Surge Arrester Requirements Study for Transformer Protection in 132 kV GIS Substation

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***Abstract*--Insulation coordination study for a substation requires accurate prediction of possible overvoltages generated within or external to the substation. Protective devices in the form of surge arresters are usually installed to protect substation equipment from overvoltages caused by both switching and lightning surges. In this work, the decision whether to install or not to install ZnO surge arresters for power transformer protection in a 132 kV GIS substation was made with the aid of ATP-EMTP software. Various models such as those for underground cables and ZnO surge arresters were carefully studied since the results of the simulation study were very much dependent on the models chosen. The resulting overvoltages at the power transformer due to possible lightning impulses at various injections points were studied. A decision was finally made based on the simulation results.**

***Index Terms*-- Lightning overvoltages, ATP-EMTP, Surge arrester, GIS substation, Insulation coordination, Transmission line model.**

I. INTRODUCTION

SUBSTATION equipment overvoltage protection design involves a proper determination and selection of protective devices. A reliable protection system is an important decision due to the significant monetary investment and required reliable continuous operation of the facility. Various overvoltage stresses include those due to the switching surges, lightning surges on connected transmission lines, or even direct strikes to the substation facility. Since ZnO gapless surge arresters are now commonly used as a means of protection against those stresses, its application in a given substation set-up requires some performance study. This includes the determination of the arrester rating and the locations of the surge arrester within a substation. Simulation studies using transient programs can be carried out as an aid to important substation design decision [1-7]. This work aims to study the behaviour and response of a substation system when subjected to overvoltages. The results of the study can be used to determine the need, or otherwise, of surge arresters at the power transformer terminals for the substation under study.

II. COMPONENT MODELS

In carrying out the modelling work, there is a need to accurately identify the models of power system components [1]. Among the key power system equipment are the ZnO surge arrester, underground cable, circuit breaker, busbar, and power transformer. The lightning impulse source also needs to be accurately modelled.

A. Underground Cables

For this work, the substation incoming transmission line was a single core XLPE underground cable. The cross section of this cable is shown in Fig. 1. Four models are available in ATP-EMTP software to represent the transmission line, namely the Bergeron, PI, JMarti and Semlyen models [8].

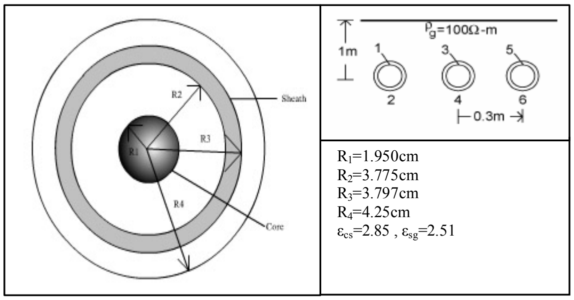

Fig. 1. The underground cable configuration

The Bergeron model is basically a constant parameter model and therefore no frequency effect is modelled [9]. The PI model is based on the PI equivalent circuit of short transmission lines [8, 10]. The JMarti model is a frequency dependent model with a constant transformation matrix [8, 11-13]. The Semlyen model is also a frequency dependent utilising a simple fitted model.

B. Surge Arrester

There are various ZnO surge arrester models [14-19]. In this work, the model proposed by Pinceti [18] as shown in Fig. 2 was used. For the 120 kV-rated arrester used the corresponding residual voltage ($V_{r8/20}$) for a 10 kA current is 270 kV. For fast front waves, the residual voltage ($V_{r1/T2}$) at 10 kA current is 286 kV. The V-I characteristics used are as in Table 1. Note that the 1 MΩ resistor was inserted in the equivalent circuit to avoid numerical troubles. The values of

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L_0 and L_1 were calculated as 0.59 µH and 1.8 µH respectively. Fig. 3 shows the simulated residual voltage and discharge current oscillograms of the arrester.

C. Other Equipment

For lightning transient analysis, the power transformer is usually represented as a lumped port capacitance [14]. For the 132 kV system under study, the power transformer is represented by a capacitance of 2 nF. The voltage transformer, on the other hand, is represented by a capacitance of 0.4 nF [20].

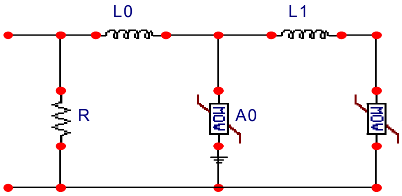

Fig. 2. ZnO surge arrester model (proposed by Pinceti)

TABLE 1
V-I CHARACTERISTICS USED FOR A_0 AND A_1 IN THE ARRESTER MODEL

I (A)	A_0 (p.u)	A_0 (V)	A_1 (p.u)	A_1 (V)
0.002	0.810	218700	0.623	168210
10	0.932	251640	0.749	202230
100	0.974	262980	0.788	212760
1000	1.052	284040	0.866	233820
3000	1.108	299160	0.922	248940
10000	1.195	322650	1.009	272430
20000	1.277	344790	1.091	294570

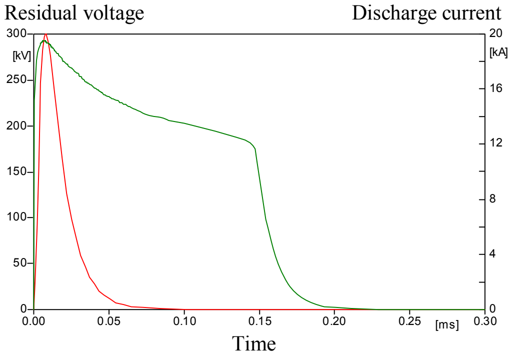

Fig. 3. 120kV-rated ZnO surge arrester residual voltage and discharge current

The circuit breakers and isolators are simply represented by time controlled switches. The substation busbars were represented by the three phase distributed parameter of transposed line represented by the Clarke model. Other power system equipment such as current transformer, earthing switch and high speed earthing switch can be considered negligible [1] and hence not modelled in this simulation work.

D. Lightning Source

The lightning impulse was represented as an impulse current source of the Heidler type [8]. For this model, the user can set the amplitude, the front time, as well as the tail time.

III. VERIFICATION OF TRANSMISSION LINE MODEL

In order to determine the most accurate model for the underground cable, each of the available models in the ATP-EMTP software was analysed using a step input as well as variable frequency AC input.

A. Simulation with Step Input

A certain length of a 3-phase cable with an intercable distance fixed at 30 cm was simulated. A step input with a peak magnitude of 100-kV was injected at the sending end of phase B. The induced voltages at the other two phases due to coupling effects were analysed. Fig. 4 shows the peak voltages at the sending ends for all phases. Fig. 5 shows the peak voltages at sending ends for all phases due to for an intercable distance of 300 cm.

B. Simulation with Variable Frequency AC Input

The 3 phase transmission line was injected with AC input with frequency of 5 Hz, 50 Hz, 500 Hz, 5 kHz and 50 kHz at phase B with the magnitude of 100 kV. The cable distance fixed at 30 cm from other phases of cables. The induce voltage at other phases was analysed due to coupling effect for all the models. The peak voltage at sending end of phase A was recorded since phase A and phase C have the same peak voltage. Fig. 6 shows the peak voltage at sending end of phases A due to coupling effect with cable distance of 30 cm.

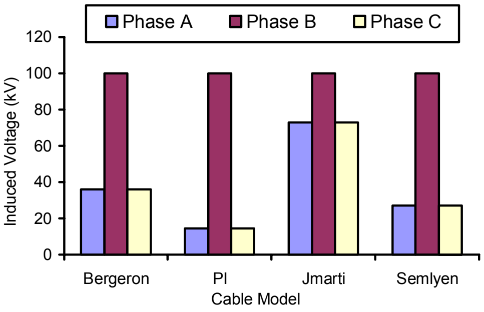

Fig. 4. Coupling effect for intercable distance of 30 cm for various transmission line models with 100kV step injected at phase B

From the simulation of the transmission line response to a step input, it can be summarized that the Bergeron, PI and Semlyen models induce only a small voltage at nearby phases compared to the larger value for the case of JMarti model.

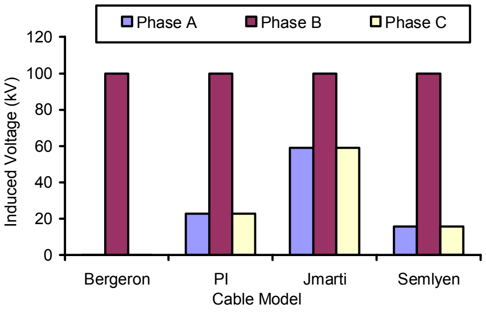

Fig. 5. Coupling effect for intercable distance of 300 cm for various transmission line models with 100kV step injected at phase B

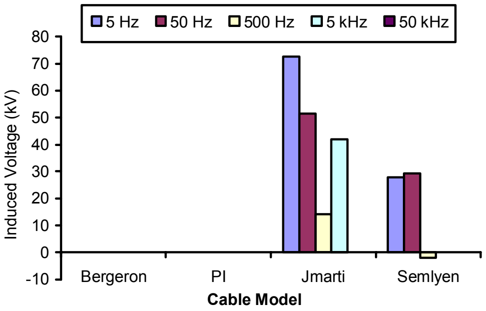

Fig. 6. Coupling effect on phase A as a function of frequency for various transmission line models with 100kV rms injected at phase B

C. Summary of Transmission Line Model Analysis

In the case of frequency effects, energisation on one phase results in very low induced voltages at two other phases for Bergeron and PI models compared to higher induced voltages for JMarti and Semlyen models. For the JMarti model, the magnitude of induced voltage decreases when the frequency increases up to 5 kHz, then the voltage increases again until the frequency reaches 50 kHz. For the Semlyen model, the simulation can only be done for frequency up to 5 kHz because of some limitation in the model.

From the analysis of various transmission line models with the step input and the variable frequency AC input, it can be concluded that the Bergeron model is the most suitable model to represent the underground cable.

IV. ANALYSIS OF THE SUBSTATION

The above preliminary simulation work gives valuable information and confidence on the types of models used to represent various power system components. Fig. 7 shows the simulated circuit of the substation as drawn in the ATPDraw program using the chosen models. This circuit was based on the single line diagram of the actual substation to be constructed.

A. Effect of Lightning Current Amplitude

The effect of lightning current amplitude on the generated overvoltage is investigated. The shape of the lightning current was fixed at 1.2/50 µs. The four underground cables (2 from Ampang and 2 from Kg Lanjut) are energised and the arresters are installed at the power transformers (Transformer 1 at Line 3 and Transformer 2 at Line 4) (see Fig. 7). Different lightning current amplitudes, namely, 17 kA, 8.5 kA, 4.25 kA, 2.1 kA, 1 kA and 0.5 kA were applied to the substation from the sending end of Line 1. Fig. 8 shows the voltages at the power

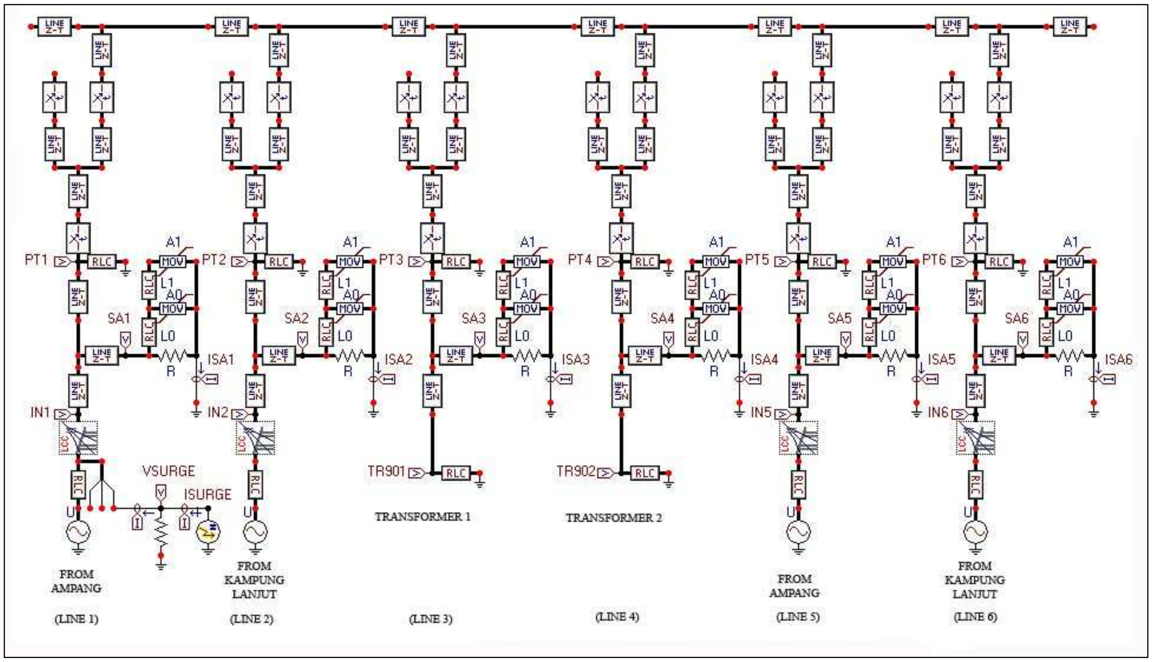

Fig 7. Simulated circuit of the substation

transformers for the case of with and without ZnO surge arresters installed across the transformers.

Fig. 9 shows an example of the oscillograms obtained (current amplitude of 17 kA) at Transformer 1 without a ZnO surge arrester installed. The voltage at Transformer 1 increases to a peak value of 1.3 MV. Figure 10 shows the corresponding oscillograms obtained when ZnO surge arresters are installed. It is noted that the voltage at the transformer is now clamped at 333 kV with an accompanying discharge current of 10.3 kA.

B. Effect of Lightning Current Waveshape

The effect of the lightning current waveshape was also investigated. This was done by changing the front time and the tail time of the injected lightning current. A fixed lightning current of 17 kA was injected at the end of Line 1.

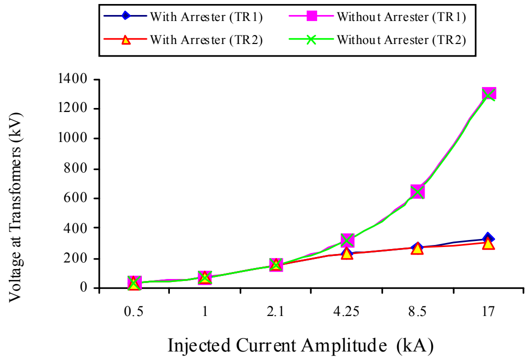

Fig. 8. Voltage at the power transformer terminals with and without arrester installed as a function of the injected current at the end of Line 1

Fig. 11 shows the effect of lightning current front time on the overvoltages. It is observed that the increase in front time slightly reduces the peak voltage at Transformer 1.

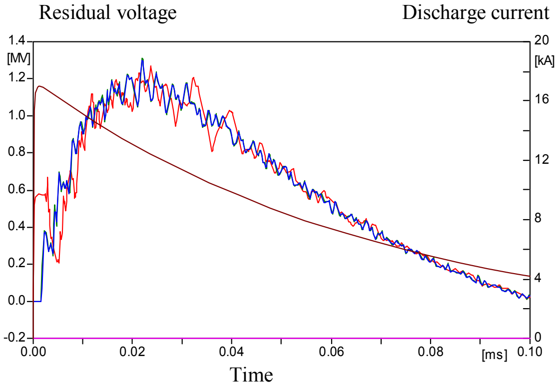

Fig. 9. Voltage at Transformer 1 due to lightning current amplitude of 17 kA injected at Line 1 (without surge arrester protection)

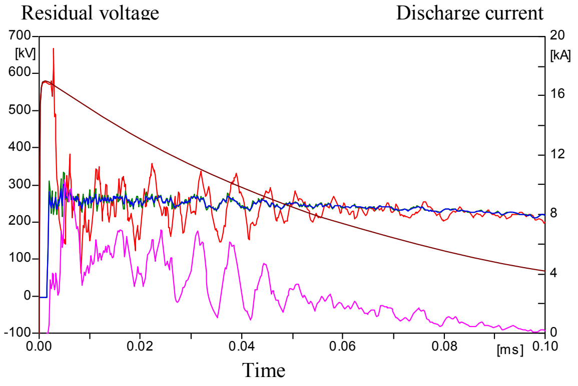

Fig. 10. Voltage at Transformer 1 due to lightning current amplitude of 17 kA injected at Line 1 (with surge arrester protection)

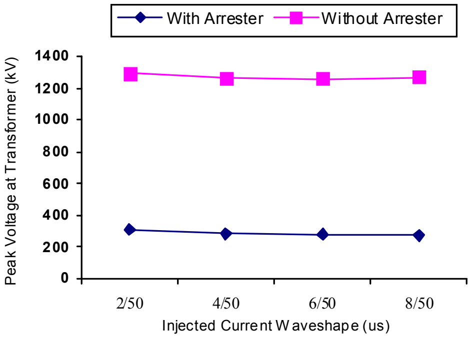

Fig. 11. Voltage at the power transformer terminals with and without arrester installed as a function of the injected current front time

Figure 12 shows the effect of variation in the injected lightning current tail time on the overvoltage generated at Line 3. The front time and the amplitude are fixed at 1.2 µs and 17 kA respectively, and the tail time was varied from 5 µs to 50 µs. There is a marked influence of the tail time on the overvoltages generated for the case of no surge arresters protection.

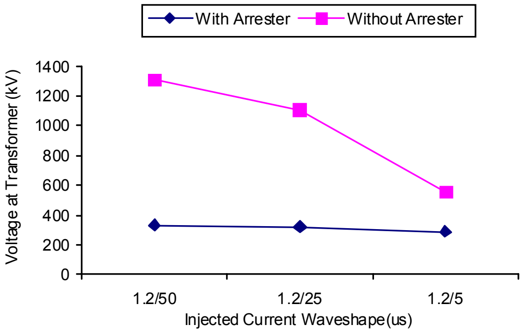

Fig. 12. Voltage at the power transformer terminals with and without arrester installed as a function of the injected current tail time

C. *Effect of Overvoltage Source Injection Point*

Simulation was done with two lightning current source locations, namely at the sending end of the underground cable (Line 1) and at a point near the transformer. Figure 13 shows the effect of lightning strike location with and without surge arrester installed.

For the case of a direct 17kA lightning strike near the transformer, the voltages at the transformer were 1434 kV (without arrester) and 522 kV (with arrester). It is noted that even for the worst case of a direct strike near the transformer terminal, the 120kV-rated ZnO surge arrester used can still protect the transformer to well below its BIL.

D. *Arrester Location*

Selection of suitable location in the substation for the installation of surge arrester is an important aspect of controlling the overvoltages at different points in the substation. Identifying the best location for surge arrester will have a large effect on the cost of the substation. Equal lightning currents (17 kA peak) were injected at the ends of all four lines.

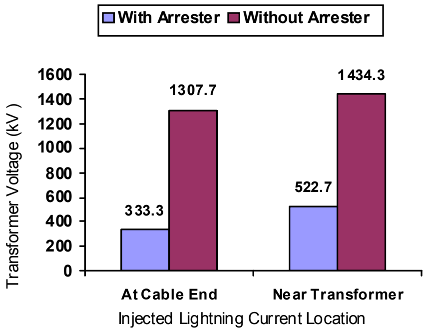

Fig. 13. Voltage at the power transformer terminals with and without arrester installed as a function of the injected current location

Investigation was done on five different cases of surge arrester configurations. Case 1 is with surge arresters installed at the transformers as well as at all the termination points of the lines in the substation. Case 2 is with surge arresters installed at the transformers and at Lines 2 and 6 only. Case 3 is with surge arresters installed at the transformers only. Case 4 is with no single surge arrester installed. Case 5 is with surge arresters installed at all the termination points of the lines in the substation only. Table 2 shows the resultant peak voltage at Transformers 1 and 2 for all five cases.

TABLE 2
EFFECT OF SURGE ARRESTER LOCATION ON THE OVERVOLTAGES

Arrester Location (Alternative)	Arrester at Line 1 and 5		Arrester at Line 2 and 6		Arrester at Line 3 and 4		Transformer at Line 3 and 4	
	Peak Residual Voltage at Arrester (kV)	Peak Discharge Current at Arrester (A)	Peak Residual Voltage at Arrester (kV)	Peak Discharge Current at Arrester (A)	Peak Residual Voltage at Arrester (kV)	Peak Discharge Current at Arrester (A)	Peak Voltage at Transformer 1 (kV)	Peak Voltage at Transformer 2 (kV)
Case 1	358.9	9031.3	333.8	12772	332.8	9031.3	404.1	404.1
Case 2			345.2	24036	350.6	12326	427	470.1
Case 3					375.6	34230	493.3	493.3
Case 4							1705.1	1705.1
Case 5	358.9	18297	333.7	20193			653.1	653.1

V. CONCLUSIONS

Based on the results of the above study, the following conclusions are made:

i) Analysis of surge arrester location effect shows that surge arrester installation across the transformers is on its own sufficient to protect both transformers from overvoltages. Alternatively, surge arresters can be installed at all cable terminations only, and this configuration on its own is also sufficient to protect the transformers.
ii) Since this substation does not have any incoming or outgoing of the overhead line type, the only possible way for a lightning surge to enter the substation is by voltage induction due to lightning strikes on the ground near to the underground cables. From this work, it is noted that protection by means of surge arresters is not required if an equivalent induced current of 4.3 kA and below exist anywhere within the underground cable.

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