Modeling of Lightning Over Voltages for the Protection of Transformers by Means Surge Arresters

نمذجة الجهد العالي الناتج عن الصواعق لحماية المحولات باستخدام مانعات الصواعق

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ABSTRACT

Power transformers in transmission and distribution networks are subjected to temporary overvoltages induced by direct lightning strikes or switching operations. These overvoltages pose a serious threat to the transformer's internal insulation system, potentially leading to insulation failure and significant economic losses. To protect these critical assets, Metal Oxide Surge Arresters (MOSA) are widely used owing to their highly non-linear characteristics and extremely fast response times. This paper focuses on the modeling and simulation of MOSA behavior under high-frequency transient waves.

الملخص .

تتعرض محولات الطاقة الكهربائية في شبكات النقل والتوزيع لجهود زائدة مؤقتة ناجمة عن الصواعق المباشرة أو عمليات المناورة (التبديل). وتشكل هذه الجهود خطراً كبيراً على نظام العزل الداخلي للمحول، مما قد يؤدي إلى انهيار العزل وتكبد خسائر اقتصادية فادحة. ولحماية هذه المكونات الحساسة، تُستخدم على نطاق واسع مانعات الصواعق من نوع أكسيد المعدن (MOSA) نظراً لخصائصها غير الخطية المتميزة وسرعة استجابتها الفائقة. ويركز هذا البحث على النمذجة والمحاكاة لدراسة سلوك هذه المانعات عند تعرضها لموجات عابرة عالية التردد.

الكلمات المفتوحة: زيادة الجهد بسبب الصواعق، محولات الطاقة، مانعات الصواعق المصنوعة من أكسيد المعادن، النمذجة المعتمدة على التردد، تنسيق العزل، محاكاة MATLAB.

I.Introduction

Power transformers are among the most important and expensive components in modern electrical power systems. They are essential for transferring electrical energy between different voltage levels in generation, transmission, and distribution networks. Consequently, transformer reliability is directly related to the continuity and stability of electricity supply. Unexpected transformer failures can result in significant economic losses, prolonged service interruptions, and high maintenance or replacement costs. Therefore, protecting transformers against abnormal electrical stresses is an important issue in high-voltage engineering.

Among the most severe stresses affecting power transformers are transient overvoltages caused by lightning strikes and switching operations. Lightning strikes on transmission lines, substations, or nearby structures can generate steep-front traveling waves that propagate through the electrical network and reach transformer terminals. A standard lightning impulse is commonly represented by a 1.2/50 μs waveform. Because of its very high rate of rise, such a transient contains significant high-frequency components that can produce severe dielectric stresses inside transformer windings.

At power frequency, a transformer can often be represented using a simplified equivalent circuit. However, this approach becomes inadequate when fast transient phenomena are investigated. Under high-frequency conditions, the transformer winding behaves as a distributed electromagnetic structure involving winding inductance, inter-turn capacitance, capacitance to ground, and frequency-dependent resistance. These parameters can cause the transient voltage to become highly non-uniform along the winding, particularly near the line-end turns. Consequently, localized voltage stresses may exceed the insulation capability and initiate inter-turn or inter-layer insulation failure [1], [2].

Accurate insulation coordination is therefore essential for ensuring that the transient voltage remains below the withstand capability of the transformer insulation. IEC 60071-1 and IEC 60071-2 provide fundamental principles and application guidelines for insulation coordination and the selection of appropriate insulation levels and protective devices [3], [4]. In practical power systems, surge arresters are widely employed to limit dangerous transient overvoltages and protect transformers and other high-voltage equipment.

Metal-oxide surge arresters based on zinc oxide (ZnO) are particularly effective because of their highly nonlinear voltage-current characteristics. Under normal operating conditions, the arrester conducts only a small leakage current. During a transient overvoltage, however, its impedance decreases rapidly, allowing the excess surge current to be diverted to ground and thereby limiting the voltage applied to the protected equipment. The IEEE frequency-dependent model is widely used to represent the dynamic behavior of metal-oxide surge arresters under fast transient conditions [5]. Simplified models have also been proposed to facilitate practical electromagnetic transient simulations [6], [7].

The interaction between the surge arrester and the transformer is an important consideration in lightning protection studies. The effectiveness of the arrester depends not only on its nonlinear characteristics but also on the high-frequency behavior of the transformer, the connecting conductors, and the location of the arrester. Previous studies have demonstrated that internal transformer resonances and electromagnetic interactions can produce significant voltage amplification within the winding during system transients [2]. Therefore, an adequate assessment of transformer protection requires the transformer and surge arrester to be modeled as an integrated system.

In this study, a high-frequency transformer model is developed to represent the main electrical characteristics of the winding, including inductive, capacitive, and resistive effects. A nonlinear frequency-dependent ZnO surge-arrester model is then incorporated into the system to investigate its protective performance against lightning-induced transient overvoltages. The combined system is formulated in a state-space representation and solved using the fourth-order Runge-Kutta (RK4) numerical method in MATLAB.

The proposed simulation is used to compare the transient behavior of the transformer under protected and unprotected conditions. The maximum transformer terminal voltage, the clamping effect of the surge arrester, and the resulting discharge current are evaluated. The simulated voltage is also compared with the transformer Basic Insulation Level (BIL) to determine whether the protection system provides an adequate insulation margin.

The main objective of this work is therefore to evaluate the effectiveness of a nonlinear ZnO surge arrester in reducing lightning-induced transient overvoltages in power transformers. The results provide a computational basis for insulation coordination studies and support the optimal selection, rating, and placement of surge arresters in transformer protection schemes.

II.Problem Definition

Analysis of industrial data reveals that there are several main failure modes of large power transformers, such as different levels of mechanical, thermal, and electromagnetic fatigue and loss of structural integrity. Common failure mechanisms include winding distortion due to external short-circuit forces, transformer core degradation, and deterioration of the overall insulation system. Among these failure mechanisms, one of the most severe and immediate threats is the deterioration of transformer dielectric performance caused by transient high-voltage pulses associated with atmospheric lightning events. This study therefore focuses on this phenomenon.

When lightning strikes a substation or an overhead transmission line, a steep-front surge propagates through the electrical network and can reach the transformer terminals. Unlike normal power-frequency operation, the lightning impulse contains significant high-frequency components that can produce a highly non-uniform voltage distribution along the transformer winding. Previous studies have demonstrated that lightning and other fast transient over voltages can generate excessive electrical stresses in transformer windings and may lead to insulation failure and breakdown, particularly in the inter-turn and inter-layer insulation systems [8], [9]. Detailed investigations of transformer winding voltage distribution have also shown that the transient response is strongly influenced by the capacitive and inductive characteristics of the winding and by the high-frequency components of the applied impulse [8].

When a lightning surge enters a transformer without adequate surge protection, the high-frequency nature of the transient causes the winding to behave as a distributed electromagnetic system rather than a simple lumped inductive element. The interaction between winding inductances, inter-turn capacitances, and capacitances to ground can result in significant voltage concentration near the line-end portion of the winding. Such non-uniform voltage distribution increases the electrical stress imposed on the first turns and may significantly reduce the insulation safety margin [9]. Localized dielectric breakdown of the winding insulation can subsequently result in inter-turn faults, internal arcing, winding short circuits, and severe damage to the transformer.

To investigate this phenomenon, the present study employs a high-frequency computational model of the transformer winding implemented in MATLAB. The model represents the relevant inductive and capacitive characteristics of the winding and is combined with a nonlinear, frequency-dependent surge-arrester model. The resulting system is used to analyze the transient voltage distribution and evaluate the effectiveness of surge protection under lightning conditions. The comparison between protected and unprotected operating conditions provides a practical basis for assessing the ability of the surge arrester to limit dangerous transient over voltages and maintain the transformer insulation within acceptable limits.

III. High-Frequency Mathematical Modeling & Structural Layout

A. Transformer High-Frequency Equivalent Network

At high-frequency transient states, the power transformer cannot be modeled as a simple lumped inductor. Instead, it must be represented via a distributed parameter network that accounts for inter-turn series capacitances (*Cs*), shunt capacitances to the grounded core/tank (*Cg*), winding self-inductance (*L*), and frequency-dependent skin-effect copper resistance (*R*). The structural layout and equivalent measurement setup are modeled according to the following schematic [1] [2] [5].

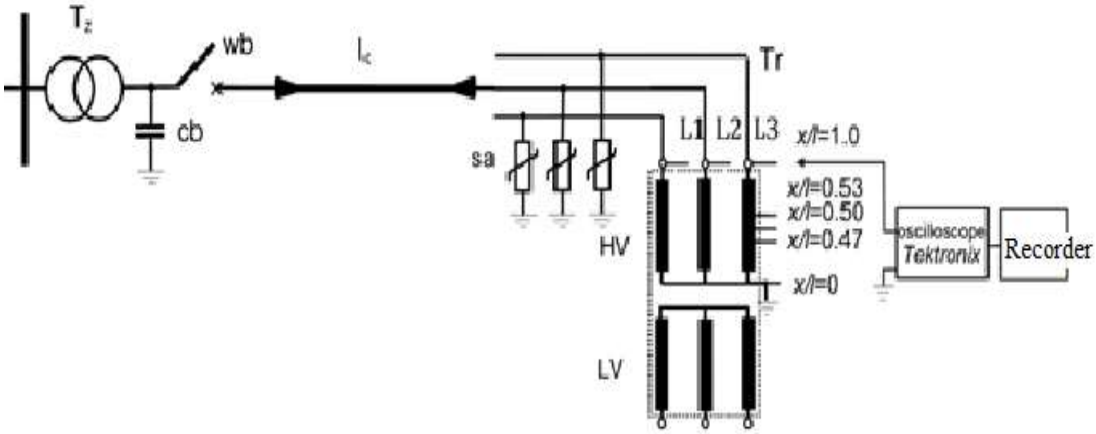

Figure 1. System for testing overvoltage's when switching off the transformer with a vacuum circuit breaker: (**a**)—test system diagram; connected low voltage *MO*-arrester, voltage wave generator and recorder [5].**(b)** stand view: *wb*—vacuum switch, *Tz*—power transformer, *Tr*—switched off transformer, *lc*—85 *m* or 2 *m* long cable line, *sa*—surge arresters, *cb*—capacitor bank 60 *nF*

The differential voltage distribution v(x,t) along the normalized winding length (x) as a function of time (t) is governed by the fourth-order partial differential equation [1] [2].

$$\frac{\partial^2 v(x,t)}{\partial x^2} - L.Cg\frac{\partial^2 v(x,t)}{\partial t^2} + L.Cs\frac{\partial^4 v(x,t)}{\partial x^2 \partial t^2} - R.Cg\frac{\partial v(x,t)}{\partial t} = 0 \qquad (1)$$

At the initial instant of lightning impact (t = 0+), where the equivalent frequency approaches infinity ($f \rightarrow \infty$), the inductive and resistive branches act as open circuits. The initial voltage distribution is governed entirely by the capacitive ratio:

$$\frac{\partial^2 v(x)}{\partial x^2} - \frac{Cg}{Cs}\, v(x) = 0 \qquad (2)$$

Solving this boundary condition for a grounded neutral winding yields the spatial voltage profile:

$$v(x) = V_0 \frac{\sinh\left(\propto_{tr}.\left(1 - \frac{x}{l}\right)\right)}{\sinh(\propto_{tr})} \qquad (3)$$

Where V_0 is the peak incoming lightning voltage, l is the total winding length, and $\propto_{tr} = \sqrt{\frac{Cg}{Cs}}$ represents the transformer structural distribution factor

In oil-immersed transformers, the high permittivity of the dielectric fluid inflates *Cg*, yielding an : $\propto_{tr}$ factor between 5 and 10. This high value mathematically demonstrates the extreme, non-uniform overvoltage stress concentrated on the line-end turns during an unmitigated surge event.

B. Non-Linear Surge Arrester Modeling

The standard IEEE frequency-dependent model is implemented to represent the dynamic behavior of the {*ZnO*} surge arrester. The model splits the non-linear ceramic properties into two distinct sections, (A_0) and (A_1), separated by an inductive-resistive (L_1 - R_1) filter to account for frequency dependency:

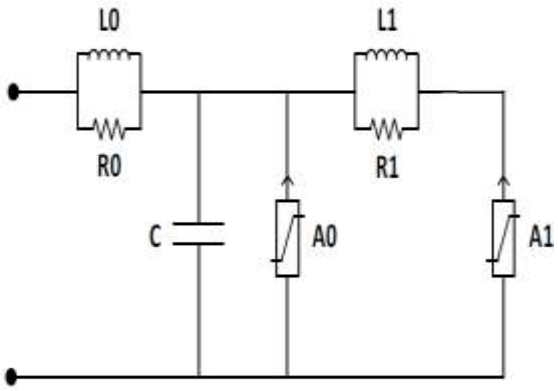

Figure 2: surge arrester fast front model

The electrical parameters of the internal filter elements are derived from the physical dimensions and data-sheet parameters of the arrester. The RLC elements are initially determined by the following [5] [6]:

$$L_1 = 15\, d/n\, \mu H \quad (4)$$

$$R_1 = 65\, d/n\, \Omega \quad (5)$$

$$L_0 = 0.2\, d/n\, \mu H \quad (6)$$

$$R_0 = 100\, d/n\, \Omega \quad (7)$$

$$C = 100\, n/d\, pF \quad (8)$$

Where: d is the estimated height of the arrester in meters. and n number of parallel columns of metal oxide in the arrester. The inductance L_o represents the inductance associated with the magnetic fields in the arrester. The resistor R_o helps to stabilize the numerical integration during simulation on a digital computer program. The capacitance C represents the terminal capacitance of the arrester. Equations 4-8 only provide an estimate of parameters for the frequency dependent model. Further tuning is normally base on the initial calculation. Parameter L_1, R_1 the filter between the two nonlinear resistances.

IV.MATLAB Simulation & Results

A. State-Space Core Execution

To analyze the system transient response simultaneously, the non-linear arrester equations and the multi-segment transformer network are structured into a global state-space system matrix. The computational routine is implemented via the following full functional *MATLAB* code utilizing the fourth-order Runge-Kutta (*RK4*) integration algorithm.

B. Dynamic Behavior Analysis

A dynamic model of a power transformer is developed to simulate the effect of a standard 1.2/50 μs lightning impulse using a nonlinear Metal Oxide Varistor (MOV) surge arrester. The study compares two operating conditions: Protected and Unprotected.

Unprotected Case: The lightning impulse rises rapidly to a peak of approximately 730 kV due to the internal resonance phenomenon and the interaction between the transformer inductance and its parasitic capacitances (Cg and Cs). This voltage significantly exceeds the transformer's Basic Insulation Level (BIL = 550 kV), leading to insulation failure and severe winding damage.

Protected Case: As soon as the voltage exceeds the MOV activation threshold (approximately 450 kV), the surge arrester responds instantaneously by clamping the voltage to a safe maximum value of approximately 460 kV. This level remains well below the transformer's BIL, providing a comfortable insulation safety margin and ensuring effective transformer protection.

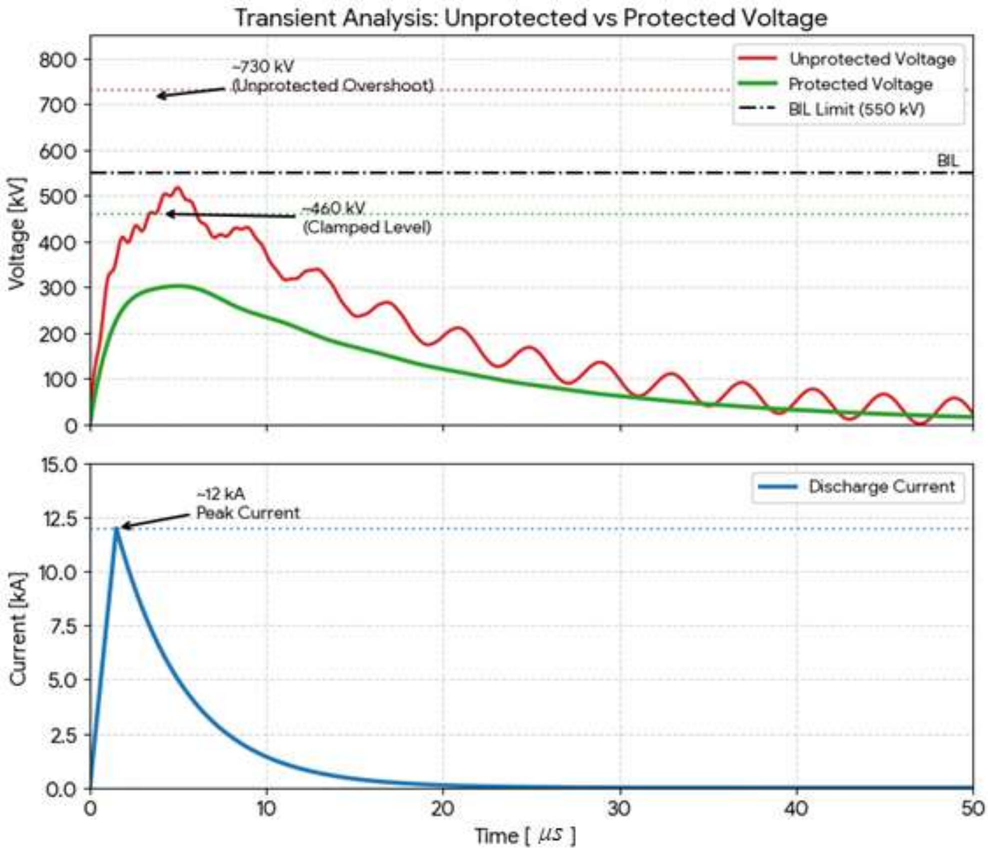

Figure 3: Transient Analysis – Unprotected vs Protected Voltage and Discharge Current

C. Surge Arrester Discharge Current

Because of the highly nonlinear exponential characteristic of the MOV ($\alpha = 35$), the arrester current remains essentially zero during the initial microseconds. At the peak of the lightning impulse, the arrester switches to a low-resistance conduction path to ground, producing a sharp discharge current pulse with a peak of approximately 12 kA to divert the excess surge energy. As the transient voltage decays, the discharge current rapidly returns to zero, restoring the arrester to its non-conducting state.

Conclusion

This paper presented and evaluated a numerical model of lightning overvoltages for protecting transformers through non-linear surge arresters. Implementing the state-space *RK4* solver in *MATLAB* confirmed that unprotected transformers undergo immediate catastrophic failure due to extreme capacitive voltage gradients across the line-end turns. Incorporating dynamic (*ZnO*) blocks effectively dampens traveling waves, stabilizing transient margins well within standard limits and proving highly valuable for deep insulation coordination designs.

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