Resonant overvoltages produced in EHV transformer windings due to power system transients

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Resonant Overvoltages Produced in EHV Transformer Windings due to Power System Transients

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Abstract—**Electrical transients generated in power systems due to switching operations comprise of voltages and currents of complex waveshapes ranging over broad spectrum of frequencies. Such transients when travel through transformers can excite the winding's natural resonate frequencies. The resulting winding resonance leads in severe internal voltage amplification and abnormal stresses on the insulation. In the present paper the authors have conducted studies to ascertain how the winding insulations of a 400 KV EHV power transformer are stressed when one or more of the winding's natural frequencies are triggered by power system transients.**

Index Terms—**transformer, resonance, power system transients.**

I. INTRODUCTION

TRANSFORMERS operating in EHV power networks often encounter voltage transients of complex and varying waveshapes. Switching events in electrical grids produce oscillatory transient voltages spreading over broad spectrum of frequencies. Such transient voltages due to their comparatively lesser amplitude, remain undetected by surge protectors and often pass on directly to terminal equipments like transformers. Interestingly, such transient voltages, even with their lower magnitude can cause much greater excitation to transformer when frequency of the oscillatory voltage closely match with the winding's natural resonate frequencies. Such incidents may result in severe internal voltage amplification within the winding, which may lead to breakdown of winding insulations [1].

Reliable design of transformers, thus, necessitates thorough understanding of the behavioural response of transformers to system transients.

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In developing countries, where the power grids are continually going through the process of reforms, non-ideal switching events often prevail and such switching events in power networks can cause adverse effects to terminal devices connected even at further locations [2]. It is imperative that the development of a reliable transmission and distribution system would require critical attention to these oscillatory transient overvoltages generated out of perturbations in electrical grids. and it is necessary to explore how these transients would affect the windings and insulations of EHV transformers.

II. SCOPE OF WORK

In the present paper studies have been conducted on the developed model of a 400/220 kV EHV power transformer to explore the behavioral response of the 400 kV winding under oscillatory system transient voltages. A high frequency circuit model for the concerned transformer has been developed and the frequency response characteristics of the 400 kV winding have been determined. Studies have been conducted to investigate the nature of internal voltage amplification and the magnitude of voltage stresses developed on major and minor winding insulations when the external transient excitation triggers one or more of the winding's natural resonate frequencies.

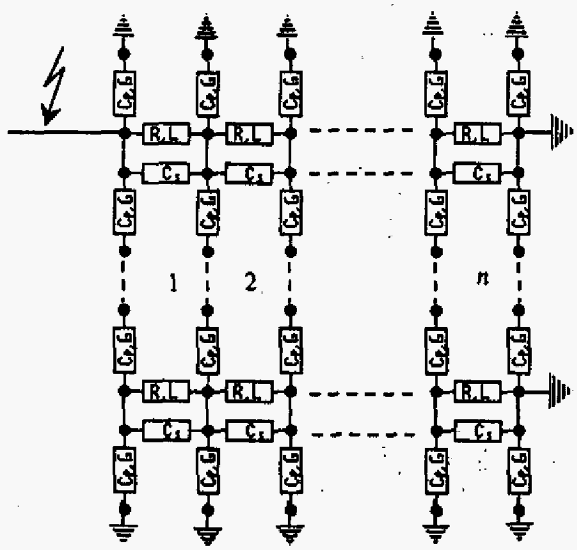
III. HIGH FREQUENCY MODELLING OF THE TRANSFORMER

A lumped parameter high frequency circuit model of the concerned 400/220 kV transformer has been developed by the authors based on transformer geometry and configuration [3,4]. The developed model envisages a coil-by coil representation of the original 400 kV winding, which is sufficient for the purpose of the present investigation. A part of the developed model comprising of n number of identical sections has been shown in Fig.1. The parameters of the model were computed from the transformer geometry and physical properties of materials.

- Coil-to-ground capacitance values have been calculated assuming that the coils and core leg and the metal tank form cylindrical electrode systems [3,4,5].

- Coil-to-coil capacitance values have been calculated from the principles form electrostatic energy conservation using the method described in [3,4].
- Self and mutual inductance parameters have been calculated on the basis of the assumptions that the core permeability is constant and its value is estimated on the basis of operating conditions. This assumption is valid since, the transformer is not operated near saturation [5,6,7].
- Skin effect in the winding conductors has been taken into consideration in the calculation of ohmic resistance [3,4].
- Dielectric losses in capacitances and associated damping effects have been taken into account in the form of conductance [6,7].

The validity and accuracy of the proposed modeling technique has been established in [3,4].



R, L : Series resistance and inductance (self + mutual) of an winding element
C_s : Series capacitance of an winding element
C_p, G : Parallel capacitance and conductance between winding elements

Fig. 1. Developed *n* section circuit model for the 400/220 KV transformer

IV. DETERMINATION OF FREQUENCY RESPONSE CHARACTERISTICS OF THE 400 KV WINDING

The frequency response of the disk coils on the 400 KV winding of the transformer has been determined by analyzing the developed circuit model using EMTP (ATP). To determine the frequency responses, each phase of the transformer has been excited at its terminals by 400/√3 KV(rms) variable frequency sinusoidal voltage source. The response obtained from ATP simulation has been shown in Fig.2. The voltage amplification in the disk coils has been represented in relative terms as multiples of the nominal coil voltage under power frequency operation. The frequency response of the group of 15 disk coils of the 400 kV main winding of the transformer shows one single major resonance around 7.25 kHz with voltage amplification factor of about 4.5 (Fig.2). This signifies that excitation at the transformer terminal at this frequency would force internal resonance in the main winding coils and theoretically, would produce internal overvoltage of magnitude as high as 4.5 times the nominal voltage experienced by these coils under normal power frequency operation.

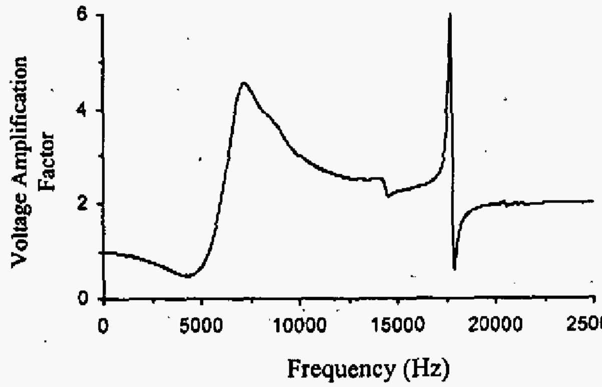
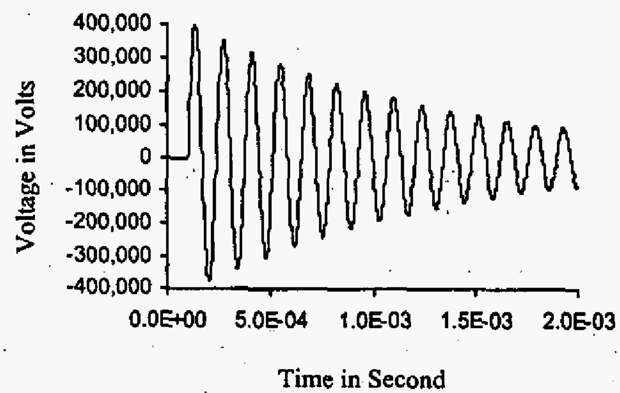


Fig. 2. Frequency response of a group of 15 disk-coils of 400 kV winding

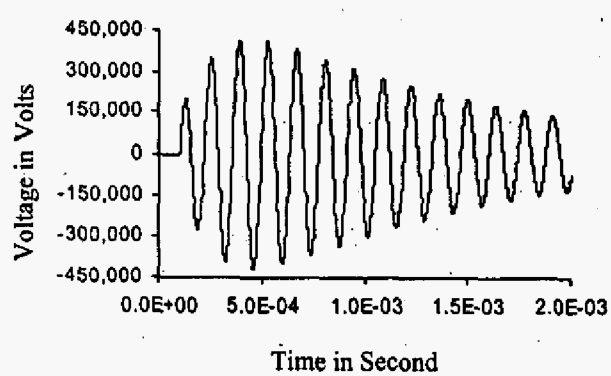
V. RESPONSE OF THE 400 KV WINDING UNDER OSCILLATORY TRANSIENT OVERVOLTAGES

The behavioral response of the 400 KV winding under oscillatory transient over voltages have been analyzed using EMTP. As already discussed, if the frequency of the exciting oscillatory voltage at the terminals of the transformer coincides with one of the fundamental natural frequencies of a winding or a part of a winding, resonant overvoltages are likely to occur. To study the phenomena, oscillatory transients of suitable amplitude and frequencies have been simulated and impressed on the transformer terminal. As majority of the system generated transients resemble damped sinusoids of the form: $Ve^{(-kt)}\sin 2\pi ft$, where k determines the degree of damping, such a form of wave has been the natural choice for simulation of excitation voltage. The amplitude V of the terminal excitation has been chosen a very practicable 1.2 p.u. of the nominal system's line to ground voltage, i.e. $1.2 \times \left(400\sqrt{2}/\sqrt{3}\right) \approx 392\ KV_{peak}$ per phase. Since the terminal voltage is much below the basic insulation level of the transformer (only 27.5% of the BIL voltage of 1425 kV), the disturbance will pass on to the winding without being detected by the surge arrester.

The frequency "f" of the damped sinusoid has been chosen to match the natural frequency of the 400 KV winding, i.e. 7.25 kHz (Fig.3a) as closely as practicable. The corresponding voltage-time graph depicting the voltage response of the group of 15 disk coils of the 400 kV winding has been shown in Fig.3b. Fig.3c presents the response of the same group of coils when the excitation frequency is de-tuned from resonance by about 30% to 5 kHz, keeping the amplitude unchanged. It is interpreted from Fig.3b that terminal excitation at frequency coinciding with the 400 kV winding's resonate frequency has forced the winding disk coils to resonance. Severe internal voltage amplification has been noticed across the resonating disk coils. The amplitude and duration of the resonant overvoltage in the disk coils under such condition were limited solely by the damping. The maximum amplitude of voltage across the group of 15 coils reached 411 kV (Fig.3b), which is about 4.4 p.u. of the nominal voltage under normal power frequency operation. The peak of the voltage, however, falls to a low 162 kV (1.7 p.u.) and settles down to ≈ 1.1 p.u. in less than 1ms time when the excitation frequency is detuned to 5 kHz (Fig.3c). Thus 30% detuning from resonate frequency results in as large as 400% reduction in voltage amplification, illustrating the sensitivity of the winding to resonate frequency.



(a)



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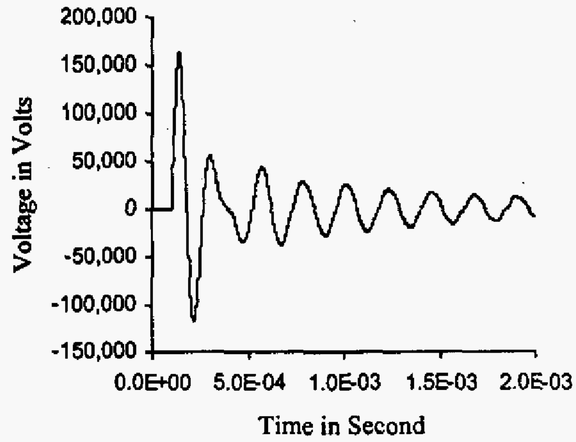

(c)

Fig.3. a) Terminal excitation at frequency 7.25 kHz.
b) voltage response of the group of 15 disk coils of 400 kV winding under resonance.
c) voltage response of the same group of disk coils when de-tuned from resonance.

VI. Conclusion

The present study has revealed that terminal excitation at frequencies coinciding with any one of the winding's natural frequencies may lead to large voltage amplification inside a transformer and can cause severe stresses on insulation. Switching events in power systems generate oscillatory transient voltages, which may eventually excite theses internal resonances and can produce very high voltage internal stresses even though the terminal voltage of the transformer remains well below the basic insulation level. It is therefore important to recognize the potential hazards associated with these low amplitude oscillatory system transients and to assess how the windings will respond to such transient voltages.

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