

Simulation of Capacitively Graded Bushing for Very Fast Transients Generated in a GIS during Switching Operations

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Abstract – In a gas insulated substation (GIS), Very Fast Transient Over-voltages (VFTOs) are generated due to switching operations and ground faults. These fast transients are associated with high frequency components of the order of a few hundreds of MHz. These transients may cause internal faults i.e., layer-to-layer faults or minor faults in a capacitively graded bushing, which is one of the important pieces of terminal equipment for GIS. In the present study, the PSPICE model has been developed to calculate the voltage distribution across the layers of 420 kV graded bushing for high frequency pulses of rise time 1 to 50 ns, which simulate the VFTO. For this simulation, an equivalent electrical network of bushing with different equivalent layers has been considered. The effect of different equivalent layers modeling circuits on the non-uniform voltage factor has been analysed. The influence of copper strip inductance on voltage distribution across layers has also been analysed for various rise times of high frequency transients. Finally, the leakage current of the bushing is calculated for evaluating the bushing condition under these transients.

Keywords: Capacitively graded bushing, Gas Insulated Substations (GIS), PSPICE and VFTOs

1. Introduction

Very Fast Transient Over-voltages (VFTOs) are generated during switching operations of the disconnecter switch (DS) or of the circuit breaker (CB) in gas insulated substations [1, 2]. SF₆ gas-to-air capacitively graded bushing is one of the most important components as it connects the gas insulated substation (GIS) to an overhead transmission line. In GIS, two types of bushings are commonly used depending on the system voltage. The first is non-condenser bushing. The second is capacitively graded bushing. In non-condenser bushings, the electrical stress distribution is not uniform through insulation or along its surface. Concentration of stress in the insulation may give rise to partial discharge (PD) and reduce service life. Further, high axial stress may result in tracking and surface flashover. To overcome the above problems, electrical stresses are generally controlled by means of a capacitively graded mechanism. In this design, the insulation thickness is divided into a number of capacitors by using concentric

conducting layers. The parameters which control the stresses to safe level are radius of high voltage conductor, radius of outer layer, length of first layer, length of last layer, and system voltage.

The VFTOs generated within the GIS are associated with high frequency components in the range of a few tens of MHz to a few hundreds of MHz [3]. The VFTOs combined with the associated transient currents generated within the GIS propagate partly to the overhead transmission line and partly to the enclosure of the gas insulated bus section.

The transient voltages propagating along the overhead transmission line may result in turn-to-turn or winding-to-winding breakdown in transformers or layer-to-layer to breakdown in capacitively grading bushings connected to the GIS [1-3]. This may be due to the fact that the electrical transit time between turns or windings is comparable to the rise time of the transient voltages. It was practically noticed that the disconnecter-induced transients could clearly cause failure of the equipment connected to the GIS if it is not designed for high frequency transient voltages. When the transient voltage encounters the grading structure (comprising of a large number of metallic layers insulated with PET film), the incident travelling wave divides among the concentric coaxial transmission lines formed by the foils [4]. The resulting transmission characteristics for an incident wave signify a slight reduction in magnitude and increase in rise time. For the high frequencies of VFTOs, the

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voltage distribution across the layers of graded bushing may not be uniform. Moreover, the non-uniformity of distribution depends on terminal equipment of the bushing. Further, continuous application of these oscillating, aperiodic voltage transients to the capacitively graded bushing may cause discharges within the bushing. This phenomenon can progressively degrade the insulation strength of the bushing [4-6].

In the present study, an equivalent electrical network is developed for a 420kV SF₆ gas-to-air capacitively graded bushing to simulate transient voltage distribution across its layers. For this purpose, an impulse waveform with rise time of 1 to 50 ns has been considered to simulate VFTOs. The effect of different equivalent layer's modeling circuits on non-uniform voltage factor has also been analysed as part of this study. Further, the influence of copper strip inductance (L_c) on the voltage distribution across the layers is studied for different rise times of high frequency transients. Finally, the effect of abnormality on the leakage current waveform has been studied.

2. Description of the Bushing Model

420 kV SF₆ gas-to-air capacitively graded bushing consists of 120 aluminium grading layers separated by Poly Ethylene Terephthalate (PET) film with a dielectric constant of 2.8 ($\epsilon_r = 2.8$). The basic structure of the capacitively graded bushing is shown in Fig. 1. The layers form a system of coaxial cylinders whose length increases from the outermost to the innermost one. The capacitance between consecutive graded layers is constant and is about 60nF. The outermost layer is connected to the external coaxial flange by means of a copper strip, which has an inductance of about 0.05 to 0.4 μ H. The effect of this inductance on the voltage distribution across the equivalent layers is analysed for different rise times of the high frequency transients.

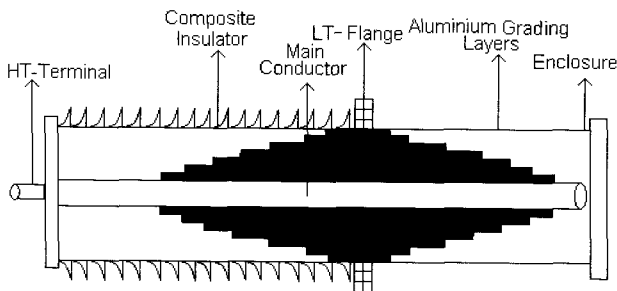


Fig. 1. Structure of 420 kV SF₆ gas-to-air capacitively graded bushing.

3. Modeling of the Capacitively Graded Bushing

The general simplified model of capacitively graded bushing is given in Fig. 2. By using this as the basic model, different equivalent layer's modeling circuits are developed. To get a satisfactory compromise between modeling simplicity and accuracy, it is necessary to optimise the number of equivalent layers represented for the model. In view of the above, up to sixty equivalent co-axial layers have been considered to simulate capacitively graded bushings. The diameter of each equivalent layer is calculated in such a way that the capacitance between consecutive graded layers is constant. Each equivalent layer is divided into number of sections depending on its length. Further, each section is represented by means of a Π -model (L-C network). Finally, the bushing model is formed like a cascade of Π sections. The total capacitance of the actual bushing, C_{tot} , must be shared among the N_{eq} equivalent layers. In the present study, the partial capacitance C_{lay} between two adjacent layers is constant and is simply calculated as:

$$C_{lay} = C_{tot} * N_{eq} \tag{1}$$

By using the equivalent capacitance between two concentric cylindrical layers (C_i), the diameter of equivalent layer is calculated. For this purpose, the following equation has been employed:

$$C_i = \epsilon_0 \epsilon_r A_i / t_i \tag{2}$$

- Where, A_i is area of i^{th} equivalent layer.
- t_i is thickness of i^{th} equivalent layer.
- ϵ_r is relative permittivity.

For $i=1$, D_1 is the diameter of the central conductor. By knowing D_1 , l_1 , t_1 , A_1 , C_1 and using the above formula, D_2 i.e., diameter of the first equivalent layer can be calculated. The inductance of i^{th} equivalent layer (L_i) is

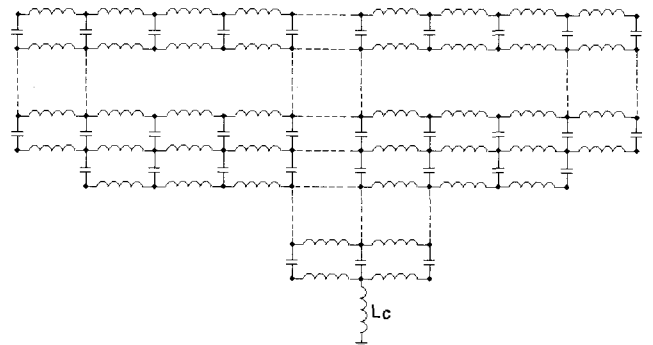


Fig. 2. General Modeling circuit of a capacitively graded bushing.

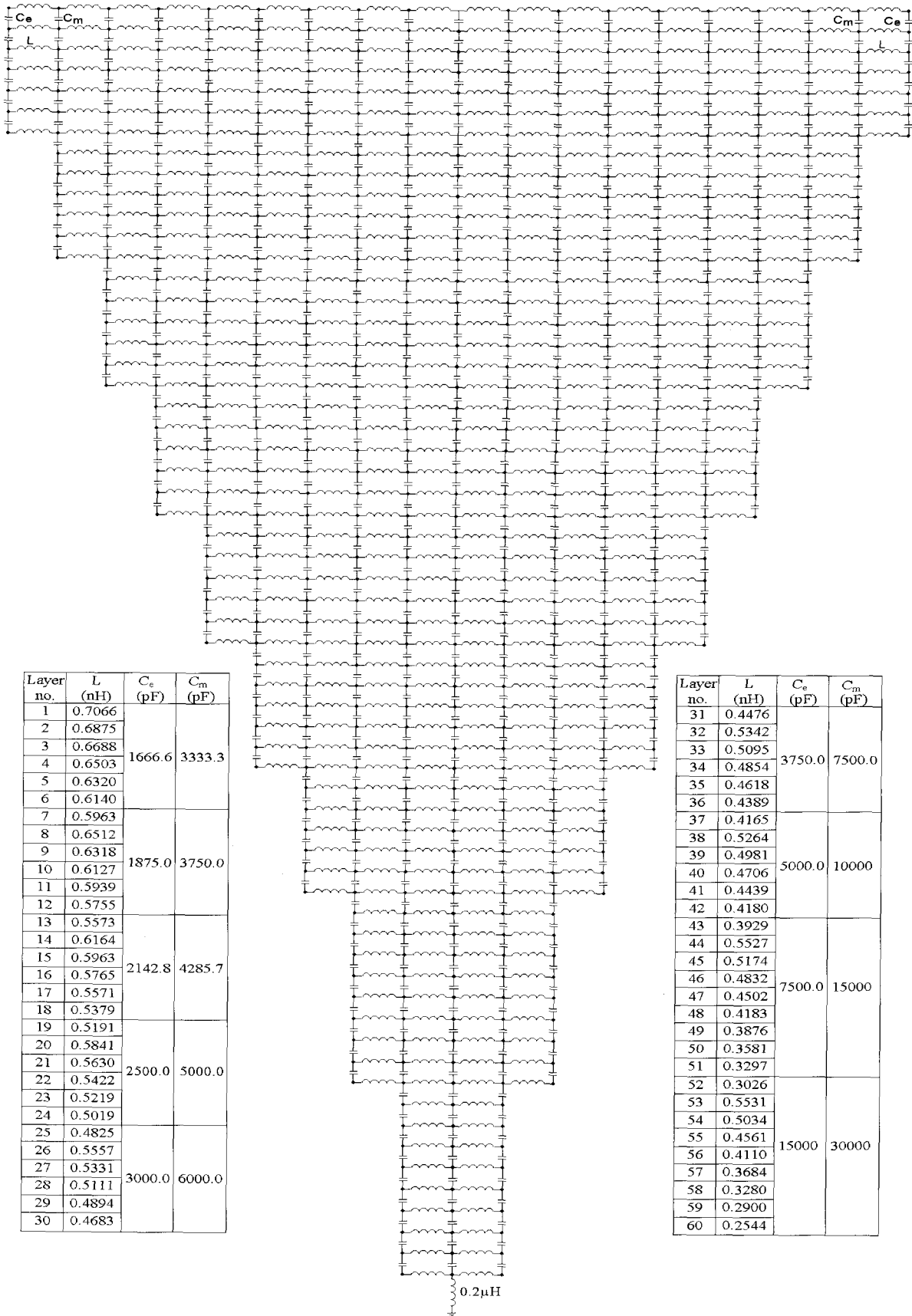


Fig. 3. Sixty Equivalent Layer's Modeling Circuit of 420kV

calculated by using the following formula:

$$L_i = (\mu_0 / 2\pi) \ln (D_{i+1} / D_i) * l_i \quad H \quad (3)$$

Where, l_i is length of i^{th} equivalent layer. Inductance of each section is calculated by dividing the inductance of that equivalent layer with the number of sections. Fig. 3 indicates the sixty equivalent layer's modeling circuit for capacitively graded bushing. Here, the first layer is divided into eighteen sections to understand the propagation of high frequency signal along the HT conductor of the bushing. From the figure, it is clear that section inductance is highest for an innermost layer and section capacitance is highest for an outermost layer. The VFTOs are simulated by means of an impulse waveform with a rise time 1 to 50 ns and a tail time of 1 μ s. In general, the gas insulated substation is connected to an overhead transmission line by means of SF₆ gas-to-air bushing. Thus, the modeling circuit of the capacitively graded bushing is terminated with an overhead transmission line of surge impedance 350 Ω .

4. Results and Discussions

Fig. 4 shows the output waveform of bushing for an impulse excitation of 1 ns rise time with 1 p.u. amplitude. From the figure, it is clear that there is a moderate increase in voltage at the bushing terminal. The over-voltage factor

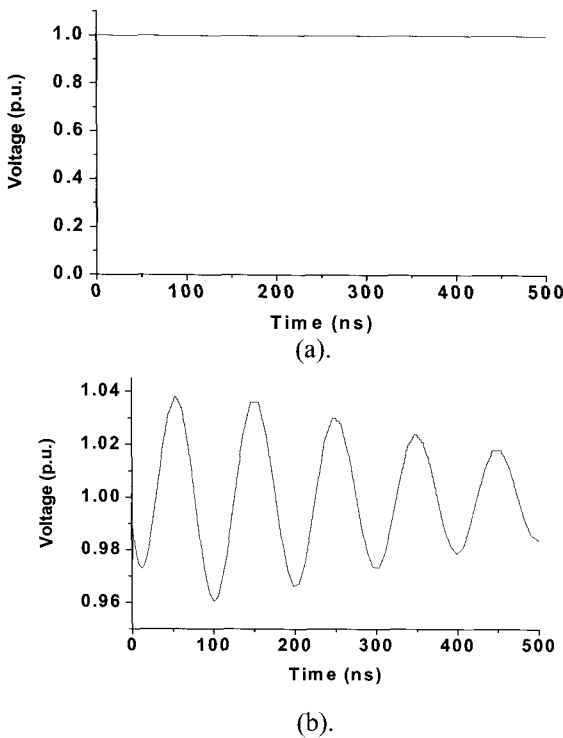


Fig. 4. Input and output voltage waveforms of sixty equivalent layer's modeling circuit for impulse excitation of 1 ns rise time.

is of the order of 1.0373 (3.7% increase in voltage). The frequency of oscillations depends on the electrical length of the bushing. The output voltage waveform has been calculated using the PSPICE software.

4.1 Effect of equivalent layer's modeling circuit

To understand the effect of VFTOs on the simulation model, different equivalent layer's modeling circuits have been considered. Fig. 5 shows the voltage distribution across layers of these circuits for 5 ns rise time of impulse waveform. The PSPICE model has been used to calculate the voltage distribution across the equivalent layers of the proposed modeling circuits. From the results, it is clear that the voltage distribution across equivalent layers is highly non-uniform. Further, highest voltage drop occurs across the first equivalent layer. Interestingly, the voltage drop is almost flat for more than 85% of the outermost layers. In order to understand the simulation model on the SF₆ gas-to-air capacitively graded bushing, transient voltage distribution, modeling circuits of capacitively graded bushing are developed with ten, twenty, forty, and sixty equivalent layers (eighteen sections of the first equivalent layer). In order to calculate optimal layers required for the calculation of transient voltage distribution, non-uniformity factor is calculated for different modeling circuits and shown in Fig. 6. Here, an impulse waveform of 5 ns rise time is applied to the bushing as the source. From this figure, it is clear that the non-uniform voltage factor is about 330% for ten equivalent layers model. However, this factor is in the same range for twenty, forty, and sixty equivalent layers modeling circuits. The non-uniformity factor for these modeling circuits varies from 209 % to 192%. Even though the twenty equivalent layer's modeling circuit provides accurate voltage distribution, the sixty layer's circuit has been considered to simulate inter-layer faults.

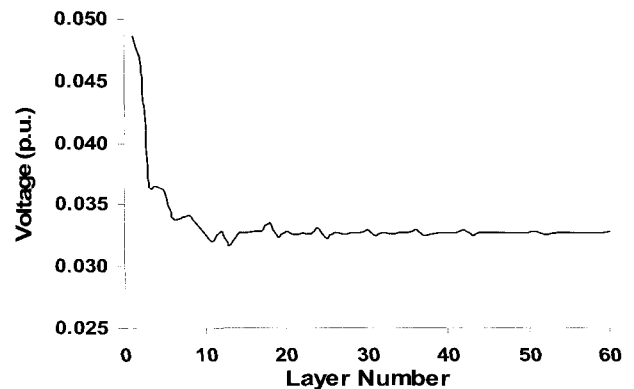


Fig. 5. Voltage distribution across the layers of sixty equivalent layers modeling circuit.

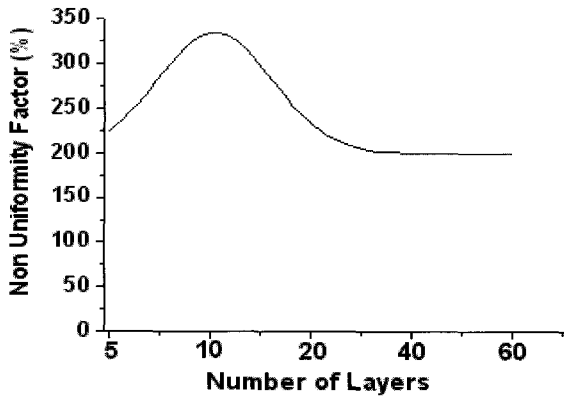


Fig. 6. Non-uniform voltage factor for various modeling circuits of the capacitively graded bushing

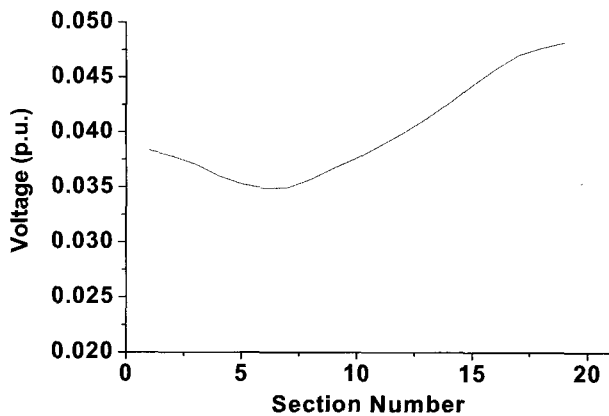


Fig. 7. Voltage drop along the first equivalent layer of sixty equivalent layers modeling circuit.

The highest voltage drop is 0.04863 p.u. when 1p.u impulse voltage with 5 ns rise time is applied to the H.T conductor. This voltage is more than the value obtained under normal a.c. voltage conditions. Further, the voltage drop across equivalent layers, which are near the ground terminal, is of the order of 0.03284 p.u. (refer Fig. 5). It is further confirmed that the voltage drop is highest on the equivalent layers near the HT conductor. It may also be noted that the voltage drop along a particular equivalent layer increases as we move towards the overhead transmission line (refer Fig. 7). From the figure, it is very clear that there is a significant variation in voltage distribution along the equivalent layer. In order to understand the effect of rise time on voltage drop across layers, transient voltage distribution is calculated at different rise times and shown in Fig. 8. From the figure, it is evident that the highest voltage drop across the layers decreases with increase of rise time. The reduction is of the order of 33% as rise time of the impulse waveform increases from 1 to 50 ns and is found to be almost linear.

4.2 Effect of copper strip inductance

The effect of copper strip inductance on the voltage distribution across the equivalent layers is analysed by considering inductances from $0.05\mu\text{H}$ to $0.4\mu\text{H}$. Fig. 9 shows the voltage distribution across the layers with different copper strip inductances. From the results, it is seen that the highest voltage drop across equivalent layers decreases with increase of inductance. Further, the variation in voltage drop across the layers is highest at lower inductance values and becomes moderate at higher values of inductance. More clearly, the voltage distribution is highly non-uniform at lower values of copper strip inductance. Interestingly, the highest voltage drop occurs mostly across the first few equivalent layers of the modeling circuits. Similarly, the effect of rise time on the voltage distribution is found to be significant for lower values of copper strip inductance (Fig. 10). Moreover, this variation is found to be linear with rise time. At higher values of inductance, the variation in highest voltage drop with increase of rise time of high frequency transients is moderate. In other words, voltage drop across outermost layers is also significant and hence design is not reliable from a high voltage point of view. Thus, it is important to limit the copper strip inductance well below $0.2\mu\text{H}$.

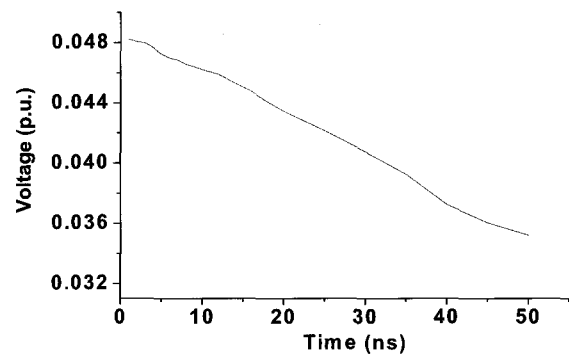


Fig. 8. Highest voltage drop across first equivalent layer for different rise times of the high frequency transients.

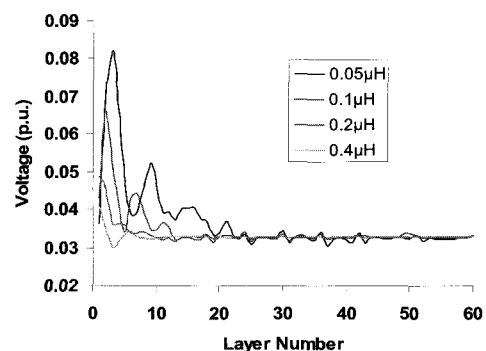


Fig. 9. Voltage distribution across the equivalent layers for different copper strip inductances.

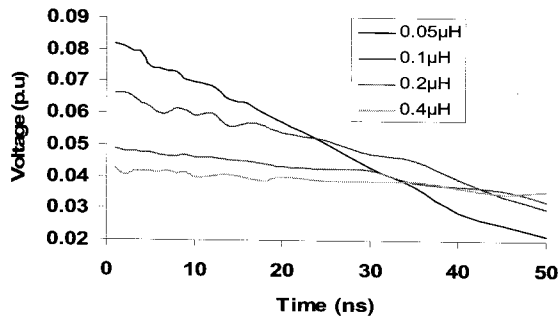


Fig. 10. Variation of highest voltage drop w.r.t. rise time for different copper strip inductances.

4.3. Calculation of Leakage Current

The condition of the bushing may be evaluated by measuring its leakage current during switching operations. This current is found to be sensitive to the inter-layer faults, which may occur due to high frequency transients. Fig. 11 shows the leakage current calculated through bushing with and without inter-layer fault. For this purpose, an impulse waveform of amplitude ($420 \text{ kV} \cdot \sqrt{2}/\sqrt{3}$) with a rise time of 1 ns is considered. From the results, it is seen that, even though current magnitude is almost identical, there is a substantial change in current waveform. In the present study, a single equivalent layer fault is considered (in the

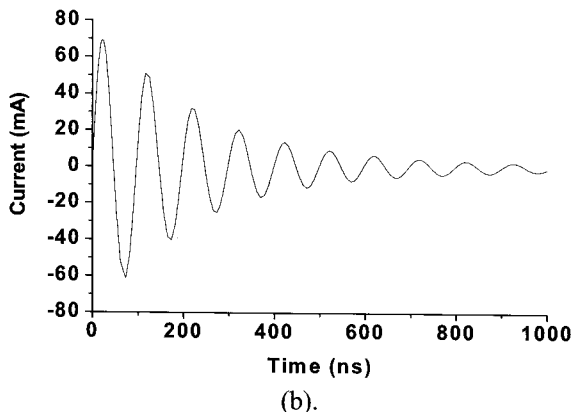
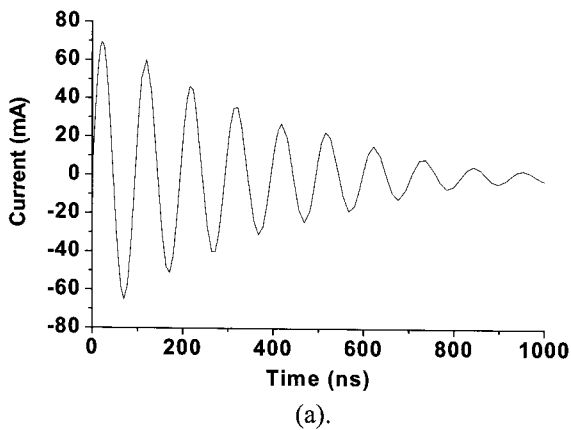


Fig. 11. Leakage current of the bushing. (a). without inter-layer fault. (b). with inter-layer fault.

first equivalent layer) with fault resistance of 0.1Ω . The attenuation of current amplitude with time is found to be a function of type of abnormality i.e., type of fault (single layer, multiple-layers), PD phenomena, etc.

5. Conclusion

An optimal equivalent layer's modeling circuit for 420 kV SF₆ gas-to-air capacitively graded bushing has been developed to simulate its behavior for very fast transient over-voltages generated during switching operations. The capacitively graded layers are divided into number of equivalent layers and each layer of the bushing is further divided into finite number of sections depending on its length. The following conclusions can be drawn from the study:

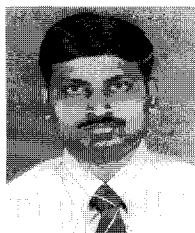
1. The voltage distribution across graded layers of SF₆ gas-to-air capacitively graded bushing is highly non-uniform for high frequency transients.
2. The voltage distribution across layers of capacitively graded bushing could be calculated accurately by considering the sixty equivalent layer modeling circuit.
3. The highest transient voltage drop across an equivalent layer is 192% more than the value obtained for normal system voltage application and this non-uniformity factor decreases with increase of rise time.
4. The highest voltage drop across the layers of bushing decreases with increase of rise time of the high frequency transients. Further, this reduction in voltage drop is found to be linear with rise time.
5. The voltage distribution across the equivalent layers is found to be a function of the copper strip inductance.
6. The condition of bushing can be evaluated by measuring its leakage current during switching operations. The attenuation of current amplitude with time is found to be a function of the type of abnormality i.e., type of fault, PD phenomena etc.

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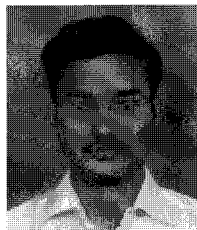
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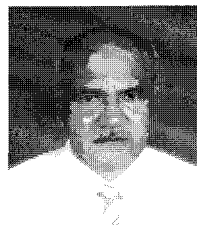
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