American Journal of Sciences and Engineering Research

E-ISSN -2348 – 703X, Volume 7, Issue 5, 2024

Examining the UHV Converter Transformer's Second Harmonic Suppression for Various Protective Applications

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ABSTRACT *—Differential protection using second harmonic suppression is a crucial method for safeguarding converter transformers, particularly against maloperation during energization and internal faults. This paper focuses on analyzing the second harmonic response in ultra-high voltage (UHV) converter transformers, which exhibit distinct behaviors due to their unique design and operational conditions. The accurate distinction between magnetizing inrush and fault currents is essential for the reliability functioning of differential protection schemes. In this study, a three-winding autotransformer model is developed based on the Unified Magnetic Equivalent Circuit (UMEC) and implemented in the EMTDC/PSCAD software environment. Both energization events and various internal faults, including phase-to-ground and interturn faults, are simulated to evaluate their impact on the second harmonic content. This paper also quantifies the effects of different fault severities, such as 30% and 60% winding short circuits, on the harmonic components. The simulation results are crucial in determining optimized parameters for the second harmonic blocking technique, thereby ensuring the efficacy of differential protection in UHV converter transformer applications. This research provides valuable insights into the behavior of UHV transformers under different operating conditions, offering practical guidelines for improving converter transformer protection schemes.*

Keywords: *UHV converter transformers; Differential protection; Second harmonic suppression; Internal fault simulation; EMTDC/PSCAD modeling; Transformer protection schemes.*

I. INTRODUCTION

The global transition towards renewable energy sources has significantly increased the reliance on advanced power transmission technologies to integrate these variable and geographically dispersed energy inputs into the electrical grid [1,2]. Converter transformers play a pivotal role in this integration, especially within high-voltage direct current (HVDC) transmission systems that are essential for efficiently transporting electricity over long distances from renewable generation sites, such as offshore wind farms and remote solar installations, to urban demand centers [3,4]. These transformers facilitate the crucial conversion between alternating current (AC) and direct current (DC), enabling the seamless connection of renewable energy sources to the existing grid infrastructure [5]. As the penetration of renewable energy continues to grow, the reliability and protection of converter transformers become increasingly vital to ensure stable and uninterrupted power delivery. Converter transformers are critical components in high-voltage direct current (HVDC) transmission systems, facilitating the conversion between alternating current (AC) and direct current (DC) to enable efficient

 Received-10-10-2024, Accepted- 20-10-2024

long-distance power transmission [6]. These transformers are designed to operate under extreme electrical conditions, such as ultra-high voltages (UHV) exceeding 1000 kV, requiring specialized protection mechanisms to ensure their reliable operation. A key challenge in protecting converter transformers lies in distinguishing between magnetizing inrush currents, which are normal during energization, and fault currents, which signal system malfunctions. This distinction is crucial to avoid false tripping and ensure the transformer remains operational under normal conditions while responding appropriately to faults.

A significant area of research on converter transformers focuses on enhancing differential protection schemes, which detect discrepancies in current between the transformer's primary and secondary windings to identify faults [7,8]. One widely used technique to improve the accuracy of differential protection is second harmonic suppression, which blocks protection relay operation during inrush conditions. The second harmonic component is more prominent during inrush currents compared to fault currents, allowing this suppression technique to differentiate between the two. However, UHV converter transformers exhibit unique characteristics that complicate this task, necessitating advanced modeling and simulation approaches to optimize protection settings [9,10].

Literature on converter transformer protection has explored various methods for refining differential protection schemes. For instance, some studies have employed electromagnetic transient models to simulate the behavior of UHV transformers under different fault conditions, such as phase-to-ground and interturn faults. These models help quantify the harmonic content generated by different fault severities, which is essential for tuning second harmonic suppression mechanisms [11]. Other research has investigated the use of wavelet transforms and higher-order harmonics to enhance fault detection sensitivity. This body of work highlights the complexity of protecting converter transformers, particularly in UHV applications, where operational conditions significantly influence the harmonic behavior of the system [12,13]. The second harmonic suppression technique is particularly effective in mitigating the impact of inrush currents during transformer energization. When a converter transformer is energized, the sudden application of voltage causes a surge of inrush current, which contains significant harmonic content, especially in UHV transformers with highly nonlinear magnetic cores. Simulations of energization events have shown that higher-order harmonics, such as the seventh harmonic, can also play a role in differentiating between inrush and fault conditions. As a result, ongoing research aims to fine-tune the parameters used in second harmonic blocking to ensure reliable protection without compromising system stability [14,15].

In this study, we employ the Unified Magnetic Equivalent Circuit (UMEC) model for simulating the behavior of UHV transformers under various internal fault scenarios. This model, implemented using the EMTDC/PSCAD software suite, allows for the accurate representation of the converter transformer's magnetic core and winding interactions. By simulating both phase-to-ground and interturn faults, we aim to quantify the impact of different fault severities (e.g., 30% and 60% short circuits) on the generation of second harmonic components. Such simulations are essential for validating the efficacy of second harmonic suppression techniques in UHV transformer differential protection. Furthermore, energization transients, which occur when converter transformers are switched into service, also generate substantial harmonic content, complicating the protection process. It is well-known that energization results in a surge of inrush current, which contains significant harmonic components, particularly in UHV transformers where the magnetic core exhibits higher nonlinearity compared to lower voltage systems. As highlighted, the abundance of higher-order harmonics during energization further underscores the need for robust protection mechanisms capable of discriminating between normal operating conditions and actual faults. Building upon previous work in the field, this research investigates how varying fault conditions influence harmonic behavior, with a specific focus on second harmonic suppression for differential protection. By modeling a single-phase UHV converter transformer and simulating internal faults and energization events, we aim to enhance the understanding of converter transformer protection schemes and propose optimized parameters for second harmonic blocking in UHV applications.

II. MODELING OF THE UHV TRANSFORMER

2.1. How to Model Internal Faults

Breakers between the primary windings should be considered while simulating UHV converter transformer failures. We can imitate internal failures with the help of these breakers. Equations 1, 2 [16] are used to produce different percentages of windings that short circuit:

$$X_2 + X_3 = X_C \quad (1)$$

$$\frac{X_2}{X_3} = \left(\frac{N_2}{N_3}\right)^2 \quad (2)$$

The leakage reactance of the series winding is defined as where and the leakage reactance of the number two and number three windings and are the turn quantities of the two and three windings, respectively. Figures 1 and 2 depict the basic shape of the UHV converter transformer and the internal fault simulation model [17,18]. It is possible to replicate the turn-to-ground fault with a short-circuit turn ratio larger than 50% and the interturn fault with a turn-ratio shorter than 50% using Figure 2. We may mimic the other ones by shifting the #4 winding in relation to the #2 and #3 windings while maintaining the same locations for the breakers. One end of the #4 winding in this instance is linked to the HV side terminal, while the other end is connected to one end of the #2 winding. We can properly examine the internal defects of the UHV converter transformer because of this configuration [19].

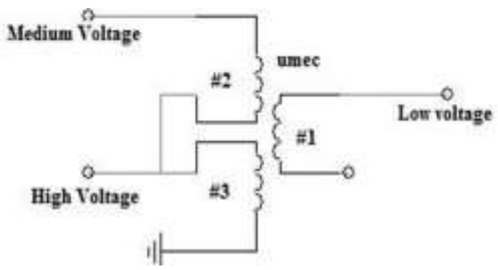

Fig. 1 Basic configuration of the UHV converter transformer.

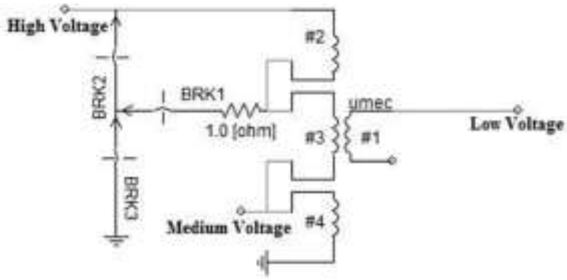

Fig. 2 Internal faults of the converter transformers.

One end of the #4 winding in this instance is linked to the HV side terminal, while the other end is connected to one end of the #2 winding. We can properly examine the internal defects of the UHV converter transformer because of this configuration.

2.2. 30% Internal Fault Simulating

Figure 3 displays 30% fault modeling. As can be observed, this problem involves breakers BRK1 and BRK2, which result in a partial circuit of the number two windings. Thirty percent of the converter transformer's primary windings are disconnected when these two breakers are closed. Results of the harmonics of the fault current and output voltage are displayed in Figure 4 and Figure 5. Differential protection relies heavily on the second harmonic (the green one), as seen in Figure 4, which has a substantially larger quantity than other harmonics. As we discussed in Figure 4, there exist harmonics that may be detrimental to UHV converter transformers, even though Figure 5 shows that the output voltage has not changed significantly [20,21].

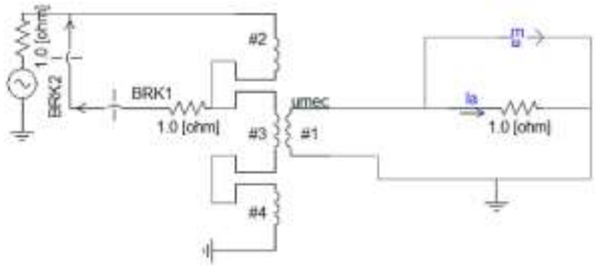

Fig. 3 30% internal fault modeling.

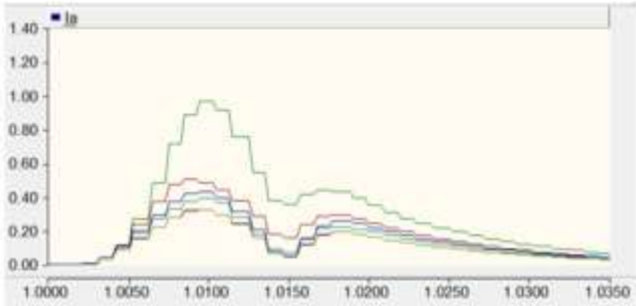

Fig. 4 Harmonics in the case of 30% internal fault.

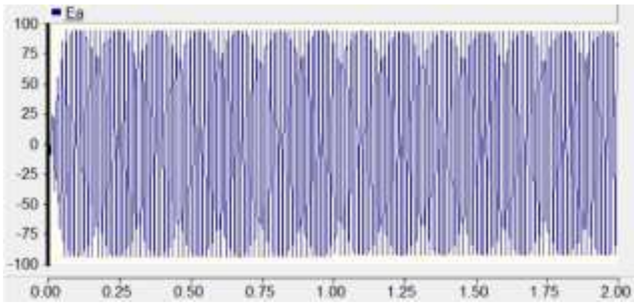

Fig. 5. Output voltage in the case of 30% internal fault.

2.3. 60% Internal Fault Simulating

The 60% internal fault model is shown in Figure 6. 60% of the converter transformer's primary windings are disconnected by shutting BRK1 and BRK3. In this instance, two of the three primary windings short circuits, and Figure 7 shows the associated harmonics that result. The converter transformer's output voltage in the event of an internal 60% failure is seen in Figure 8. Figure 7 shows that harmonics are present following a defect, with the second harmonic having a higher % than the other harmonics. The larger second harmonic in this instance compared to the 30% fault may be the result of additional short circuit windings. However, following the malfunction, the output voltage decreased. The output voltage decreases and its impact following a failure are depicted by the red line. However, following the malfunction, the output voltage decreased. The output voltage decreases and its impact following a failure are depicted by the red line.

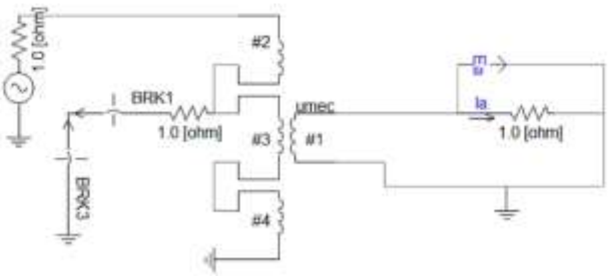

Fig. 6 60% internal fault modeling.

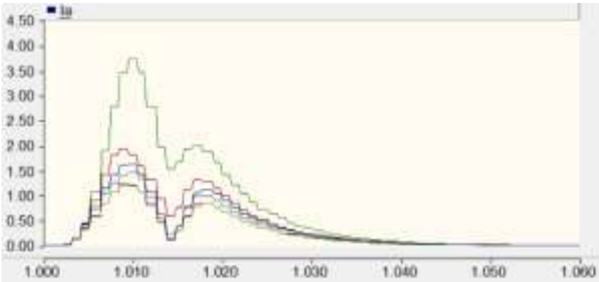

Fig. 7 Harmonics in the case of 60% internal fault.

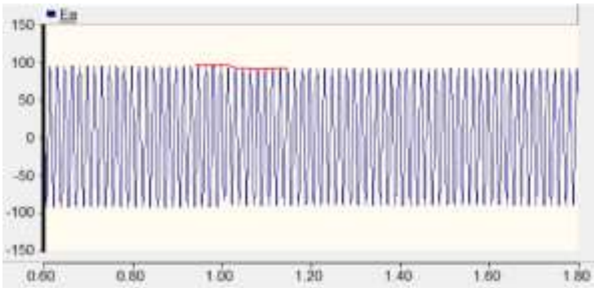

Fig. 8 Output voltage in the case of 60% internal fault.

2.4. Short Circuit to Ground Fault

Another closing combination of the breakers is needed to represent this issue. Therefore, when breakers BRK2 and BRK3 operate simultaneously, a fault is detected, and the primary windings of the transformer are all shorted to ground. Which breakers are involved in this fault scenario is depicted in Figure 9. Figure 10 displays the harmonics in the event of a short circuit to ground fault, whereas Figure 11 displays the output voltage. As can be seen in Figure 10, the second harmonic increases and reaches a greater position than in the other situations we've seen. This might be because there are more windings involved in the short circuit issue. Here, we find a rapid increase of the seventh harmonic vs the previous situations. However, because of the filters that a true grid system would consider, it is not an issue. Figure 11 illustrates how the output voltage nearly drops to zero following a short circuit to ground fault, indicating that there is no output voltage at all.

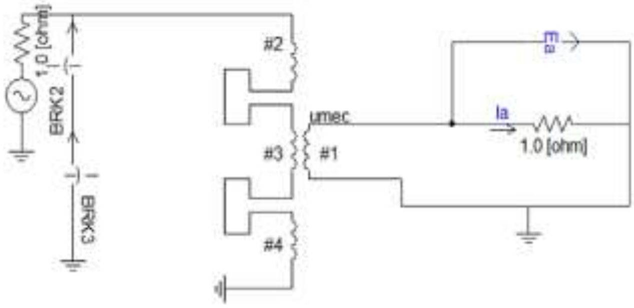

Fig. 9 The short circuit to ground fault modeling of Figure 6.

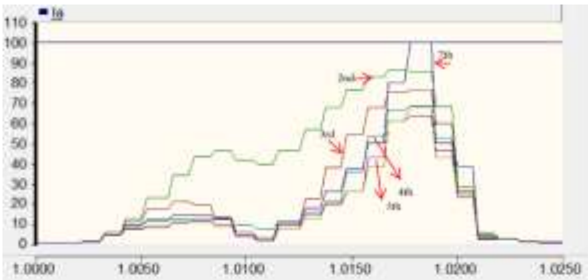

Fig. 10 Harmonics in the case of short circuit to ground fault

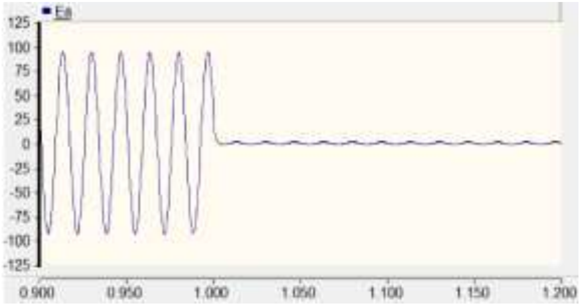

Fig. 11 Output voltage in the case of short circuit to ground fault.

2.5. Energization Simulation

It has been noted that to use second harmonic restraint in protective relay applications, we must evaluate the harmonics—particularly the second harmonic in various faults—and consider their modeling since there exist harmonics during energization. For example, Figure 12 shows how harmonics during energization affect a three-phase UHV converter transformer's output current [8]. As can be observed in Figure 12, in EHV and lower-level systems, the inrush harmonic is more numerous than the converter transformer's, resulting in more atypical waveforms. Energization harmonics are shown in Figure 13. It is evident that there are a lot of higher-order harmonics, particularly the odd harmonics of the UHV converter transformer's inrushes. First, the seventh harmonic has a greater amount than the second harmonic; nevertheless, with time, the second harmonic increases. Compared to the three preceding examples, we have a higher second harmonic content and a quicker rise in all harmonics.

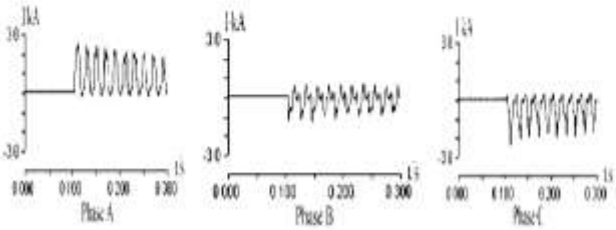

Fig. 12 Magnetic inrush currents in the condition of typical energization, Initial angle of phase A is 0; remnant flux densities of the three phases are all 0.

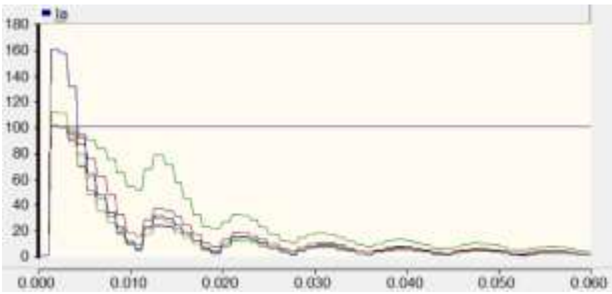

Fig. 13 Harmonic change in the case of energization

III. DISCUSSIONS

Through the process of simulating various internal faults, we discovered that when internal faults increase, so does the quantity of output current, potentially leading to unintended consequences for the system. Figure 14 illustrates the increasing output current during additional fault percentages, as noted by earlier literature [8]. As observed, no matter for interturn short-circuited faults or phase-to-ground faults are short-circuited, the larger the main current is. Numerous sources have reported second harmonics in other % of faults [8]. Therefore, we must provide the percentage of second harmonic suppression for use in differential protection by simulating various internal defects and energization. This sum was given to be 10% in the scenario that was simulated in reference [8], albeit it may be different in other circumstances. Studies reveal that the outcomes are nearly the same with and without a long queue.

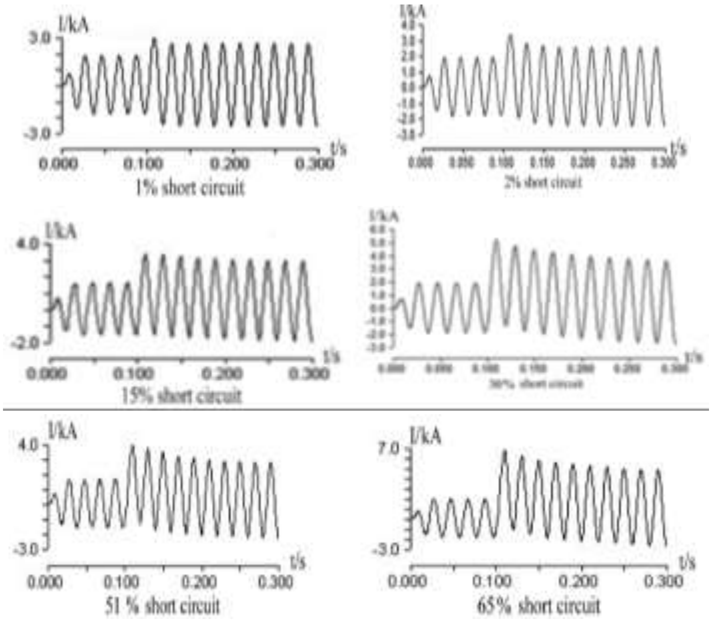

Fig. 14 Phase Currents in the case of internal faults

IV. CONCLUSIONS

Using a benchmark autotransformer model in the EMTDC/PSCAD software environment, this study describes a comprehensive investigation of differential protection for UHV converter transformers. Understanding the harmonic behavior of UHV converter transformers, especially regarding the function of the second harmonic in differentiating between inrush and fault currents, has been made possible by the models for internal faults and energization that have been created. According to the findings, differential protection schemes may be made more reliable by successfully preventing erroneous tripping during energization events with second harmonic suppression. But the study also shows that in some failure conditions, when system performance might be impacted by a protective response delay, changes are required. It is clear from modeling various internal fault severities and harmonic trend analysis that protection reliability may be greatly increased by fine-tuning the blocking levels for second harmonic suppression. The study's conclusions may be used to use UHV converter transformer protection systems throughout both the design and testing stages, thereby enhancing the security and stability of power networks. Inrush and fault current differentiation algorithms will be further refined in future studies, particularly in complex network situations where higher-order harmonics are important.

V. NOMENCLATURES

X_2: Leakage reactance of number two windings
X_3: Leakage reactance of number three windings
X_C: Leakage reactance of the series winding
N_2: turn quantities of number two winding
N_3: turn quantities of number three winding

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