Effect of VFTO on Transient Voltage Distribution in Power Transformer Windings (Postprint)

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Abstract

When disconnectors in Gas Insulated Switchgear (GIS) perform opening and closing operations, the resulting Very Fast Transient Overvoltage (VFTO) is highly likely to cause insulation failures in internal GIS equipment and connected power equipment, with power transformers being particularly vulnerable to severe damage. This paper employs EMTP to simulate and calculate VFTO at various nodes induced by disconnector operations in GIS, analyzes the amplitude characteristics of VFTO, applies VFTO to transformer windings, examines the transient voltage distribution across transformer windings, and identifies the insulation weak points in transformer windings.

Full Text

Study of the Transient Voltage Distribution of Transformer Windings Caused by VFTO

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Abstract

When disconnector switching operations occur in gas-insulated switchgear (GIS), the resulting very fast transient overvoltage (VFTO) can cause insulation failures in GIS internal equipment and connected power apparatus, with power transformers being particularly vulnerable. This paper employs EMTP to simulate and calculate VFTO at various nodes in GIS caused by disconnector operations, analyzing the amplitude characteristics of VFTO. By applying VFTO to transformer windings, the transient voltage distribution within the windings is analyzed, the potential gradient between coils and turns is obtained, and the insulation weak points of the transformer windings are identified, which are located at the forward end of the windings.

Keywords: Very fast transient overvoltage (VFTO), gas insulated switchgear (GIS), transient voltage distribution, EMTP, multi-conductor transmission line (MTL) model

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1 Introduction

With increasing voltage levels in power systems, the problem of very fast transient overvoltage (VFTO) caused by disconnector operations in gas-insulated switchgear (GIS) has become increasingly prominent. Since disconnectors in GIS lack specialized arc-extinguishing devices and operate at relatively slow speeds, multiple reignitions and pre-strikes occur between the contacts during opening and closing operations, generating impulse waves with extremely short rise times. These waves undergo numerous reflections and refractions within the GIS, forming ultra-fast transient overvoltages with extremely steep wavefronts and frequencies reaching tens or even hundreds of megahertz [1-2]. Such VFTOs, characterized by steep wavefronts and high-frequency oscillations, not only affect the reliability of GIS components but also pose a serious threat to the insulation of connected power equipment, particularly power transformers. This phenomenon can be attributed to two main factors: First, when VFTO reaches a transformer, its extremely steep wavefront creates a highly non-uniform voltage distribution, with most of the voltage drop concentrated across a small portion of the winding near the entrance, potentially causing inter-turn insulation failures [3]. Second, when the oscillation frequency of VFTO approaches the natural resonant frequency of the winding, it can excite internal electromagnetic oscillations, producing local resonant overvoltages even higher than those caused by lightning impulse full waves or chopped waves. Currently, the Electromagnetic Transients Program (EMTP) is widely used for simulating VFTO generated by switching operations of disconnectors and other components in GIS [4-6]. This paper applies EMTP to simulate VFTO at various nodes in GIS caused by disconnector operations. The key to analyzing transient voltage distribution in transformer windings under VFTO lies in determining the appropriate transient circuit model and parameter values for the transformer windings. This paper establishes an equivalent circuit model for transformer windings using EMTP [7] to analyze and calculate the transient voltage distribution within transformer windings under VFTO, which holds significant importance for improving transformer insulation design and enhancing operational stability.

2.1 Experimental Circuit Establishment

[Figure 1: see original paper] shows a schematic diagram of the GIS bus charging current test circuit based on IEC standards. Terminal B1 connects to the power supply transformer, while B2 connects to a DC voltage generator. Initially, disconnector D1 is closed to charge the load bus between D1 and D2. After at least one minute, D1 is opened to perform the disconnector switching test on the load bus. The test requires that the ratio of load-side bus length to source-side bus length be 0.36. The enclosed bus is filled with SF gas at a pressure of 0.4 MPa. The measurement results are presented in Table 1 .

Table 1 shows that VFTO amplitudes are not particularly high, and the overvoltage on the load bus side is significantly greater than that on the source side. Unlike lightning impulse voltage, each pre-strike or reignition at the contact gap generates a step voltage wave with a very steep wavefront that propagates in both directions. Due to the compact size of GIS, the distances between adjacent equipment and bus lengths are much shorter than in conventional air-insulated substations (AIS). Consequently, step voltage waves are continuously generated and repeatedly propagate within the GIS, undergoing complex refraction, reflection, and superposition, which ultimately results in dramatically increased transient oscillation frequencies that endanger insulation.

[Figure 2: see original paper] illustrates the equivalent circuit diagram of this test circuit. A capacitor C is added on the source side to obtain a more pronounced fast transient process, with C = 400 pF. C1, C2, and DSM are used to measure the power frequency voltage of the supply transformer.

2.2 Simulation Circuit Establishment

In modeling the charged busbar, particular attention must be paid to residual charge, which is closely related to VFTO simulation accuracy. During disconnector operations, the arc undergoes multiple reignitions, leaving a certain amount of charge on the busbar between the disconnector and circuit breaker, with residual charge accumulating as reignitions continue. In actual simulation, the unloaded busbar is equivalent to a fixed capacitance to ground. To obtain the maximum overvoltage waveform, calculations assume that disconnector reignition occurs when the source voltage is opposite in polarity to the residual voltage on the load bus.

The overvoltage simulation model is established in ATP-Draw as shown in [Figure 3: see original paper], with component model parameters listed in Table 2 .

2.3 Mathematical Model Establishment

For GIS transient process calculation, network elements are replaced with current sources, resistors, and capacitors to establish an equivalent network node equation. Solving the node admittance matrix yields the node potential equation:

$$Y(\Delta t)U(t) = I_S(t - \Delta t)$$

where Y is the node admittance matrix, an $n \times n$ square matrix with each element related to component parameters and time step; $U(t)$ is the time-varying node voltage column vector, an $n \times 1$ matrix; and $I_S(t - \Delta t)$ is the node current column vector, also an $n \times 1$ matrix.

2.4 Simulation Results

The simulated VFTO waveform at the transformer entrance is shown in [Figure 4: see original paper]. The analysis reveals that although the VFTO amplitude at the transformer entrance reaches 1.3 pu—a value not high enough to activate the transformer protection surge arrester—its steep voltage rise poses a significant threat to inter-turn insulation.

To investigate transient voltage distribution in transformer windings, the equivalent circuit under transient overvoltage must first be understood. In actual transformer windings, capacitance exists between turns and to ground, but these values are negligible at power frequency, allowing the equivalent circuit to be represented by lumped inductance and resistance only. However, under high-frequency VFTO, the coupling capacitances between winding components must be considered, making the circuit considerably complex. Therefore, the key to analyzing transient voltage distribution in transformer windings under VFTO lies in determining an appropriate high-frequency transient circuit model.

The multi-conductor transmission line (MTL) model for transformer windings described in literature [8-10] most closely approximates the actual model and yields satisfactory results. Consequently, this paper adopts the MTL model to analyze transient voltage distribution in transformer windings under VFTO. Given the special structure of transformer coils, each turn of the winding is treated as a transmission line [11], with the entire winding constituting a multi-conductor transmission line system. The coil is axially dissected at the line end, with turns stretched into straight lines and numbered according to their electrical connection sequence. The boundary conditions require that the voltage and current at the end of the i-th turn equal those at the beginning of the $(i+1)$-th turn $(i = 1, 2, \dots, n-1)$. The first turn connects to a voltage source, while the n-th turn end is either grounded, connected to a load impedance, or left floating. The corresponding MTL model can thus be regarded as a $2n$-port network with a total of $2n$ boundary conditions [12-14]. The mathematical equations can be expressed as:

$$\frac{\partial U(x,t)}{\partial x} = -RI(x,t) - L\frac{\partial I(x,t)}{\partial t}$$

$$\frac{\partial I(x,t)}{\partial x} = -GU(x,t) - C\frac{\partial U(x,t)}{\partial t}$$

where $U(x,t)$ and $I(x,t)$ are $n \times 1$ voltage and current column vectors, respectively; and R, L, G, and C are $n \times n$ matrices representing resistance, inductance, conductance, and capacitance per unit length.

The simulation calculation for the transformer MTL model is implemented using the multi-conductor transmission line model in Simulink, as shown in [Figure 5: see original paper]. The transformer high-voltage winding selected for this study contains 68 disks, each comprising 12–14 turns, with a conductor cross-section of 3.15×11.8 mm^2. The distances between turns and between disks are 0.9 mm and 3.9 mm, respectively. The VFTO amplitude at the transformer entrance is 1.3 pu (see [Figure 4: see original paper]), which is applied as the excitation to analyze the overvoltage distribution within the winding.

[Figure 6: see original paper] and [Figure 7: see original paper] present the transient voltage distribution waveforms for disks 2, 4, 6, and 8 (front portion of the winding) and disks 34, 36, 64, and 66 (middle and rear portions), respectively. The simulation results demonstrate that the voltage amplitudes are relatively high for disks near the transformer entrance (disks 2, 4, 6, and 8), with correspondingly high oscillation frequencies. In contrast, the VFTO amplitudes for the middle disks (34 and 36) and rear disks (64 and 66) decrease sequentially, with oscillation frequencies also diminishing. Therefore, the simulation clearly shows that the maximum voltage across winding disks under VFTO occurs in the region near the winding entrance, indicating an extremely non-uniform inter-disk voltage distribution with the maximum concentrated in a small area near the entrance. This phenomenon aligns with the observed pattern that insulation failures in transformer windings caused by various impulse voltages typically occur at the winding front end.

4 Conclusions

(1) This paper establishes an EMTP simulation model for gas-insulated switchgear to analyze VFTO caused by disconnector operations, demonstrating that the maximum VFTO amplitude occurs at the transformer entrance.

(2) Based on the multi-conductor transmission line model of transformer windings and using Simulink for modeling and simulation with turn-by-turn analysis, the results show that VFTO amplitudes are relatively high for disks near the winding front (disks 2, 4, and 6), with high oscillation frequencies. The amplitudes decrease sequentially for middle disks (34 and 36) and rear disks (64 and 66), with corresponding reductions in oscillation frequency.

(3) Simulation analysis reveals that VFTO most easily damages the first few disks of transformer windings. Although the amplitude is not high enough to activate the transformer protection surge arrester, the steep voltage rise and high-frequency oscillation components pose significant threats to transformer insulation.

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