The other components are modeled by similar procedure [4, 6-13].



(a) Open status (b) Close status

Fig. 5. The equivalent model of the circuit breaker

In order to simulate the effect of various transients on control circuit, the model of control circuit is shown in Fig. 6. Based on the feature of real control circuit, the model of control circuit is simplified.

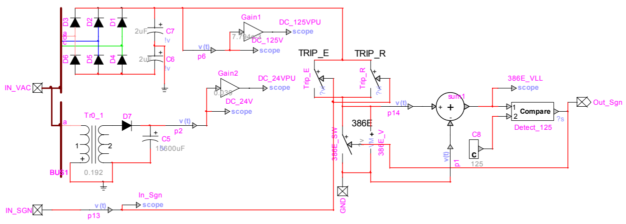
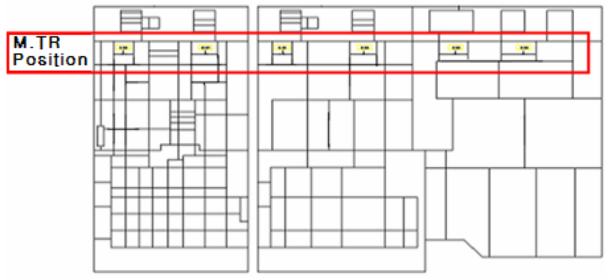


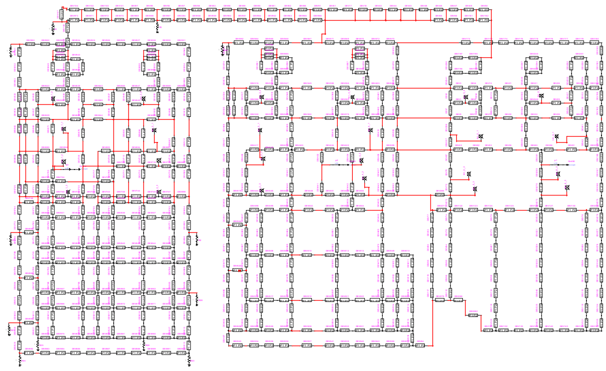
Fig. 6. The model of control circuit

In addition, the entire grounding system is modeled by the layout of real grounding system and the equivalent model in Figs. 2 and 7 shows the model of the entire grounding system used in this paper.

Fig. 8 shows the layout of the 345kV thermal plant, also shown in Fig. 4, when modeled by EMTP.



(a) The layout of real grounding system



(b) the model of the entire grounding system

Fig. 7. Model of the grounding system

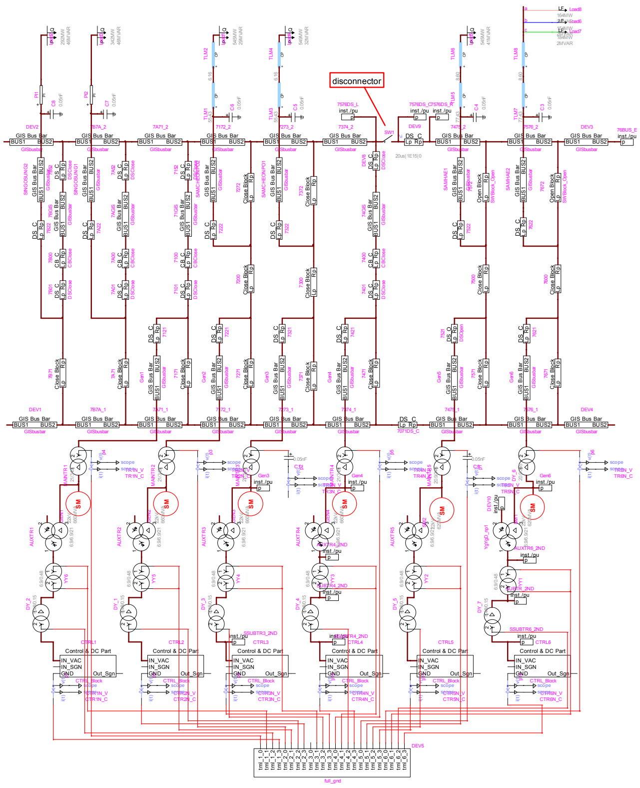


Fig. 8. 345kV thermal plant for very fast transients and lightning surges

3.1.2 A switching transients section

In order to simulate switching transients due to a pre-strike on the disconnector switch, the system model uses the pre-strike model mentioned previously. Fig. 9 shows the GIS part of the system model applied to the pre-strike model. The system model is same except the GIS part with the pre-strike model.

3.2 Simulation conditions

In order to analyze very fast transients, switching transients, which occur due to disconnector switching within the system model, and lightning surges, the simulation conditions are fixed, as shown in Table 1, 2, and 3, respectively.

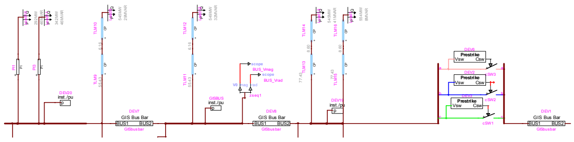


Fig. 9. System model for the switching transients

Table 1. Simulation conditions for very fast transients

Time step	3ns
Maximum simulation time	30us
System condition	76BUS have been de-energized
Simulation condition	75-76 DS close when simulation starts

Table 2. Simulation conditions for switching transients

Time step	125ns
Maximum simulation time	1.3s
System condition	76BUS have been de-energized
Simulation condition	75-76 DS close when simulation starts

Table 3. Simulation conditions for switching transients

Time step	3ns
Maximum simulation time	100us
Simulation condition	Lightning strike transmission lines at 20us

3.3 Simulation results

3.3.1 Very fast transients

(1) Analysis of the transients in the time domain

Fig. 10 shows the voltage waveform, which has a 1.9pu maximum value and a high speed oscillation, of the energized 76BUS after closing the disconnect switches (DS).

Fig. 11 shows voltage waveforms, which are different at each measuring point, for each generator. The voltage at the #4 generator terminals, close to the 75-76 DSs that caused the overvoltage, is more affected by the VFTOs than the voltage at the terminals of the other generators. Therefore, the voltage for the #4 generator is higher than

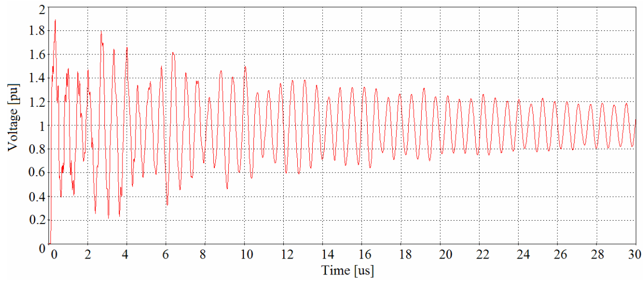
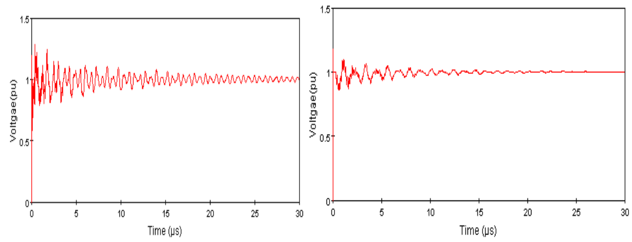


Fig. 10. Voltage waveform at 76BUS



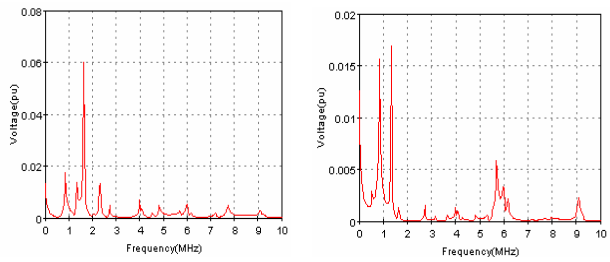
(a) #4 Generator (b) #6 Generator

Fig. 11. Voltage waveforms for some generators in the time domain

the voltages for the others. As shown in Figs. 10 and 11, overvoltages from the disconnector switching propagate through the GIS and are reflected and refracted at every transition point.

(2) Analysis of transients in the frequency domain

Fig. 12 shows the frequency spectrum of the measured voltages at each generator terminal. Due to the main frequencies of the VFT overvoltages being in the range of 100kHz to 50MHz, the simulation results shown in Fig. 12 are the same as in the theoretical studies. Additionally, since the propagation route of the traveling wave is different from the GIS layout and length, the main frequency is different from the frequency at the measuring point. Therefore, both an accurate GIS layout and length are very important for obtaining exact simulation results when a VFT is simulated with disconnector switching within a GIS. Tables 4 and 5 show the summarized the simulation results.



(a) #4 Generator (b) #6 Generator

Fig. 12. Voltage waveforms for some generators in the frequency domain

As shown in the simulation results below, it is clear that the overvoltages generated by disconnector switching propagate through the GIS. The propagated overvoltages affect transformers, generators and buses, especially for a bus that is energized. As mentioned before, VFTOs caused by disconnector switching have very high frequencies and propagate through the GIS and reach all pieces of equipment. Hence, these high frequency overvoltages may cause improper operation of low-voltage control circuits.

Table 4. Measured voltage at each generator

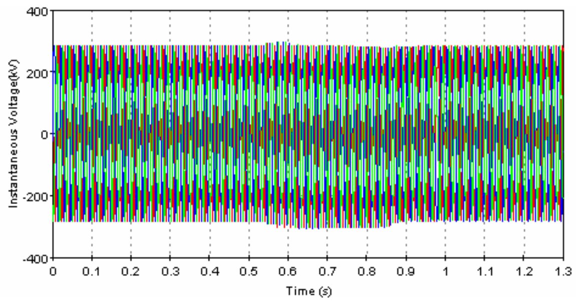
Measured / Point	Voltage at each generator (unit : p.u.)				
	#1 Gen.	#2 Gen.	#3 Gen.	#4 Gen.	#6 Gen.
Max. voltage	1.184	1.311	1.377	1.336	1.111
Max. voltage deviation	0.432	0.651	0.729	0.787	0.270

Table 5. Measured voltage at each bus

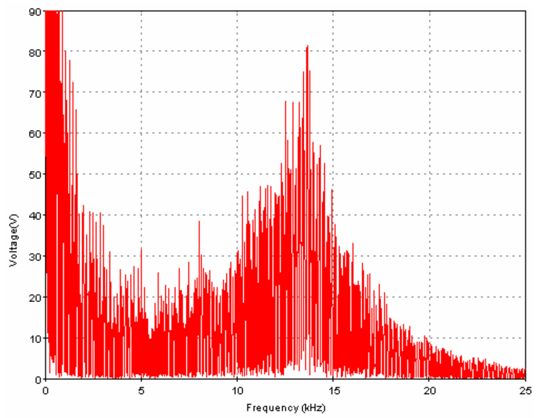
Measured / Point	Voltage at each bus (unit: p.u.)			
	70BUS	71BUS	75BUS	76BUS
Max. voltage	1.27937	1.11887	1.22162	1.89149
Max. voltage deviation	0.55189	0.29512	0.49931	1.67597

3.3.2 A switching transients

Fig. 13 shows the 3-phase instantaneous voltage waveforms and frequency spectrum for the GIS bus bar



(a) Instantaneous voltages



(b) Frequency Spectrum

Fig. 13. 3-phase voltage at the GIS bus bar

after the disconnector switching occurred. Also shown is the slight difference in the overvoltage magnitude at the GIS bus bar, of approximately 7kV, from the magnitude of the normal voltage during disconnector switching. The dominant frequency of the transient overvoltages is 60Hz, which is the power frequency, but the disconnector switching within the GIS creates high frequency components rather than the dominant one, even if they have a relatively small magnitude.

Moreover, voltages and currents at the neutral point of the main transformer have a large magnitude due to the phase unbalance. Fig. 14 shows the voltage waveforms at the neutral points of the main transformers.

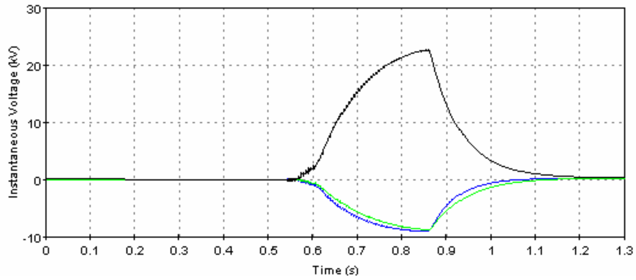


Fig. 14. Voltage waveforms at the neutral point of the main transformer

Even if the magnitudes are different at each measuring point, the average of the neutral voltage magnitudes is approximately 15kV. As a result of the neutral voltages, the grounding system is affected and the ground voltage is temporarily changed to a non-zero voltage value.

Fig. 15 shows the waveforms of the ground voltages for the low-voltage control circuits. The duration is short, about 0.5 seconds, but the voltages have large magnitudes and high frequencies and, because of this, the control circuits would be damaged if they did not have appropriate protection devices, such as a surge protection device.

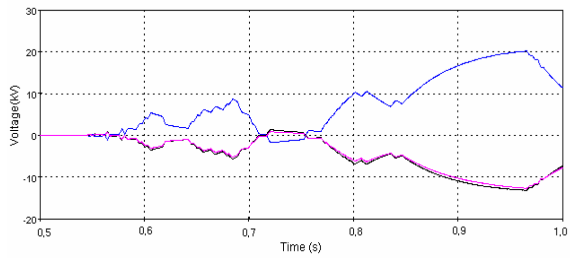


Fig. 15. Ground voltage at low-voltage control circuits

3.3.3 A lightning surge

Fig. 16 shows the phase voltages at the terminals of each generator when lightning strikes the BB #2 transmission line. The simulation results for the other transmission lines are slightly different from the results shown in Fig. 16.

As shown in Fig. 16, when the lightning surges propagate through the GIS, the generator transformers also experience overvoltages, approximately 140kVpeak, due to lightning surges. Figs. 17-18 show the voltage waveform at the neutral point of the main transformer and ground voltage of the low-voltage control circuits, respectively.

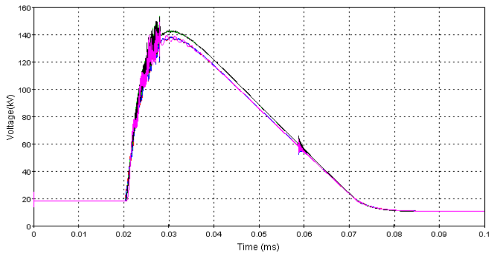


Fig. 16. The voltage waveforms at each generator when the lightning strikes BB #2 T/L

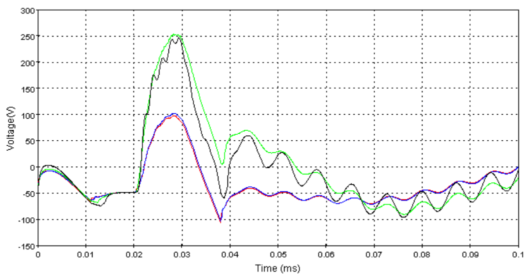


Fig. 17. Voltage waveforms at the neutral point of the main transformer

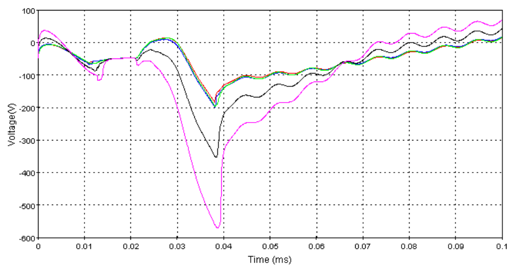


Fig. 18. Ground voltage of the low-voltage control circuits

The voltages of the neutral point of the main transformer and at the ground point of the low-voltage control circuits should be close to zero. However, each voltage has a large magnitude during a lightning surge strike, as in the case of switching transients. The magnitude at the neutral point of the transformers and at the ground point of the control circuits is approximately 250Vpeak, -580Vpeak, respectively. These magnitudes are smaller than the magnitudes of the switching transients, but the lightning surges and the magnitudes have significantly high frequencies. Therefore, several control circuits may be damaged by the overvoltages.

5. Conclusions

This paper demonstrates an equivalent model for various pieces of equipment implemented via EMTP in order to accurately simulate VFTOs by disconnector switching within GIS. Also, calculated voltages are shown in both the time and frequency domains at various measuring points.

It can be concluded from the calculated results that the VFT overvoltages via disconnector switching within GIS propagate and reach all pieces of equipment. Also, the high frequencies of the VFT overvoltage can have an impact on the low-voltage control circuits. Due to the pre-strike phenomenon that causes different reactions for each phase, the phase voltage becomes unbalanced during disconnector switching and then the generated zero sequence voltage has a large magnitude. These zero sequence voltages are revealed as neutral voltages at the neutral point of the transformer and they will affect the grounding system. The simulation results show that the switching transient overvoltages occurring via disconnector switching in GIS are smaller than ones from other origins. Also, when the lightning surge enters the various equipment pieces, such as the GIS, generators, transformers and various devices electrically connected to the GIS in thermal plant, they experience significant overvoltages similar to those stated for the previous cases, i.e. VFTs and switching transients.

However, though the magnitudes of the overvoltages are small, it is clear that overvoltages have high frequencies and can cause high voltages in the grounding system and will, therefore, damage low-voltage electronic devices.

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