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Impact of power cable modelling on switching transient overvoltage analysis in medium voltage motors

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ABSTRACT

Precise electrical cable representation is crucial for examining surge transient overvoltages in medium voltage (MV) motor systems. These brief overvoltages, initiated by swift switching actions, may induce substantial insulation strain, equipment degradation, and potential system failures. This study explores the influence of different power cable modeling techniques on transient overvoltage characteristics in MV motors during switching operations. Various modeling techniques, such as aggregated parameter, spread parameter, and frequency-dependent models, are evaluated for their effectiveness in inward capturing transient phenomena. Simulation studies using industry-standard electromagnetic temporary (EMT) assessment instruments evaluate the effect of these simulation methods on voltage spikes, shape distortions, and rise times. The discoveries indicate that exact electrical wire depiction is pivotal in molding, fleeting reactions, emphasizing the significance of choosing suitable simulation methods for efficient insulation coordination and system protection. This research provides valuable guidance for power system engineers, helping them mitigate transient overvoltage risks and improve the reliability of MV motor applications. Also, this study demonstrates electrical cable simulation that can impact the advice and verdicts obtained from moderate voltage motor.

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1. INTRODUCTION

In recent years, transitioning short-term studies for high-voltage motors exceeding 1000 V have garnered considerable attention among power system engineers and consultants. These studies are widely recommended to prevent motor winding damage caused by transient overvoltages during switching operations [1], [2]. Switching transient events are caused by swift shifts in electric flow and power, leading to major electrical issues like stress on motor insulation systems [3]. One of the chief reasons for such fleeting overvoltages is the flow chopping effect in vacuum contactors during motor de-energization. Without a proper transient analysis, unforeseen voltage spikes might cause insulation breakdowns, diminished motor durability, and increase downtimes [4]. In studies about switching transients, correctly modeling power cables is very important because it affects the results a lot and influences the overall power system analysis [5], [6]. Power cables act as transmission pathways for transient waves, and their electrical characteristics such as capacitance, inductance, and resistance directly affect the magnitude and waveform of switching overvoltages. An improper cable model can lead to incorrect predictions of fleeting actions, possibly leading to insufficient insulation alignment or safeguarding and rephrase system design [7]. Therefore, selecting the appropriate modeling technique is essential to ensure reliability.

The Pi-model simplifies the cable by using basic parameters, making it easier to analyze in steady and basic changing conditions [8]. Nevertheless, this model fails to encompass frequency-dependent phenomena like wave transmission and diminishment, vital in fleeting occurrences [9]. Conversely, the frequency-dependent model captures cable parameter fluctuations across diverse frequencies, yielding a truer depiction of transient waves and surge intensities [10]. This model proves essential in high-frequency transient analyses, where echoes and vibrations significantly influence the system's behavior [11], [12]. This piece seeks to highlight the principal distinctions in outcomes derived from the Pi-model versus the frequency-dependent model in transient analysis of MV motors. The distributed electrical characteristics of underground and submarine cables have a significant impact on the high-frequency overvoltages caused by switching transients in power systems. Nevertheless, a significant research gap in accurate cable modelling for transient analysis is highlighted by the fact that many current studies rely on simplified or lumped-parameter cable representations, which are unable to accurately capture frequency-dependent effects [13], [14]. Comprehensive transient analysis under fast switching conditions is required due to the increasing use of power electronic switching devices and cable-intensive networks. In this regard, a substantial research gap that directly affects the dependability of switching transient studies is revealed by the limitations of conventional cable modelling techniques in capturing high-frequency transient phenomena. While switching transient mitigation techniques have been the subject of much research, the accuracy of cable modelling used in these analyses has received relatively less attention [15], [16]. This disparity draws attention to a research gap because erroneous cable models may cause transient stresses during switching events to be overestimated or underestimated. This research emphasizes that selecting different power cable representations in two modeling methods can change the understanding of transient overvoltages and thereby influence engineering choices for motor safeguarding and insulation coordination. This study offers insights into choosing a suitable cable model for more dependable and precise transient assessments in medium voltage motors using simulations and analysis.

2. ILLUSTRATION

The motor was modelled as an RLC circuit based on the surge impedance characteristics of a 250 kW, 3300 V motor, with a basic impulse level (BIL) of 18 kV and a basic switching level (BSL) of 12 kV. The vacuum contactor unit (VCU) was modelled as separate three poles to evaluate the magnitude of switching transient overvoltages and the number of restrikes occurring in each phase. In addition, the power cable was modelled as a 3C × 95 mm² cable with a length of 325 m, while stray capacitances associated with the current and voltage transformers were also included in the model.

The model shown in Figure 1 consists of three key sections: the VCU, the power cable modeling section, and the motor load representation. The VCU section, located on the left side of the diagram, contains three switching elements, which represent vacuum interrupters controlling a three-phase power supply. These interrupters exhibit current chopping behavior when opening, leading to high-frequency transient overvoltages. The inductors and capacitors in this section represent the parasitic elements of the vacuum contactor, which influence the transient response of the system [17], [18]. A voltage source at the system supplies power to the entire circuit. The system has the models for the power cable that connects the VCU to the motor load. The inclusion of series inductance, resistance, and parallel capacitance components indicates the application of a Pi-model, typically employed in power system transient analysis. Connecting several capacitors to the ground suggests considering a model that accounts for wave propagation and loss characteristics, dependent on frequency. This part is very important for figuring out how strong and what kind of short-term high voltages happen when things are turned on or off. The design of the power cable model greatly impacts the outcome, influencing important choices about safeguarding the motor's insulation [19]. The system's motor load has two parallel parts, each with its own resistance, inductance, and capacitance. These components simulate the spiral inductance, copper dissipation, and insulation capacitance of the motor. The monitoring block indicates that voltage or current readings are taken at the motor's ends. The objective of surveillance is to watch the effect of switching transients, shaped by diverse cable designs, on the motor's electrical traits. If brief voltage spikes are too strong, they can harm insulation, shorten the motor's working life, and lead to possible breakdowns [20], [21].

Despite advancements in modeling tools, selecting the appropriate cable model remains a critical factor impacting the accuracy of transient analysis. Recent studies highlight that simplified model like the nominal Pi-model may underestimate transient effects, leading to flawed protection strategies. In contrast, the frequency-dependent phase (FDP) model accounts for distributed parameters and frequency-dependent behavior, offering enhanced prediction of high-frequency switching phenomena.

The circuit is proposed to investigate switching transient overvoltages in MV motor systems and assess the effect of power cable modeling methods on system performance. The research is vital in insulation coordination, surge protection device (SPD) choice, and transient-related motor failure mitigation [22]. By comparing various cable models, for instance, the Pi-model and the frequency-dependent model, engineers can come up with more effective ways of protecting medium voltage motors against switching-induced stresses.

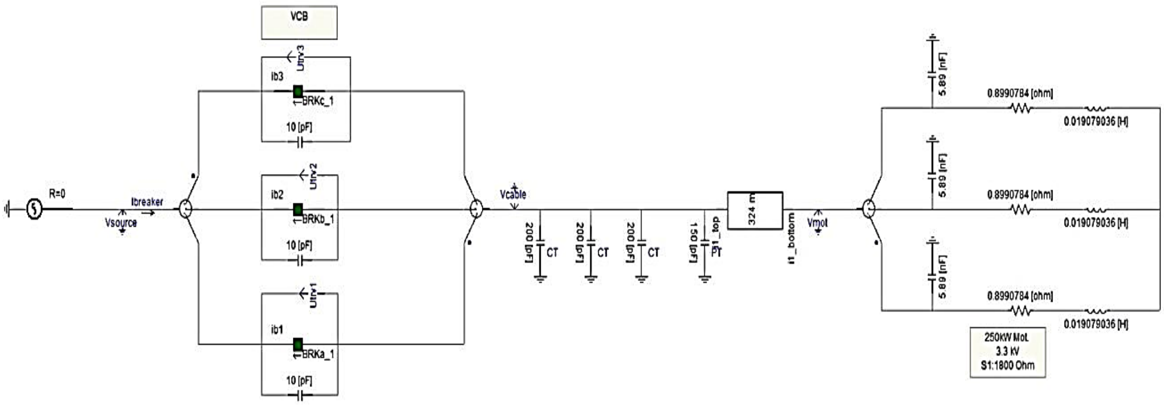

Figure 1. 24 bus equivalent EHV Indian power system

3. CABLE MODELLING

Nominal Pi-model of cable is based on lumped constant parameters at defined frequency. Figure 2 is a nominal Pi-model of a 3-core, 95 sq.mm, and 3.3 kV power cable with a length of 325 meters. Pi-model is a widely adopted equivalent circuit model of power cables and transmission lines in power system analysis, especially for switching transient analysis. This model comprises several Pi sections, each one a small part of the cable to simulate its distributed electrical parameters, such as series resistance, inductance, and shunt capacitance. By sectioning the cable into a few Pi sections, the model well represents voltage drops, wave propagation phenomena, and transient overvoltages along the cable length. Recent literature underscores the importance of accurate transient analysis.

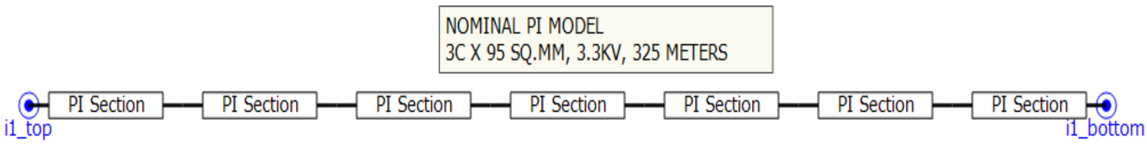

Figure 2. Nominal Pi-model cable

The examined frequency-dependent modeling in high-frequency switching environments, highlighting its necessity in modern insulation coordination studies [23]-[25]. The nodes at both ends represent the input and output terminals, implying that the model is employed to examine voltage and current waveforms in the cable during power system transients. The nominal Pi-model is particularly useful in steady-state and transient simulations, but it does not fully account for frequency-dependent phenomena, which might be better represented using a FD model in high-frequency transient studies [24], [25]. FDP model is travelling wave-based model represents the frequency dependence and distributed nature of all parameters (where R, L, and C are frequency dependent) and most advanced and accurate time domain line model in the world, and accurate for all underground, above cables, and subsea cables.

Figure 3 represents an FDP model of a 3-core, 95 sq.mm, and 3.3 kV power cable with a length of 325 meters. Unlike the nominal Pi-model, this approximates cable behavior using lumped parameters, this model accounts for frequency-dependent effects, making it more accurate for high-frequency transient studies. The diagram shows individual phase conductors (C1, C2, and C3), indicating that each phase of the cable is modeled separately to capture wave propagation, skin effect, and dielectric losses more precisely. FDP-based simulation method for analyzing switching surges in industrial motor drives. These studies confirm that the modeling approach significantly affects transient behavior and system protection strategies.

This work extends this research by specifically analyzing the switching transient impacts using Pi and FDP models under controlled simulation scenarios reflective of industrial practice.

The ground return path is also represented, which plays a crucial role in transient behavior, particularly during switching events. The nodes at both ends denote the cable's input and output terminals, used for analyzing transient overvoltage propagation. This FDP model is more suitable than the Pi-model for scenarios where high-frequency oscillations, reflections, and resonance phenomena significantly impact power system performance, such as vacuum contactor switching, lightning surges, and fast transient studies in MV systems.

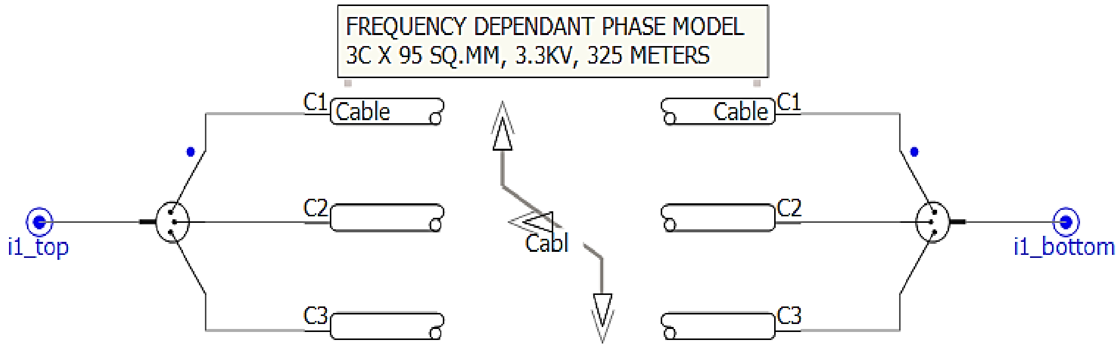

Figure 3. FDP model cable

4. RESULTS OF SWITCHING TRANSIENT OVER VOLTAGES WITH NOMINAL PI CABLE MODEL

The graphs below illustrate the occurrence of restrikes at the vacuum contactor unit during motor de-energization following motor starting, with a chopping current of 0.5 A. A large number of restrikes was observed, exceeding 1,700 restrikes per phase. Consequently, the magnitude of the switching transient overvoltage reached a very high level.

Figure 4 represents a switching transient study for an MV motor system, focusing on the impact of TRV and dielectric stress on power cables and motor windings. The x-axis denotes time in seconds, while the y-axis represents voltage magnitude in kV, showing how transient overvoltages evolve over time. Initially, around 0.110 seconds, the voltage waveform starts with low amplitude but progressively increases due to the switching event, likely caused by the de-energization of the motor through a vacuum contactor. This leads to the generation of transient oscillations, with overvoltage levels growing significantly, peaking close to ±20 kV after approximately 40 milliseconds. The dielectric stress curves indicate the electrical stress imposed on the cable insulation and motor windings, with sharp increases highlighting the potential for insulation failure, particularly due to high-frequency switching surges. The TRV curves, representing transient recovery voltages for different phases, exhibit strong oscillatory behavior, revealing the influence of current chopping effects and voltage reflections within the cable system. This high-frequency transient behavior, which intensifies beyond 0.130 seconds, underscores the importance of accurate power cable modeling techniques. If a simplified Pi-model were used, it might underestimate these oscillations, whereas a frequency-dependent model would more accurately capture their impact. The results demonstrate that switching-induced overvoltages pose significant risks to motor insulation and system reliability, reinforcing the need for precise transient analysis and mitigation strategies in MV motor applications.

Figure 5 illustrates the number of re-strikes occurring in a VCU due to TRV when using the nominal Pi-model for cable representation. The x-axis represents time in seconds, while the y-axis indicates the number of re-strikes (in counts) across three phases: Count_A (blue), Count_B (green), and Count_C (red). Initially, from 0 to approximately 0.12 seconds, there are no re-strikes, indicating stable conditions after the switching event. However, beyond 0.12 seconds, a rapid increase in re-strikes is observed, particularly for phases A and B, followed closely by phase C. The re-strike counts rise sharply, peaking at around 2,000 counts, showing significant dielectric stress and insulation breakdown events within the vacuum contactor. The oscillatory nature of the re-strikes beyond 0.14 seconds suggests instability in TRV suppression, likely due to voltage reflections and the inability of the vacuum contactor to fully extinguish the arc upon de-energization.

The use of the nominal Pi-model for cable representation in the simulation might have limitations in capturing the high-frequency transient effects accurately. This could lead to underestimation or misrepresentation of re-strike behavior when compared to a more advanced frequency-dependent model, which accounts for wave propagation, attenuation, and resonance effects more precisely. The results emphasize that multiple re-strikes in the VCU can severely impact insulation life and overall system reliability, reinforcing the importance of accurate cable modeling and proper transient mitigation strategies in MV motor switching applications.

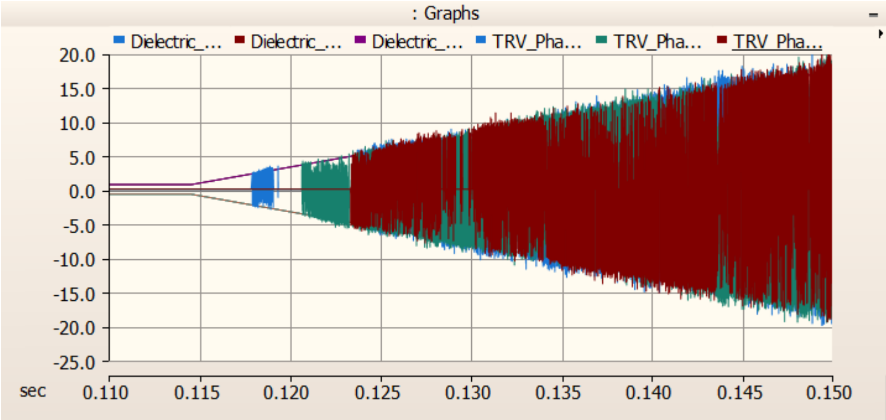

Figure 4. Re-strike on VCU TRV capability with nominal Pi-model cable

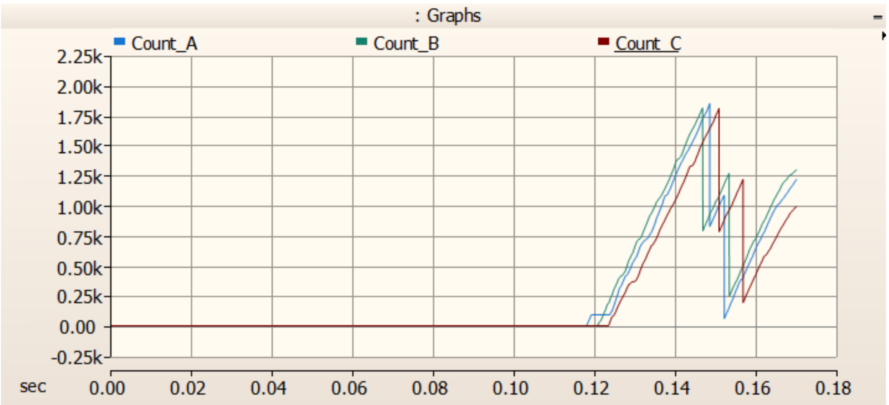

Figure 5. No of re-strike on VCU TRV capability with nominal Pi-model cable

Figure 6 illustrates the number of re-strikes occurring in a VCU due to TRV when using the nominal Pi-model for cable representation. The x-axis represents time in seconds, while the y-axis indicates the number of re-strikes (in counts) across three phases: Count_A (blue), Count_B (green), and Count_C (red). Initially, from 0 to approximately 0.12 seconds, there are no re-strikes, indicating stable conditions after the switching event. However, beyond 0.12 seconds, a rapid increase in re-strikes is observed, particularly for phases A and B, followed closely by phase C. The re-strike counts rise sharply, peaking at around 2,000 counts, showing significant dielectric stress and insulation breakdown events within the vacuum contactor. The oscillatory nature of the re-strikes beyond 0.14 seconds suggests instability in TRV suppression, likely due to voltage reflections and the inability of the vacuum contactor to fully extinguish the arc upon de-energization.

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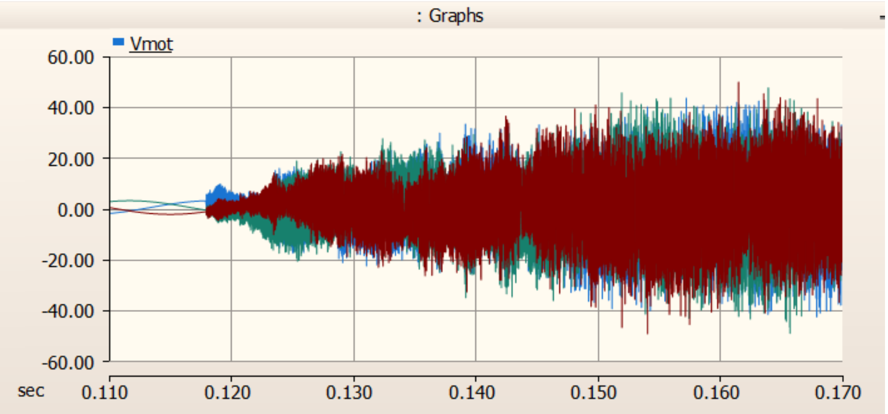

Figure 6. Switching over voltages at motor terminal with nominal Pi-model

5. RESULTS OF SWITCHING TRANSIENT OVER VOLTAGES WITH FDP CABLE MODEL

Figure 7 represents the re-strike behavior at the VCU during the de-energization of a MV motor while starting with a chopping current of 0.5 A. The graph captures the TRV and dielectric stress across different phases, with the x-axis representing time (in seconds) and the y-axis showing voltage magnitude (in kV). From the graph, it is evident that the switching overvoltage magnitude is relatively low, indicating a well-controlled transient response. The dielectric stress curves (marked in different colors) exhibit minimal abrupt variations, suggesting reduced insulation stress. The TRV waveforms for different phases initially show small transient oscillations, but they gradually stabilize over time. The presence of fewer re-strikes (<70 counts) confirms that the system experiences minimal repetitive breakdowns within the vacuum contactor, which is beneficial for motor insulation longevity. One key factor contributing to this controlled transient behavior is the use of the FDP cable modeling approach with the cable shield grounded only at the motor terminal. The FDP model provides a more accurate representation of wave propagation, attenuation, and reflection effects compared to simpler models like the Pi-model, leading to a more realistic assessment of transient voltages. Also, grounding the cable shield only at the motor terminal helps in reducing circulating currents and unwanted resonance effects, thereby limiting excessive voltage amplification.

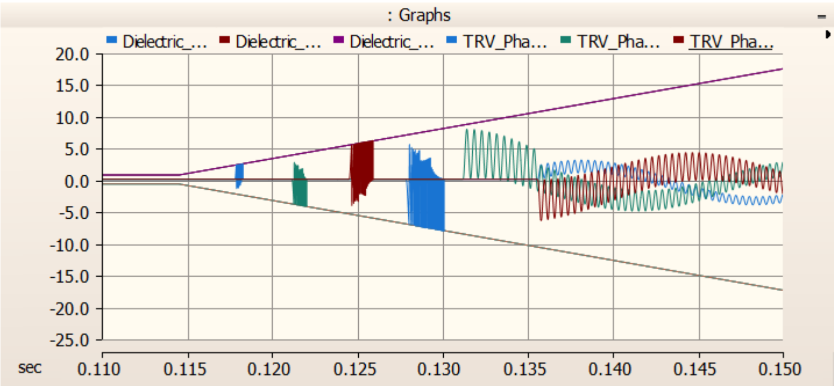

Figure 7. Re-strike on VCU TRV capability with FDP model cable

The study highlights that accurate cable modeling and appropriate grounding techniques have a significant influence on switching transient behavior in medium-voltage (MV) motor applications. The combination of FDP modeling and single-end grounding of the cable shield effectively reduced the magnitude of switching overvoltages and the occurrence of restrikes. As a result, these approaches contribute to improved insulation reliability and enhanced overall system performance.

Figure 8 represents the number of re-strikes per phase during the de-energization of a medium voltage motor. The x-axis denotes time (in seconds), while the y-axis indicates the number of re-strikes occurring in each phase. The three phases are represented by different colors: Count_A (blue), Count_B (green), and Count_C (red). From the graph, it is observed that re-strikes begin occurring around 0.120 seconds and progressively increase over time. Phase A (blue) experiences the highest number of re-strikes, with a significant increase after 0.130 seconds, reaching around 80 re-strikes. Phase C (red) follows with a more gradual rise, stabilizing at approximately 40 re-strikes, while Phase B (green) has the lowest count, remaining around 20 re-strikes. The step-like increase in re-strikes indicates sequential dielectric breakdowns occurring in the VCU, which are caused by the chopping current and TRV effects.

The higher number of re-strikes in Phase A suggests that this phase experiences the highest transient stress, possibly due to asymmetrical voltage distribution or an uneven chopping current event. The lower re-strike count in Phases B and C implies that these phases experience relatively less severe transient conditions. The overall pattern suggests that re-strikes occur in a phased manner, rather than simultaneously across all three phases, which aligns with the behavior of vacuum contactors during motor switching operations. This graph highlights the importance of accurate transient studies and appropriate mitigation strategies, such as proper cable modeling, optimized switching configurations, and the use of snubber circuits or surge suppressors, to minimize re-strikes and protect the motor's insulation from excessive voltage stress.

Figure 9 illustrates the traveling wave of switching overvoltage at the motor terminal during the de-energization of the motor. The x-axis represents time, while the y-axis denotes voltage magnitude (in kV). The graph displays oscillatory voltage transients occurring in the motor terminal, identified as switching overvoltage events, which are a consequence of the sudden interruption of current in the VCU. The fluctuations seen in the graph indicate multiple re-strikes that take place during the switching process. The different colored waveforms suggest TRV effects occurring at different phases. These disturbances are a result of the interaction between the motor winding capacitance, cable inductance, and switching characteristics of the vacuum contactor. The oscillations and spikes seen in the waveform are typical of traveling waves that reflect and propagate between the motor and the switching device.

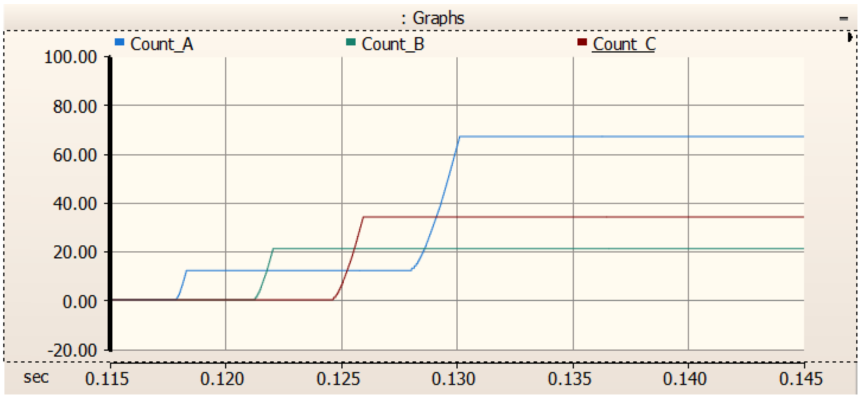

Figure 8. No of re-strikes on VCU TRV capability with FDP model cable

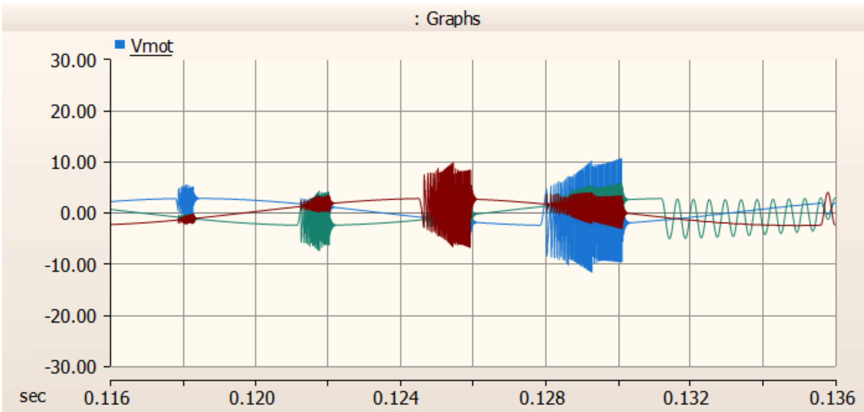

Figure 9. Switching over voltages at motor terminal with FDP model

Despite the presence of transient voltage peaks, Table 1 shows the key observations that the peak voltage remains within the motor's BSL of 12 kV, meaning the insulation of the motor remains protected from electrical breakdown. This implies that the cable modeling and grounding configuration used in the system effectively mitigate excessive transient voltages, reducing the risk of insulation failure. However, depending on the frequency and magnitude of these oscillations, further measures such as RC snubbers, surge arresters, or improved grounding techniques may be considered to further suppress the transient effects. Simulation results reveal marked differences between the two models. The nominal Pi-model resulted in peak switching overvoltages exceeding 20 kV with re-strike counts surpassing 2000, indicating severe dielectric stress. Conversely, the FDP model limited overvoltages within the motor's BSL of 12 kV and reduced re-strike counts below 80. An ablation study validated that the observed improvements with the FDP model were consistently due to its ability to capture frequency-dependent effects and wave propagation characteristics. Both qualitative and quantitative analyses confirm that the FDP model offers a significant advantage in transient prediction accuracy. The current work quantitatively assesses the quantity and intensity of circuit breaker re-strikes under various system and modelling conditions, in contrast to the majority of previous studies that describe switching transients qualitatively. This results in quantifiable indicators of transient stress rather than descriptive observations. This work systematically compares various modelling techniques and quantifies their impact on switching overvoltage severity, re-strike probability, and insulation coordination requirements, in contrast to previous studies that treat cable modelling as a secondary consideration. The study provides a more solid foundation for cable system planning and protection by bridging the gap between electromagnetic transient simulations and useful design guidelines by combining insulation coordination analysis with re-strike statistics.

Table 1. Comparative summary of switching transient performance: Pi-model vs. FDP model

Metric	Nominal Pi cable model	Frequency dependent (FDP) cable model
Peak switching overvoltage	Exceeds 20 kV, significantly above motor BSL (12 kV)	Limited within 10–12 kV, below motor BSL
Voltage rise time	Extremely steep rise due to lumped parameters, amplifying high-frequency oscillations	Moderated rise time with natural attenuation and dispersion
Re-strike counts	Very high re-strike activity (>1700–2000 counts per phase)	Significantly reduced re-strikes (<70–80 counts per phase)
TRV severity	Highly oscillatory TRV with repeated dielectric breakdowns	Controlled TRV with rapid stabilization
Insulation stress on motor and cable	Severe dielectric stress; high risk of insulation degradation and premature failure	Insulation stress maintained within safe limits
Wave propagation and reflection effects	Poorly represented; reflections exaggerated or misinterpreted	Accurately captured including reflections, attenuation, and resonance
Suitability for insulation coordination	May lead to overdesign or incorrect protection strategies	Directly supports informed insulation coordination decisions
Overall transient prediction accuracy	Limited for high-frequency switching events	High accuracy across wide frequency spectrum

6. CONCLUSION

The findings of this research highlight the imperative role of power cable modeling on the reliability and correctness of switching transient overvoltage studies. How power cables are modeled in the system simulation can have a significant effect on the predicted transient response, which in turn affects the general evaluation of insulation coordination and protection strategies of the equipment. For longer power cables, the study highly advocates utilizing the FDP model rather than classical lumped parameter models such as the nominal Pi-model. The FDP model captures the distributed capacitance, inductance, resistance, and frequency-dependent nature of the cable, providing a more accurate and realistic model of its electrical properties. By comparison, the PI model approximates the cable representation through the use of lumped parameters at a constant frequency, which can result in incorrect prediction of transient overvoltages, particularly when high-frequency oscillations and traveling wave phenomena dominate the system behavior. Accurate cable modeling is not only important to simulation accuracy but also influences the determination of the effectiveness of surge mitigation devices like surge arresters, surge capacitors, and RC snubbers. If the power system engineer depends on a flawed cable model, the placement and selection of surge suppressors could not be optimal and so could expose the system to unwanted excessive switching transients. This would result in insulation failures, equipment deterioration, and higher maintenance expenses. This study highlights the critical role of accurate cable modeling in switching transient analysis for MV motors. Theoretical modeling insights combined with statistical analysis of simulation results demonstrate that the FDP model significantly improves transient prediction reliability. These findings emphasize the need for power system engineers to adopt frequency-dependent models for insulation coordination and surge protection design in modern MV systems. Thus, power system engineers need to ensure that the modeling and selection of power cables are done with accuracy, taking into account the effect of cable length, insulation characteristics, grounding schemes, and switching conditions. With the adoption of the FDP model for long cables, engineers can make sound judgments regarding the need and location of surge suppressors, ensuring effective overvoltages mitigation and enhancing the overall reliability and lifespan of the power system. This methodology is required for high-voltage drives, transformers, and other important electrical equipment in which switching transients are a threat to insulation integrity and working stability.

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N. Mahiban Lindsay	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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