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Insulation Coordination Studies for 400 kV GIS in a Hydroelectric Project in India

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Insulation coordination studies comprising of Switching, Lightning and Very Fast Transient overvoltages has been carried out for the 400 kV Gas Insulated Switchgear (GIS) in the Tehri hydroelectric power plant in India. The studies were carried out to decide the various parameters of the switchyard equipment including arrester locations. Results of the switching overvoltages have been validated on the Transient Network Analyser (TNA). This paper discusses some of the results of all these studies.

1.0 INTRODUCTION

Tehri Hydro Electric project is one of the major hydro projects under execution by the Government of India. The hydro station is situated in the foothills of the Himalayan range. Due to geographical constraints the generator and turbine hall, transformer hall have been located inside a tunnel in the mountain. This project owned by Tehri Hydro Development Corporation (THDC) is scheduled to be commissioned in two stages. Stage I of the project would comprise of four numbers of 250 MW hydro machines at Tehri in an underground powerhouse. Stage II would include additional $4 * 250$ MW machines at Tehri and $4 * 100$ MW machines at a surface powerhouse at Koteshwar about 20 km downstream from Tehri.

A total power of 2400 MW is to be evacuated from the generating station at Tehri to major load centers including New Delhi. The evacuation scheme consists of Gas Insulated Bus ducts (GIB) having a three-phase run of 800 m in an underground tunnel from Tehri, a triple circuit 400 kV line from Tehri to a power pooling station - Tehripool, a double circuit 400 kV transmission line from Koteshwar to Tehripool and two 765 kV single circuit lines from Tehripool to the load centre Meerut. The single line diagram of the scheme is shown in figure 1. System studies were carried out to determine the overvoltages likely to develop in the Tehri 400 kV GIS due to switching of any of the 400 kV transmission lines, due to lightning and also due to disconnector operations. The studies were carried out using the Electro Magnetic Transients Program (EMTP) and EMTDC software.

2.0 SWITCHING OVERVOLTAGE

Switching overvoltage stressing the overhead lines are originated by sudden changes in the system configuration, either operation of a circuit breaker - line energisation or reclosing, or occurrence of a fault. The three-phase reclosing and line energisation operations, which generate the maximum switching overvoltage (SOV), are considered in the study. Also, the use of pre-insertion resistors and surge arresters are the only measures considered here for limiting of SOV.

For SOV studies, distributed line model was used for representing the transmission lines. The GIS bus

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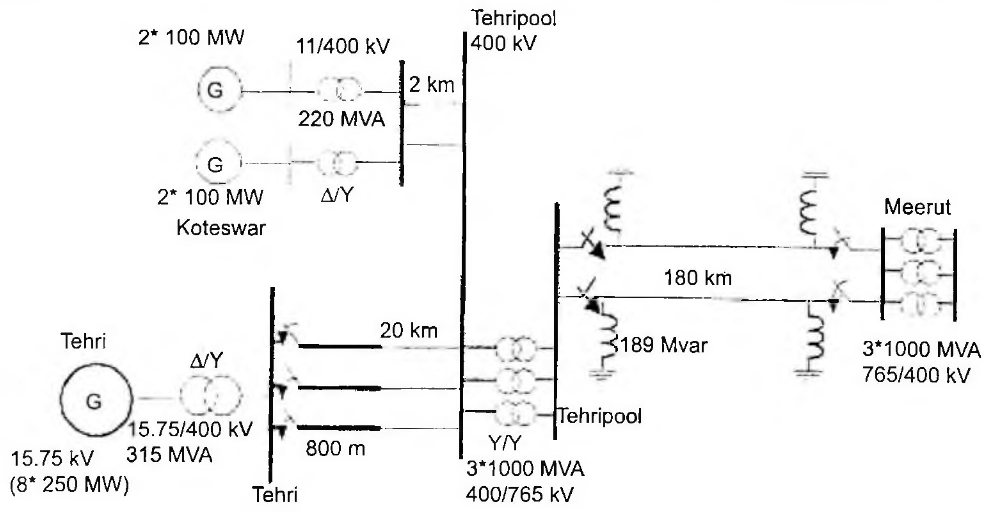

FIG. 1. SINGLE LINE DIAGRAM OF TEHRI TRANSMISSION SYSTEM

ducts were modeled by lumped capacitances - phase to ground and the synchronous generators as constant voltage sources behind transient reactance. The generator and the step-up transformers were represented by three-phase models with correct vector group and saturation characteristics. The zinc oxide arresters were modeled with type 92 arrester model in EMTP. On TNA the transmission lines were modeled by a series of pi sections and the transformers by appropriately connected single-phase transformer models along with their saturation characteristics. The SOV studies covered a number of operating conditions comprising of varying number of generators, bus ducts and transmission lines to evaluate the maximum magnitude of the overvoltage. For each case 200 statistical switching operations were considered. A pole span of 0-2-4 ms and pre-insertion resistors (PIR) of 400, 600 and 800 inserted for 8, 10 and 12 ms were considered. In case of line re-closing studies trapped charges were also simulated. On TNA, selected cases from EMTP - those yielding the maximum overvoltage were studied. The results of the EMTP and TNA studies are presented in Table 1. The overvoltage indicated here are peak values. Figure 2a shows the energisation overvoltages at Tehripool bus for switching from Tehri end, without PIR as obtained using EMTP. Figure 2b shows the same as obtained using TNA. Figure 3a shows the voltage waveforms at Tehripool bus for switching at Tehripool, with PIR of 400 ohms included for 8 ms. Figure 3b shows the same as obtained on TNA.

TABLE 1

MAXIMUM SWITCHING OVERVOLTAGE

Switching operation	PIR & Insertion time	Maximum Overvoltage in p.u.	
		EMTP	TNA
Line Energisation (Tehri 400 kV breaker)*	No	2.29	2.10
	400Ω, 8 ms	1.63	1.57
Line Energisation (Tehri Pool 765 kV Breaker**	No	2.69	2.52
	600Ω, 12 ms	1.74	1.65
3-Phase Line Reclosing (Tehripool 765 kV Breaker)**	No	3.79	3.68
	600Ω, 12 ms	1.83	1.71

*1 p.u. = 326.59 kV peak, **1 p.u. = 624.62 kV peak

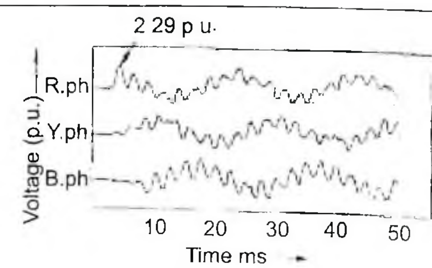

FIG. 2a. VOLTAGES AT TEHRIPOOL-EMTP

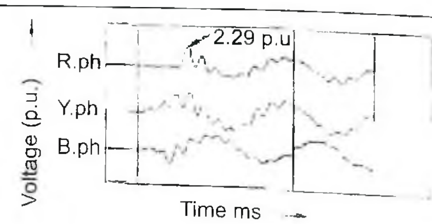

FIG. 2b. VOLTAGES AT TEHRIPOOL-TNA

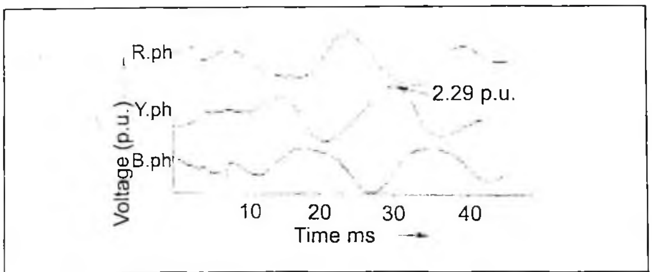

FIG. 3a. VOLTAGES AT TEHRIPOOL-EMTP

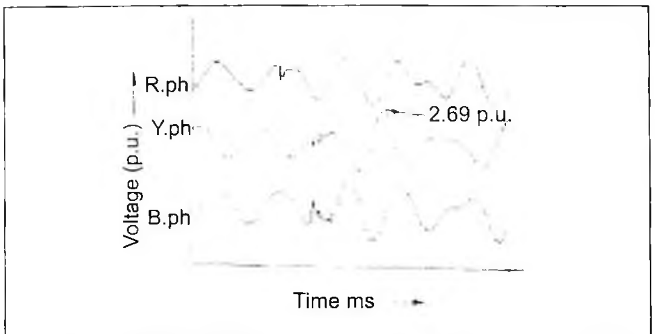

FIG. 3b. VOLTAGES AT TEHRIPOOL-TNA

2.1 Results

The results of the switching overvoltage studies indicate that to limit the overvoltage arising due to energisation and re-energisation in the 400 kV Tehri network to within 2.5 p.u., a PIR of 400 inserted for 8 ms is to be used at Tehri 400 kV breaker. Similarly, a PIR of 600 inserted for 12 ms is to be used in 765 kV breaker at Tehripool to limit the overvoltages within 1.9 p.u. in the 765 kV network. Thus a rated switching impulse withstand level of 1050 kV has been recommended. As seen from the oscillograms and the results of Table 1 the simulation results of EMTP and TNA tally well with each other thereby validating the correctness of the simulation.

3.0 LIGHTNING OVER VOLTAGE STUDIES

Lightning overvoltage studies were carried out using EMTP. The lightning surge was represented by a standard impulse of $1.2/50\,\mu$s and was applied within the 1st span of out going line from switchyard. Number of out going lines from switchyard was seen to have influence on lightning overvoltage (higher the number of outlets, lower was the overvoltage). Hence only one line and one transformer case was considered. Open disconnectors or open bus bar were seen to give highest overvoltage due to doubling effect. Different combination of generator and outgoing transmission line were considered. The overvoltage at any point other than transformer was limited to 1140 kVp and near transformer it was limited to 1083 kVp keeping 20% margin with the BIL level of 1425 kVp for switchyard and 1000 kVp for transformer. In order to adequately protect the transformer and GIS equipment, it was necessary to provide surge arresters at following locations:

(i) A GIS arrester close to every transformer
(ii) A GIS arrester on each of the outgoing GIB feeder just after the disconnected switch
(iii) An open air arrester just after the SF6 to air bushing on each outgoing line

With a rating of 390 kV, maximum energy rating of arresters were within 1.5 kJ/kV. Maximum voltage at 400 kV buses could be arrested to 990 kVp and at transformer terminals to 898 kVp.

4.0 VERY FAST TRANSIENT OVERVOLTAGE

The operation of disconnector switch and circuit breaker in a GIS typically involves numerous restrikes. These restrikes could generate a large number of Very Fast Transient Overvoltage (VFTO) with a rise-time of the order of a few ns followed by high frequency oscillations. The peak value of the VFTO could be as high as 2.5 p.u or more in extreme cases [1,2]. VFTO can lead to Transient Enclosure Voltage (TEV) as well as ElectroMagnetic Compatibility (EMC) related problems to sensitive electronic circuits used in metering and controlling equipment. VFTO can also cause low probability flashover to ground especially for system voltages above 400 kV. Hence it is important that an estimate of the VFTO magnitude is made before commissioning of substations.

In the present work, the VFTO levels were estimated for different switching conditions and at various nodal points of the proposed 400 kV GIS. A one-line diagram of the 400 kV GIS for the Tehri Hydro project is shown in Figure 4. This substation has 4 Stage I generators (G1 to G4) and 4 Stage-II generators (GA1 to GA4) feeding the three buses and three outgoing feeder lines from the substation.

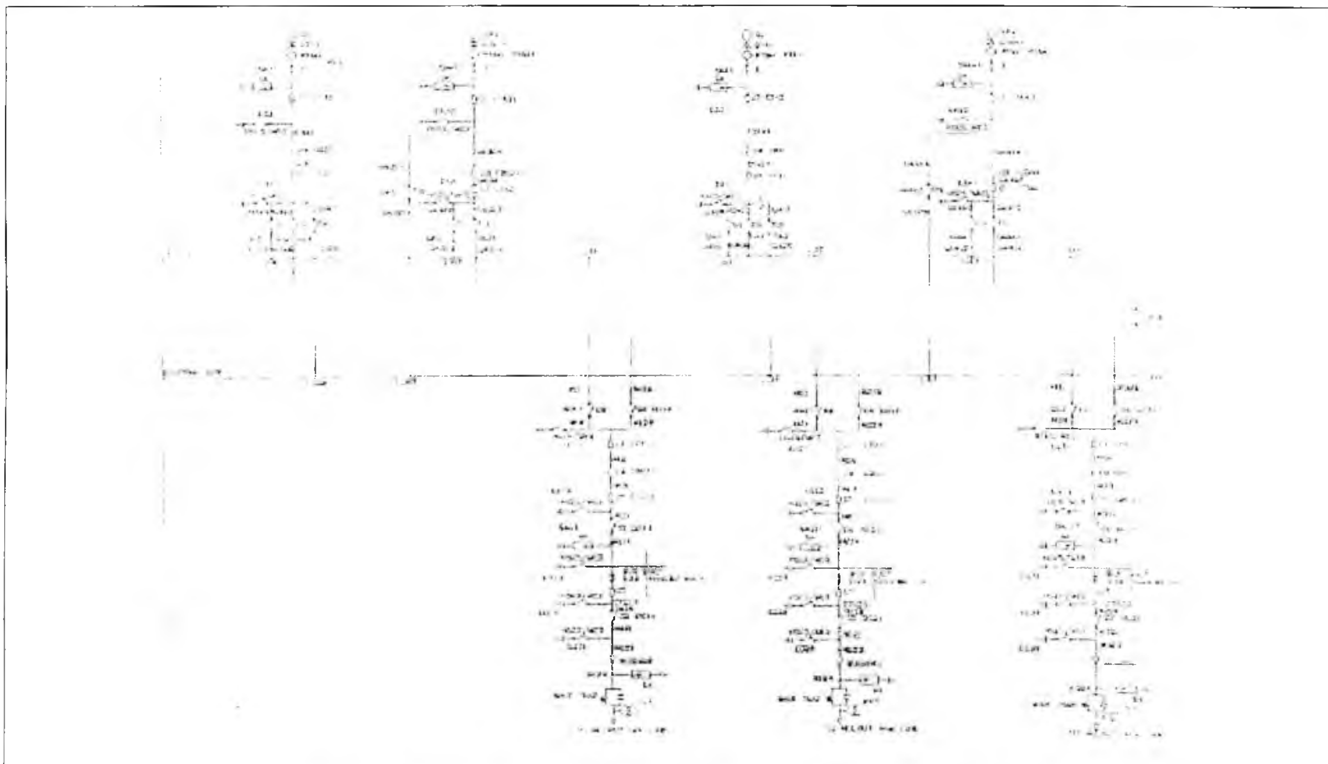

FIG. 4. SINGLE-LINE DIAGRAM OF 400 kV GIS FOR TEHRI HYDRO PROJECT

4.1 Computer Simulation

By concept the GIS behaves like an interconnected transmission line when subjected to fast transients. Therefore EMTP can be used for simulation of VFTO in a GIS. For estimating VFTO level, simulation of all the components of the GIS and other connected equipment are required. The transient caused by a single spark is damped in few μs, i.e., much earlier than a subsequent spark, if any occurs. For this reason VFTO simulation can be conducted by considering each strike separately. VFTO levels of a GIS configuration depend on the observation point as well as the switching location in addition to the impedance of its various components. Since the VFTO contain predominantly high frequency components ranging from hundreds of kHz to tens of MHz, most of the models have their capacitances dominating the other parameters.

The typical lengths of a GIS bus are much smaller than an ordinary substation and also, at high frequencies in the range of few hundreds of kHz to MHz, the GIS bus acts like a transmission line with a finite transit time and propagation velocity. The value of surge impedance of GIS bus bar which is modeled as transmission line can be obtained from the relation $Z = 60\ln(b/a)$, Where 'a' is the diameter of the HV bus and 'b' is the inner diameter of the enclosure and 'Z' is found to be 64.2 for the GIS bus.

Elbows, spacers and spherical shields are modeled by a lumped capacitance of 15 pF. Power transformer with bushing mounted is modeled as lumped capacitance to ground of 1250 pF whereas surge arresters are modeled as lumped capacitance to ground of 50 pF. Disconnector switches are modeled differently under open and closed condition. When opened they are modeled as two transmission lines in series with a capacitance. The surge impedance of each of the transmission line is taken as 69 whereas the series capacitance is chosen as 20 pF. A capacitance to ground of 52 pF is included at both ends of the switch. When closed, the capacitance in between the two transmission lines of the open disconnector switch model is replaced by a transmission line with the same parameters as before but the capacitance to ground is taken as 88 pF.

The spark is modeled as an exponentially decaying resistance. Bushings are modeled with a lumped capacitance to ground of 500 pF whereas earth switches are modeled by lumped capacitance of 45 pF. Circuit breakers are also modeled differently under open and closed condition. The open circuit

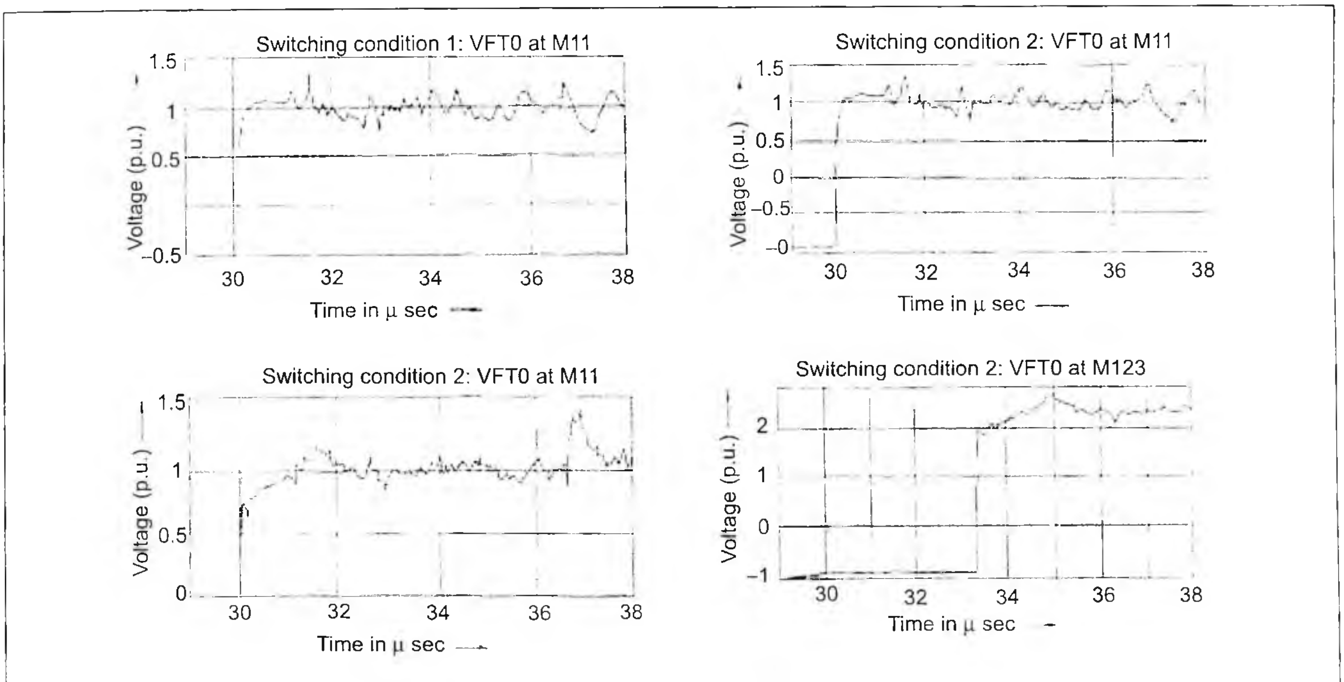

FIG. 5. VTFO WAVEFORMS

breaker is modeled as two transmission lines in series with a capacitance of 2800 pF and a 17 resistance in series between them. The capacitance to ground is 200 pF. The closed circuit breaker is modeled similar to the open circuit breaker with the capacitance replaced by a transmission line of surge impedance of 30 Ohm. The capacitance to ground is replaced by 20 pF. The overhead line, which is connected to the GIS, is considered to be of infinite length. Hence it is modeled as a transmission line terminated with a resistance to ground of value equal to the surge impedance of the overhead line (350 ohms), so that there is no reflection from this end.

A total of 61 different switching conditions have been simulated for a trapped charge magnitude of 1.0 p.u. Computer simulations have been done with EMTP and using appropriate transient models for the GIS components.

4.2 Results and Discussion

Only two specific cases have been presented and discussed here. The conditions considered are

(1) All generators connected and the disconnector switch between M11 and M14 operated with circuit breaker between M16 and M19 kept open.

(2) All generators connected to the bus and the circuit breaker between M16 and M19 operated

4.3 VFTO Waveforms

The computed VFTO waveforms for disconnector and circuit breaker switching co nditions are shown in Figure 5. In general it is seen that when the observation node is close to the switching point, the VFTO waveform has higher frequency content as compared to a farther away node from the switching point. Also, it is found that the VFTO peak magnitudes are higher in the case of circuit breaker operation as compared to that of disconnector switching operation. Out of all the 61 switching operations simulated, amongst disconnector switching operations, VFTO peak is found to be highest when the disconnector switch between M226 and M229 is operated with the circuit breaker between M26 and M29 kept open. Its value is 1.67 p.u. (node M26). In the case of circuit breaker operation, the VFTO peak magnitude is found to be maximum when circuit breaker between M16 and M19 is operated. Its value is 2.7 p.u. at the node M123 on the outgoing feeder $X = 1$.

4.4 Variation of VFTO Peak along the Nodes

The variation of the VFTO peak along the nodes of the outgoing feeder lines for each of the above mentioned switching conditions are shown in Figures 6 and 7. There is a distinct pattern of variation of VFTO peak along the nodes of the GIS in the case of disconnector switch operation as compared to that of circuit breaker operation (compare Fig. 6 and Fig. 7). From Figure 6 it is seen that the outgoing feeder line MI shows a peak value close to 1.47 p.u. The VFTO magnitudes reduce near the open circuit breaker and once again increase near the junction of the GIS with the overhead transmission line. From Figure 7, it is seen that the outgoing feeder line M1 ($X = 1$) has a maximum VFTO value of 2.70 p.u. There is a steady increase in the VFTO levels beyond the switching point till the junction of GIS with overhead line in the case of circuit breaker switching operation.

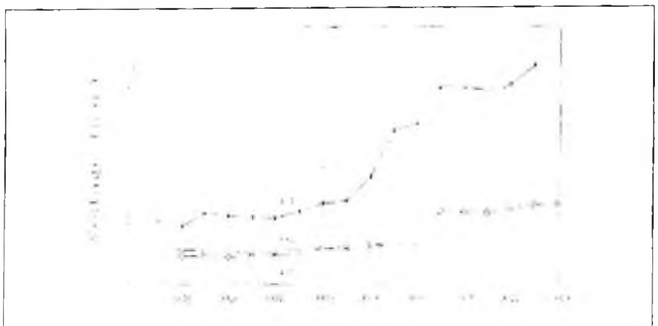

FIG. 6. VARIATION OF PEAK VFTO LEVELS FOR OUTGOING FEEDERS ALONG NODES (DISCONNECTOR OPERATION)

FIG. 7. VARIATION OF PEAK VFTO LEVELS FOR OUTGOING FEEDERS ALONG NODES (CIRCUIT BREAKER OPERATION)

5.0 CONCLUSIONS

Switching overvoltage studies decided the magnitude of preinsertion resistor and the duration of its insertion to keep the switching surge overvoltage under control. Lightning overvoltage studies revealed that additional arresters have to be installed for proper insulation coordination in the GIS station.

The VFTO peak magnitudes are higher close to the switching point in the case of disconnector operations where as they are higher at the junction of the GIS with overhead line in the case of circuit breaker operation. Also, close to the switching point, VFTO waveform has higher frequency of oscillations as compared to an observation point farther away. There is also a distinct pattern of variation of VFTO peak along the nodes of the GIS in the case of disconnector switch operation as compared to that of circuit breaker operation. The circuit breaker operation results in the highest VFTO level amongst all the switching operations done. Based on these studies, the rating, location and energy levels of the arresters was finalized to evolve a good protection philosophy for insulation coordination of a 400 kV GIS station.

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