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Original Research Article

Simulation and analysis of voltage surge and surge arrester in transmission Lines

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Abstract: The stability and reliability of electrical power systems are critically dependent on effective protection schemes. The transmission system, in particular, is the most frequent site of electrical incidents due to the high voltages and complex environmental conditions it endures. Surges on transmission lines often lead to severe consequences, including equipment failure, corona discharge, and insulation breakdown. This report aims to analyze two primary adverse phenomena on transmission lines: internal switching transients and external lightning surges. By simulating their practical occurrences, we analyze their characteristics and impacts. Furthermore, we test the performance of a core protective device—The surge arrester—And propose optimization strategies, providing a reference for future solutions.

Keywords: voltage surge; circuit breaker; surge arrester; transient recovery voltage (TRV); switching transients; transmission line; PSCAD/EMTP; breaker Arc

1. Introduction

An electrical surge in a power system is a rapid, short-duration electrical transient with an amplitude significantly larger than the system's rated values. Surges are broadly classified into two categories. Internal surges are generated by faults within the system, such as at the power source or load side. External surges are caused by external factors, most notably direct lightning strikes on transmission lines or other equipment. These events produce high electrical stress that can exceed the withstand voltage levels of equipment, leading to catastrophic failures, diminished power quality, and increased system losses. This report focuses on two of the most representative types of voltage surges: the Transient Recovery Voltage (TRV), which is the most common internal surge occurring nearly every time a circuit breaker trips, and the lightning surge, an external surge characterized by its extremely high magnitude and destructive potential. Through simulation and analysis, we will investigate effective methods for suppressing these surges, with a special emphasis on the performance evaluation and optimization of surge arresters.

2. Literature review

A comprehensive understanding of surge phenomena requires a review of existing research on TRV, lightning, and the protective devices designed to mitigate them. When a circuit breaker operates to interrupt a fault current, an internal transient known as Transient Recovery Voltage (TRV) appears across its terminals. TRV is characterized as a short-duration surge with an amplitude that can be up to twice the normal recovery voltage, accompanied by high-frequency oscillations. The high-frequency component is primarily influenced by the stray capacitance and inductance to ground of various system components. Studies have shown that the peak of the TRV typically occurs at the natural current zero crossing. In a real-world circuit breaker, an electric arc forms between the contacts during the opening process. The TRV emerges precisely as this arc is extinguished at a

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current zero. To accurately simulate this complex interaction, researchers have developed various arc models, such as the Mayr, Cassie, and the combined Schavemaker models, which are now widely used in the transient analysis of high-voltage systems. Traditional methods for suppressing TRV involve the strategic use of passive components, like a series Resistor-Capacitor (R-C) circuit placed in parallel with the breaker.

Lightning-induced surges represent an extreme threat to power systems. A typical lightning strike can carry a voltage of millions of volts and a current ranging from tens of thousands to over two hundred thousand amperes. Given its random nature and severe destructive capability, simulating lightning surges is essential for designing effective protection systems. In practice, the complex waveform of a lightning surge is often simplified for analysis and simulation using standard impulse shapes defined by bodies like the IEC and IEEE, with the 1.2./50μs waveform being a common standard for representing a lightning impulse.

The primary device used to defend against such overvoltages is the surge arrester. It functions as a non-linear resistor whose impedance changes dynamically with the applied voltage. Under normal operating conditions, it maintains a very high impedance, effectively acting as an open circuit. However, when a surge occurs, its impedance drops precipitously to a very low value, creating a safe path for the surge current to be diverted to the ground. The most prevalent type today is the Metal-Oxide Arrester (MOA), whose performance is defined by its non-linear voltage-current (V-I) characteristic. Several advanced models, including the IEEE and Pinceti models, have been developed to accurately reproduce the dynamic behavior of MOAs in simulations, allowing for detailed performance analysis and optimization.

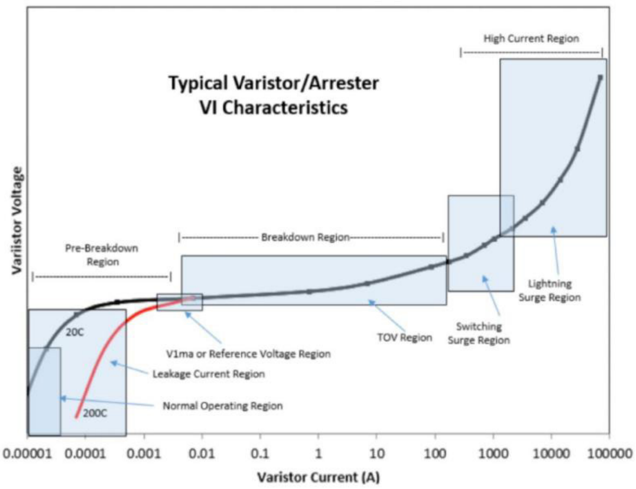

Figure 1. A typical V-I characteristic curve for a varistor/arrester.

3. Simulation of switching transients

To investigate the behavior of switching transients, we utilized the PSCAD/EMTP software to create a single-phase TRV test model. This model featured a 132kV, 50Hz power source, inductive and capacitive components representing the system impedance, and a circuit breaker. A fault was programmed to occur at 0.5 seconds and last for 0.05 seconds, with the breaker set to operate at the natural current zero point of 0.558 seconds. Our simulations compared an ideal breaker with a non-ideal model that incorporated the effects of an electric arc. The results confirmed that the non-ideal model produced a TRV that more closely resembled real-world conditions, where the arc voltage persists until the breaker is fully open, at which point the high-frequency TRV oscillation begins.

A particularly severe condition, known as "current chopping,"was also simulated. This occurs when a circuit

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breaker interrupts the current prematurely, before it reaches a natural zero. The sudden interruption of non-zero current in an inductive circuit causes the stored magnetic energy to be rapidly converted into an extremely high overvoltage. Our simulation results demonstrated that current chopping generates violent voltage oscillations and significant harmonic distortion, posing a much greater threat to the system than a standard TRV. To mitigate these transients, we simulated the application of a parallel R-C filter across the breaker terminals. The results showed that a larger resistance value helped to dissipate energy and reduce the duration of the TRV, while a larger capacitance value smoothed the voltage waveform by slowing its rate of rise. This confirmed that a properly tuned R-C snubber circuit is an effective solution for TRV suppression.

4. Distributed transmission line model

To accurately study how surges propagate along a transmission line, it is insufficient to use a simple lumped-parameter model. We therefore constructed a distributed transmission line model consisting of 30 cascaded Π-sections. Each section was comprised of a series inductor (L), a shunt capacitor (C), and a shunt resistor (R), representing a discrete segment of the line. The crucial parameter governing wave propagation is the line's surge impedance (Z_0). We determined this value experimentally by injecting high-frequency (100kHz) pulses into the model and measuring the wave reflection characteristics. Both the experimental measurements and the corresponding simulations confirmed that the surge impedance of our line model was approximately 50Ω. This parameter is fundamental to understanding how a surge interacts with the line and its terminal load. When the load impedance perfectly matches the line's surge impedance, the surge energy is completely absorbed at the load with no reflection. Conversely, a mismatch between the load and line impedance causes wave reflections, which can lead to complex and often amplified overvoltage conditions at various points along the line.

5. Surge arrester modeling and performance testing

The core of any surge protection scheme is the surge arrester, and its performance is dictated by its non-linear V-I characteristics. We conducted extensive laboratory tests on a commercial surge arrester (SHRMW RMU1-C40) to accurately model its behavior. Using a high-voltage impulse generator, we applied surges of increasing magnitude, from 200V up to 7kV, while recording the resulting current through the arrester. The collected data allowed us to plot a detailed V-I curve, which clearly showed the device's three operating regions: a high-impedance pre-breakdown region for voltages below 900V, a transitional breakdown region where the current begins to increase significantly, and a low-impedance high-current region for surges above 1.8kV, where the device fully conducts to divert the surge energy.

These 32 experimental data points were then imported into PSCAD to create a highly accurate, user-defined surge arrester model based on a real-world device. To validate this model and quantify its performance, we integrated it into our distributed transmission line simulation. We applied a 1.8kV surge to the model with an open-circuited termination. Without the arrester, the peak voltage at the end of the line reached 1.38kV. With the arrester model installed, the peak voltage was successfully clamped to approximately 1.05kV, representing a 24% reduction in overvoltage. The close agreement between these simulation results and our laboratory observations validated the accuracy of our model and confirmed the effectiveness of the surge arrester in limiting transient overvoltages.

6. Surge arrester performance optimization

While a single MOA provides a fundamental level of protection, its performance can be significantly

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enhanced through the addition of external circuitry. Existing literature suggests several advanced models that incorporate external components to improve the arrester's dynamic response. We conducted a comparative simulation study of three well-known configurations: the IEEE model, the Pianceti–Gianettoni (P-G) model, and the Fernadez–Diaz (F-D) model. Our simulations revealed that the IEEE model, which strategically combines inductors, resistors, and a capacitor with the non-linear arrester element, provided the most effective surge suppression. When this optimized IEEE model was implemented in our test circuit, it resulted in a much lower peak voltage and a significantly smoother residual voltage waveform compared to the standalone arrester. This demonstrates that a well-designed external network can substantially improve the protective characteristics of a surge arrester, proving it is a viable path for developing more robust protection schemes.

7. Conclusion

This report has successfully simulated and analyzed two of the most significant electrical threats in power transmission systems: switching transients (TRV) and voltage surges. Through a combination of PSCAD simulations and hands-on laboratory experiments, we have validated the accuracy of a distributed transmission line model and a detailed surge arrester model based on a physical device. Our analysis highlights that circuit breaker operating characteristics, especially the phenomenon of current chopping, and the impedance matching between the line and the load have a decisive influence on the severity of transient overvoltages. The surge arrester was confirmed as an effective core protective device for limiting these overvoltages. Furthermore, we demonstrated that its protective performance can be substantially improved by designing an appropriate external circuit, with the IEEE model showing the most promise. These findings provide a solid theoretical basis and practical reference for engineering more reliable and resilient protection schemes for modern power transmission systems.

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References

[1] Abdullah, M, Hamza, A, Ebrahim, A-A, Badran, A & Elyan, T 2013, A New Technique For Transient Recovery Voltage Suppression on Generator Circuit Breaker For Generator Fed.

[2] Faults ANEW TECHNIQUE FOR TRANSIENT RECOVERY VOLTAGE SUPPRESSION ON GENERATOR CIRCUIT BREAKER FOR GENERATOR FED FAULTS.

[3] Ali, M & Kk, P 2008, Effects of Transient Recovery Voltages on Circuit Breaker Ratings Term Project: - EE5220 -Power System Transients. Team: - Himanshu Bahirat.

[4] Araújo, MA, Flauzino, RA, Altafim, RAC, Batista, OE & Moraes, LA 2015, ‘Practical methodology for modeling and simulation of a lightning protection system using metal-oxide surge arresters for distribution lines', Electric Power Systems Research, vol. 118, pp. 47–54.