

Article

High-Frequency Modeling and Sensitivity Evaluation of Motor Terminal Overvoltage in Long-Cable PMSM Variable Frequency Drive Systems

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Abstract

Long-distance variable frequency drive (VFD) systems are widely used in mining and water transport applications, yet motor terminal overvoltage remains a major reliability risk when inverters and motors are separated by long cables. This study examines a mining submersible pump permanent magnet synchronous motor (PMSM) drive. Cable distributed parameters were extracted with Ansys Q2D Extractor, and a wideband simulation model was built in MATLAB/Simulink. To ensure modeling accuracy, the wideband transmission line model was calibrated and validated using a 20 m cable VFD experimental platform, demonstrating an excellent agreement with a peak voltage relative error of only 2.56%. Parametric simulations were used to quantify the effects of cable length, pulse width modulation (PWM) pulse rise time, and cable cross-sectional geometry on normalized motor terminal overvoltage. Cable length and pulse rise time were the dominant factors governing overvoltage severity. Minor changes in conductor radius or spacing produced only limited changes in peak overvoltage. These findings support EMC-oriented design priorities for long-line VFD systems, with emphasis on cable routing and inverter dv/dt coordination rather than fine cable-geometry tuning alone.

Keywords: long-distance cable; variable frequency drive; overvoltage; transmission line theory; traveling wave reflection; permanent magnet synchronous motor



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1. Introduction

VFDs are widely used in mining, pipeline transport, hydraulic pumping, and in situ leaching uranium extraction. In these applications, efficient speed control is often essential for safe and stable operation [1,2].

However, constrained by harsh site environments or safety isolation requirements against explosion, the power source (inverter) and the actuator (motor) often cannot be arranged in close proximity. Instead, power transmission must be executed via long-distance cables stretching hundreds or even thousands of meters [3,4]. While this “inverter-long cable-motor” drive system offers spatial layout flexibility, it introduces non-negligible electromagnetic compatibility (EMC) issues in power electronics. Modern inverters commonly utilize high-speed switching devices, such as Insulated Gate Bipolar Transistors (IGBTs), whose output PWM waveforms exhibit high switching frequencies and extremely steep rising edges (i.e., substantial dv/dt) [5]. When such high-frequency PWM voltage

pulses are injected into a long cable, the high-frequency harmonic energy escalates sharply as the voltage rise time shortens [6]. Consequently, the corresponding electromagnetic wavelength reduces to a scale comparable to the geometric length of the cable. Under these circumstances, the traditional concentrated-parameter circuit model is no longer applicable, and the long cable should be strictly treated as a distributed-parameter transmission line model composed of distributed inductance, distributed capacitance, conductance, and resistance [7].

As high-frequency pulses propagate along the cable, traveling-wave theory governs reflection at the motor terminal [8]. Because the motor presents a much higher input impedance than the cable at high frequency, a severe impedance mismatch can occur [9]. Superposition of incident and reflected waves may therefore produce elevated terminal voltage spikes. Under strong reflection conditions, the peak value may approach approximately twice the inverter DC bus voltage. Such overvoltage may accelerate insulation stress and partial discharge, and thus threatens long-distance VFD reliability [10].

Previous studies on long-line VFD systems have examined traveling-wave reflections, PWM switching effects, and distributed cable parameters. In particular, the application of fast-switching inverters introduces high-frequency transient excitation and non-uniform voltage distribution, which serves as a critical factor in long-distance system modeling [11]. Furthermore, when long cable distributed properties are integrated with line-end filters, the systemic resonant characteristics and network transfer behaviors drastically complicate the full-system modeling accuracy [12]. Later work showed that skin effect, proximity effect, and dielectric loss can further distort transient waveforms at high frequency. As a result, multi-dimensional electromagnetic coupling has become an active topic in motor overvoltage research.

However, three gaps remain in the current literature. First, long-cable overvoltage studies still focus mainly on induction motors, whereas mining submersible pump PMSM drives are comparatively under-reported. Second, many models rely on simplified or fixed cable parameters rather than geometry-dependent extraction from the actual three-core flat cable. Third, cable length, pulse rise time, and cross-sectional geometry have rarely been compared quantitatively within one PMSM long-cable simulation framework.

To address these gaps, this paper studies a mining submersible pump PMSM drive with a long three-core flat cable. A collaborative simulation-experimental methodology is proposed: geometry-dependent distributed parameters are extracted via ANSYS Q2D Extractor (version 2024 R1), considering high-frequency effects, a system-level wideband model is constructed in MATLAB/Simulink (version R2023b), and its accuracy is rigorously calibrated using a 20 m VFD experimental platform. The main contributions of this paper are summarized as follows:

1. Methodological framework: A validated, high-fidelity modeling and verification workflow that explicitly links analytical cable cross-sectional geometry with system-level transient overvoltage behavior.
2. Experimental calibration: Rigorous validation of the wideband transmission line model against a physical 20 m VFD platform, achieving a peak voltage relative error of merely 2.56%, which ensures the reliability of long-cable parametric extrapolations.
3. Parametric sensitivity evaluation: A comprehensive evaluation and relative sensitivity evaluation of overvoltage factors, identifying PWM pulse rise time and cable length as the dominant operational drivers over fine cable-geometry tuning.

The remainder of this paper is organized as follows. Section 2 establishes the simulation modeling of the long-distance VFD system, detailing the high-frequency distributed-parameter cable model, overall system construction, and its experimental calibration and validation. Section 3 presents the parametric simulation results of motor terminal overvolt-

age under varying cable lengths, pulse rise times, and cross-sectional geometries. Section 4 provides an in-depth discussion on the wave reflection mechanisms, parameter sensitivity evaluation, comparisons with prior literature, engineering implications, and limitations. Finally, Section 5 summarizes the main conclusions of this study.

2. Simulation Modeling of Long-Distance VFD Systems

2.1. High-Frequency Distributed-Parameter Modeling of Long-Distance Cables

The simulation system for a long-distance VFD mainly consists of a long cable model, a control and inverter unit, and a motor model. To accurately simulate wave propagation processes, the effects of the cable's distributed transmission line parameters should be taken into account. Therefore, it can be equivalent to a transmission line model coupled by multiple segments of distributed resistance, distributed inductance, distributed conductance (which is usually neglected), and distributed capacitance. Because the cores of a three-phase cable are closely spaced, their mutual electromagnetic coupling is highly significant [7]. Consequently, besides self-resistance (R_0), self-inductance (L_0), and capacitance to ground (C_0), the distributed parameters must also account for the presence of mutual impedance (R_M), mutual inductance (L_M), and mutual capacitance (C_M), as shown in Figure 1.

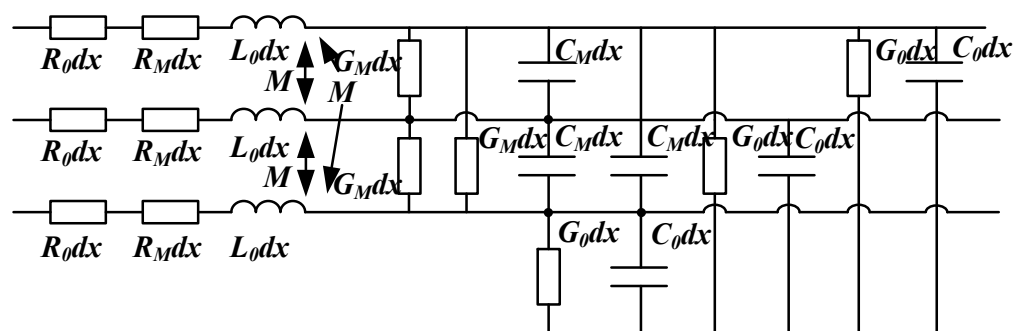


Figure 1. Infinitesimal equivalent circuit of three-phase-to-ground coupled transmission lines.

Therefore, its distributed parameters per unit length can be represented by the following square matrices, where R_{ii} , L_{ii} , and C_{ii} denote the self-resistance, self-inductance, and self-capacitance of the conductors, respectively. The off-diagonal terms R_{ij} , L_{ij} , and C_{ij} ($i \neq j$) represent the mutual parameters between phases. Note that the non-diagonal elements in the Maxwell capacitance matrix $[C]$ are inherently negative values representing the mutual coupling capacitances:

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \quad (1)$$

$$L = \begin{bmatrix} L_{11} & M_{12} & M_{13} \\ M_{21} & L_{22} & M_{23} \\ M_{31} & M_{22} & L_{33} \end{bmatrix} \quad (2)$$

$$C = \begin{bmatrix} C_{10} + C_{12} + C_{13} & -C_{12} & -C_{13} \\ -C_{21} & C_{20} + C_{21} + C_{23} & -C_{23} \\ -C_{31} & -C_{32} & C_{30} + C_{31} + C_{32} \end{bmatrix} \quad (3)$$

Based on the cross-sectional geometric parameters of the actual flat cable, the finite element analysis software ANSYS Q2D Extractor was utilized to extract its per-unit-length distributed parameters [13]. For reproducibility, the Q2D extraction setup is summarized

as follows. A 2D cross-section of the actual flat three-core cable was modeled in a 1:1 scale within the simulation environment, as illustrated in Figure 2. The structural geometric parameters, including the copper conductor radius, conductor spacing, and insulation layer thickness, were fully determined by the technical specifications provided by the manufacturer [14]. The model comprehensively includes copper conductors, PVC insulation, and rubber sheath. To ensure simulation accuracy, the electromagnetic material properties—specifically the relative permittivity and electrical conductivity for each region—were carefully assigned in strict accordance with the values obtained from the official cable datasheets, which are summarized in Table 1.

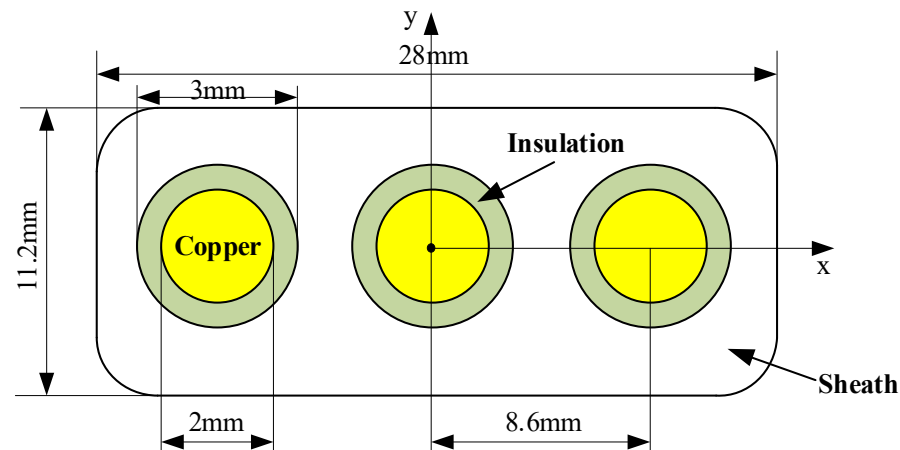


Figure 2. Cross-sectional geometric structure and element placement of the flat three-core cable.

Table 1. Material constants of the flat cable components used in the simulation.

Cable Component	Relative Permittivity	Relative Permeability	Bulk Conductivity	Dielectric Loss Tangent
Conductor (Copper)	1	0.999991	58,000,000	0
Insulation layer (PVC)	2.7	1	0	0.007
Sheath (Rubber)	6	1	0	0

AC resistance and inductance were solved in the magnetostatic/eddy-current solver, whereas capacitance was solved in the electrostatic solver (Figure 3). Consequently, the per-unit-length distributed parameter matrices for resistance (R), inductance (L), and capacitance (C) were obtained, whereas the cable dielectric conductance (G) was neglected because its contribution to the transient peak overvoltage is completely negligible relative to R , L , and C within the studied wideband spectrum.

Due to the skin and proximity effects, the per-unit-length distributed parameters of the cable exhibit significant frequency dependence. To construct a cable model suitable for PWM drive simulation, a simplified approach based on the dominant frequency is adopted, where the distributed parameter values near the inverter carrier frequency ($f_c = 5000$ Hz) are selected as the fixed parameters for the cable equivalent model. This selection represents the dominant spectral component of the steady-state PWM excitation. While the transient overvoltage is also influenced by higher-frequency content excited by the pulse rise time t_r , this fixed-parameter approach serves as a computationally efficient engineering approximation for system-level VFD evaluation. The extracted Distributed

Maxwell parameter matrices of the cable, including resistance (Ω/m), inductance ($\mu\text{H}/\text{m}$), and capacitance (pF/m), are presented as follows:

$$R = \begin{bmatrix} 0.00205 & 0.00013 & 0 \\ 0.00013 & 0.00214 & 0.00013 \\ 0 & 0.00013 & 0.00205 \end{bmatrix} \quad (4)$$

$$L = \begin{bmatrix} 1.08838 & 0.75870 & 0.62865 \\ 0.75870 & 1.08408 & 0.75870 \\ 0.62865 & 0.75870 & 1.08838 \end{bmatrix} \quad (5)$$

$$C = \begin{bmatrix} 74.48500 & -59.01015 & -9.54460 \\ -59.01015 & 121.18548 & -59.01015 \\ -9.54460 & -59.01015 & 74.48500 \end{bmatrix} \quad (6)$$

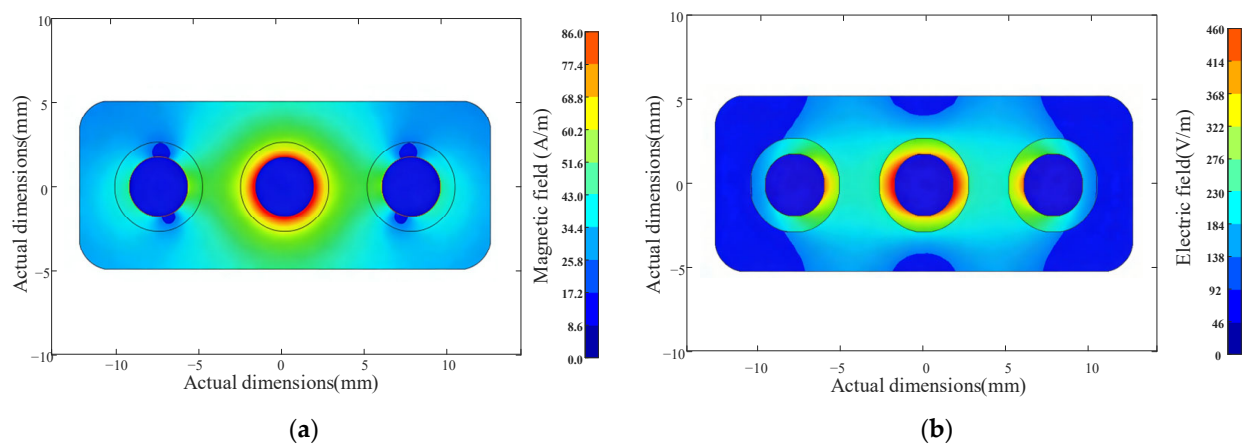


Figure 3. Finite element simulation diagrams of magnetic and electric field distribution: (a) AC resistance and inductance are calculated in the magnetic field; (b) mutual capacitance is calculated in the electrostatic field.

Transmission lines possess distributed characteristics, with their resistance, inductance, conductance, and capacitance continuously distributed along the entire line [15]. When approximating this with lumped π -type equivalent circuits, a discrete circuit is effectively used to approach a continuous system. The accuracy of this approximation depends on the length of each equivalent circuit segment; specifically, the length of a single-segment π -type equivalent circuit should typically not exceed one-tenth of the wavelength corresponding to the highest frequency in the transmitted signal. Based on this criterion, when the length of a single-segment π -type equivalent circuit is 5 m, the model maintains high accuracy across a frequency range of up to 6 MHz, thereby achieving an accurate simulation of transmission line characteristics over a wide frequency band. Figure 4 illustrates the transmission line simulation model used to simulate a 20 m-long cable via four segments of π -type equivalent circuits:

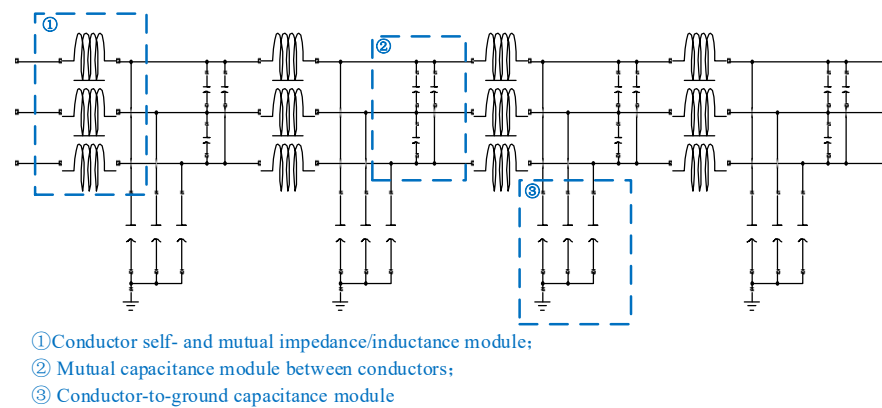


Figure 4. Simulation model of the 20 m transmission line.

2.2. Construction of the Overall VFD System Simulation Model

Taking the permanent magnet synchronous motor for mine submersible pumps as the research object, the modeling is carried out using the built-in Permanent Magnet Synchronous Machine block in the MATLAB/Simulink environment. This module is constructed based on the mathematical model of the motor in the dq-axis coordinate system and is suitable for vector-control-based system simulation. The relevant motor parameters are listed in Table 2. However, it does not explicitly resolve a separate high-frequency terminal impedance network. In the present study, the motor therefore acts mainly as a high-impedance termination in the traveling-wave path. Future work may incorporate a high-frequency equivalent circuit or measured terminal impedance data to improve the prediction of reflection coefficients at the motor end.

Table 2. Electrical and structural parameters of permanent magnet synchronous motors.

Electrical Parameters	Value	Motor Structure Parameters	Value
Power	15 kW	d-axis inductance	0.9966 mH
Fundamental frequency	250 Hz	q-axis inductance	2.3774 mH
Rated voltage	380 V	Stator resistance	0.212 ohm
Rated current	26.8 A	Back EMF waveform	Sine wave
Rated speed	5000 r/min	Number of pole pairs	3

The simulation model of the long-distance variable frequency drive (VFD) system is illustrated in Figure 5. The system utilizes Space Vector Pulse Width Modulation (SVPWM) to achieve precise closed-loop control of the motor's speed and torque. To establish a baseline for parametric analysis, the default system configuration consists of a DC bus voltage of 500 V, an inverter carrier frequency of 5 kHz, and a PWM pulse rise time $t_r = 0.1 \mu\text{s}$. After running the simulation, the model achieves stable closed-loop motor control, maintaining the motor at its rated speed under a constant torque load [12,16].

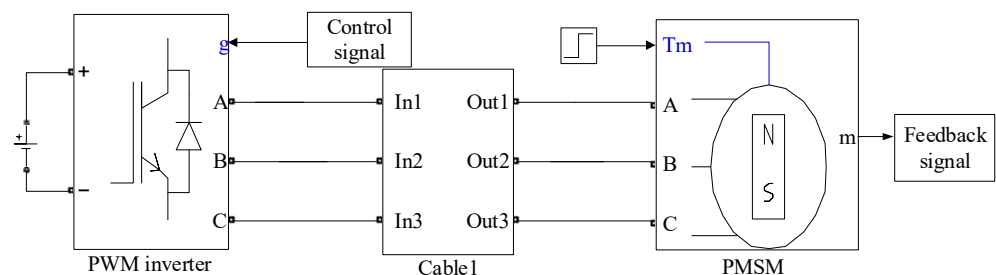


Figure 5. Simulation model of the long-distance VFD system, where the cable module corresponds to the segmented transmission-line model in Figure 4 (with A, B, and C representing the three phases).

2.3. Experimental Calibration and Model Validation

To verify the accuracy of the proposed wideband transmission line model and simulation framework, a 20 m cable VFD experimental platform was utilized for model calibration (as shown in Figure 6). The experimental setup primarily consists of a three-phase inverter (Danfoss VLT series, with the DC bus voltage set to 500 V), a single-layer loosely coiled 20 m three-core flat cable, and a 15 kW PMSM, matching the critical parameters listed in Table 1. The motor terminal overvoltage waveforms were captured using high-voltage differential probes and a digital oscilloscope with a high sampling rate.

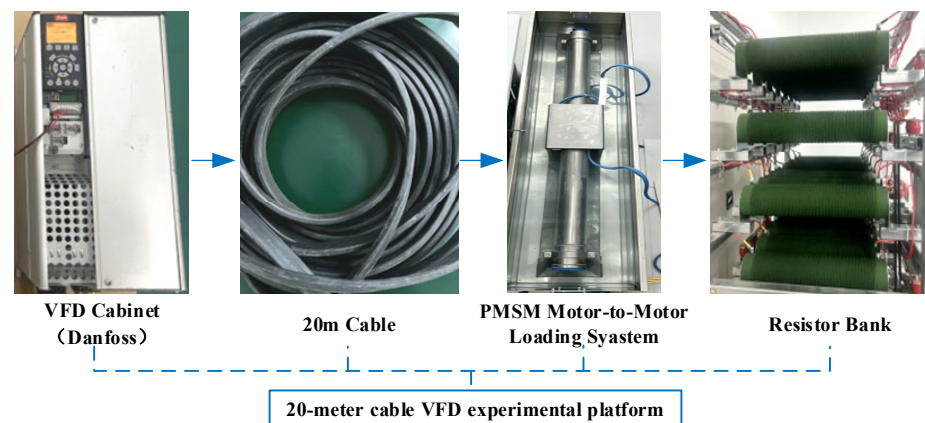


Figure 6. Physical configuration of the 20 m cable VFD experimental platform for model validation.

The experimentally measured motor terminal voltage waveform was compared with the simulation result at a cable length of 20 m. The comparison indicates that the simulated prediction matches the experimental observation well in terms of the primary transient trend and especially the peak characteristics (as shown in Figure 7).

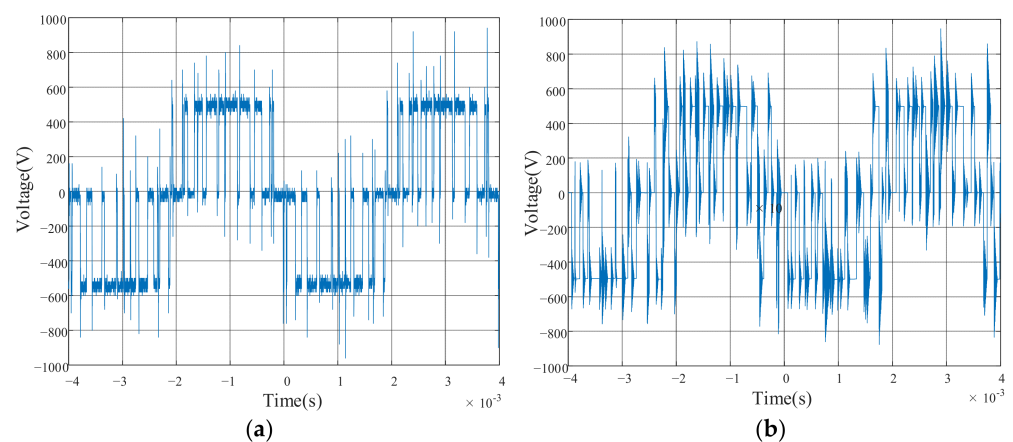


Figure 7. Comparison between simulated and experimentally measured motor terminal overvoltage waveforms under a 20 m cable length: (a) experimentally measured overvoltage waveform from the physical VFD platform; (b) simulated overvoltage waveform obtained from the MATLAB/Simulink model.

To quantitatively evaluate the peak overvoltage, this study incorporates a statistical evaluation method based on hierarchical peak detection, as shown in Figure 8. Specifically, a three-step algorithmic workflow is implemented to process the transient data:

1. Pulse identification: all individual oscillating pulses within a single fundamental cycle of the motor terminal voltage waveform are systematically identified;
2. Peak extraction: the maximum transient amplitude of each identified oscillating pulse is captured to extract the most destructive spikes;

3. Statistical averaging: the extracted peak amplitudes across multiple continuous steady-state cycles are statistically averaged to yield the definitive, stable characteristic overvoltage index for the VFD system.

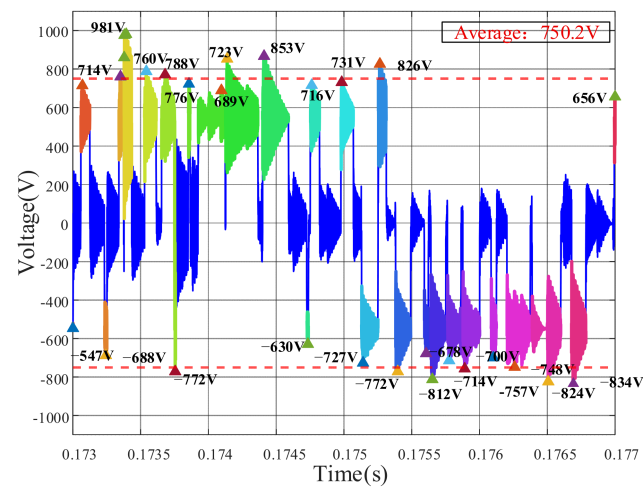


Figure 8. Illustration of data processing for overvoltage pulse detection and statistical analysis, where different colors are used to distinguish different overvoltage oscillation peaks.

Based on this statistical processing, the experimentally measured peak motor terminal voltage was 755.81 V (normalized to 1.51 pu), whereas the simulated prediction was 736.46 V (normalized to 1.47 pu). The relative error between the two is merely 2.56%. This excellent agreement demonstrates the validity of the distributed-parameter simulation model in capturing traveling-wave reflections and overvoltage behavior in long-line VFD systems, providing a solid benchmark for the longer-cable parametric extrapolations presented in Section 3.

Although the proposed wideband transmission line model is experimentally validated using a 20 m cable platform, its applicability to longer cable lengths is theoretically supported by classical transmission line theory. In the studied frequency range dominated by the inverter switching carrier and its low-order harmonics, the electromagnetic wavelength is significantly larger than the cable cross-sectional dimensions, while being comparable to or larger than the cable length, even at the upper bound of the studied range. Therefore, the per-unit-length distributed parameters (R , L , and C matrices) remain invariant with respect to cable length, enabling natural extension of the model to longer cable conditions through changes in propagation delay and attenuation characteristics.

Furthermore, since the distributed parameters are extracted from the actual cable geometry using the Q3D method and validated against experimental results at 20 m (with a peak error of 2.56%), the model is able to capture the dominant physics of wave propagation and reflection superposition. For longer cables, the system response primarily changes in terms of increased propagation delay and enhanced multiple reflections, while the model structure itself remains unchanged.

Therefore, the 20 m experimental validation serves as a reliable benchmark supporting the use of the proposed model for trend analysis and parametric studies in long-cable VFD systems.

3. Simulation Results for Motor Terminal Overvoltage

Using the inverter-long cable-motor model in Section 2, parametric simulations were conducted to evaluate motor terminal overvoltage. To isolate the impact of individual factors, a parameter sweep was executed by varying one specific variable at a time while maintaining all other configurations constant. The definitive peak overvoltage index

was quantified leveraging the hierarchical peak-detection and statistical analysis method established in Section 2.3.

3.1. Effect of Cable Length on Motor Terminal Overvoltage

Cable length changes the traveling-wave propagation time and therefore affects wave superposition at the motor end [11,17]. To fully capture the overvoltage characteristics, parametric simulations were executed across a comprehensive cable length range from 25 m to 275 m, with the pulse rise time ($t_r = 2 \mu\text{s}$) kept constant. For visual clarity and illustrative purposes, Figure 9 specifically showcases the transient motor terminal voltage waveforms under four typical lengths: 25 m, 50 m, 75 m, and 100 m. To maintain modeling accuracy across all simulated distances, the length of each single π -type segment is strictly kept constant at 5 m, and the total cable length is scaled up by systematically increasing the number of these equivalent segments.

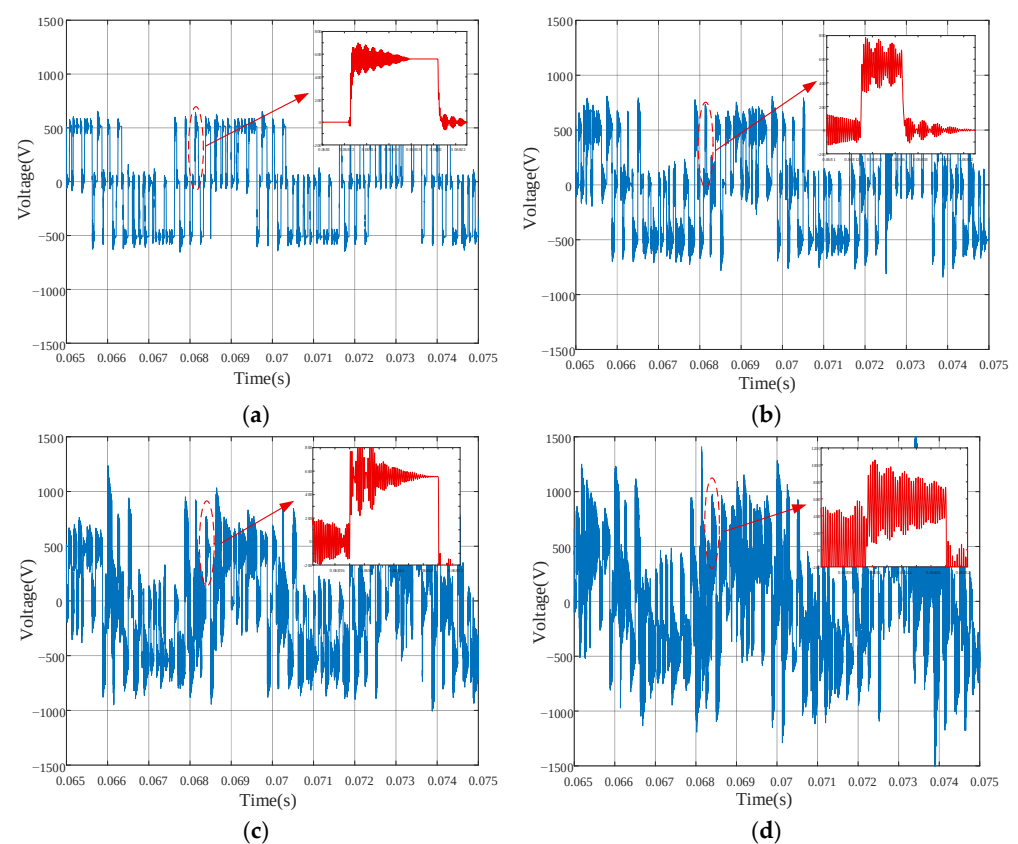


Figure 9. Motor terminal overvoltage waveforms under different cable lengths: (a) overvoltage waveform at $l = 25 \text{ m}$; (b) overvoltage waveform at $l = 50 \text{ m}$; (c) overvoltage waveform at $l = 75 \text{ m}$; (d) overvoltage waveform at $l = 100 \text{ m}$.

As the cable length increases, the overshoot phenomenon in the voltage waveforms becomes progressively prominent, and the peak overvoltage rises significantly. The simulated normalized value of the motor terminal overvoltage (defined as the ratio of the motor terminal overvoltage amplitude to the inverter DC bus voltage) as a function of cable length is plotted in Figure 10. The normalized overvoltage increased with cable length in the short-cable range and then gradually saturated. At longer lengths, the peak value approached the limit set by the reflection coefficient.

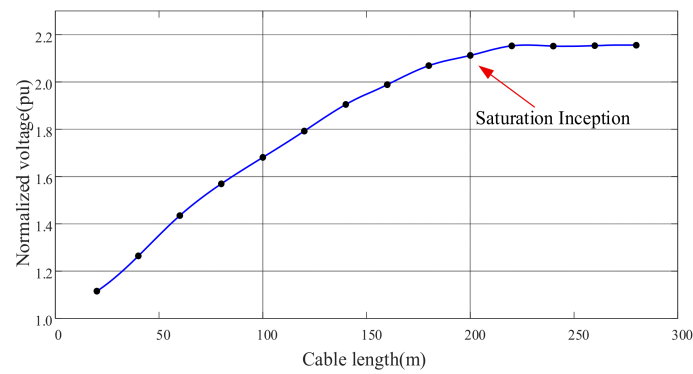


Figure 10. Variation in normalized motor terminal overvoltage with cable length.

In Figure 10, the critical inflection point marks the onset of the overvoltage saturation interval. From a practical engineering perspective, once the cable length exceeds this threshold, the marginal benefit of mitigating overvoltage solely by optimizing cable routing length diminishes significantly, making external filters a priority.

3.2. Effect of Pulse Rise Time on Motor Terminal Overvoltage

As an important indicator characterizing the steepness of the inverter output waveform, the pulse rise time directly determines the excitation intensity of high-frequency components within the cable, thereby influencing the transient overvoltage level at the motor terminal [18,19]. While keeping conditions such as the cable length ($l = 100$ m), cable characteristic parameters, and carrier frequency constant, simulations are performed by varying the pulse rise time. The simulation results of the motor terminal overvoltage are illustrated in Figure 11:

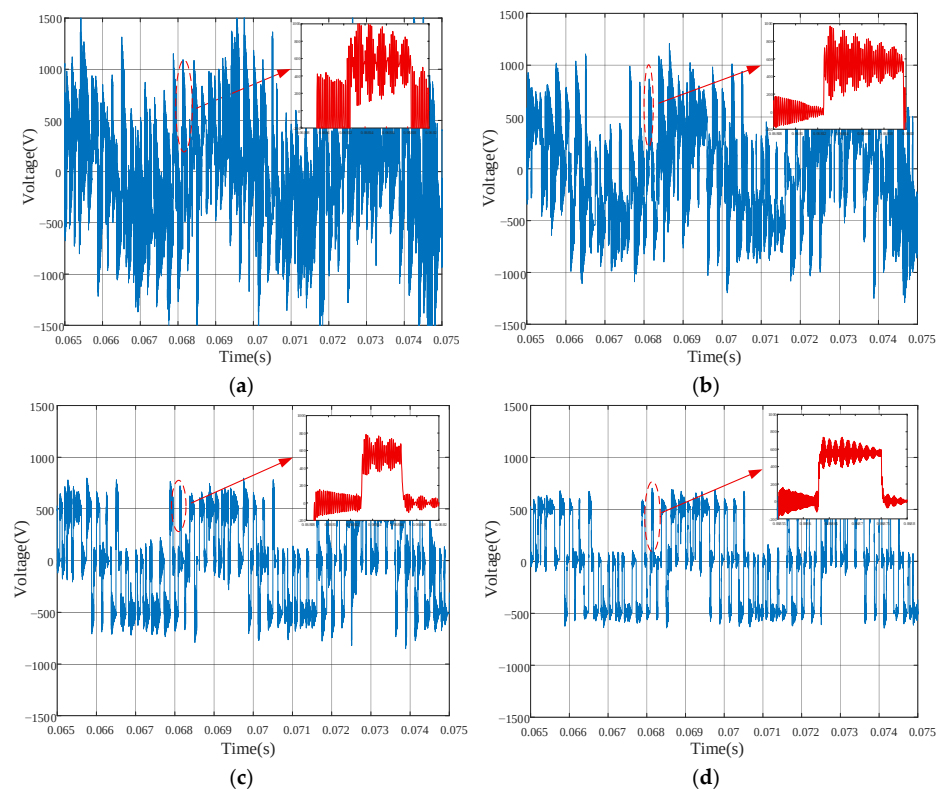


Figure 11. Motor terminal overvoltage waveforms under different pulse rise times: (a) overvoltage waveform at $t_r = 0.1 \mu\text{s}$; (b) overvoltage waveform at $t_r = 1 \mu\text{s}$; (c) overvoltage waveform at $t_r = 5 \mu\text{s}$; (d) overvoltage waveform at $t_r = 10 \mu\text{s}$.

With the increase in pulse rise time, the overshoot phenomenon in the voltage waveforms progressively weakens, and the peak overvoltage decreases significantly. The simulated curve of the normalized motor terminal overvoltage as a function of the pulse rise time is illustrated in Figure 12. The normalized overvoltage decreased as the pulse rise time increased. In the shorter rise-time range, the peak value dropped approximately linearly. For longer rise times, the decline slowed, and the normalized overvoltage approached about 1.0 pu. This trend is consistent with reduced excitation of high-frequency spectral components when dv/dt decreases.

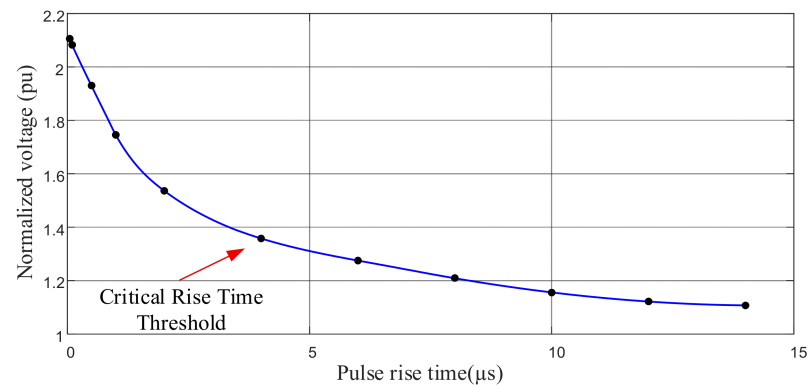


Figure 12. Variation in normalized motor terminal overvoltage with PWM pulse rise time.

The critical rise time value highlighted in Figure 12 provides a key dv/dt coordination reference for inverter drive design. Adjusting the pulse rise time above this critical threshold allows engineers to achieve an optimal balance between overvoltage suppression and inverter dynamic performance.

3.3. Effect of Cable Cross-Sectional Geometry on Motor Terminal Overvoltage

The cross-sectional geometry of the cable, including the conductor radius and conductor spacing, alters the characteristic impedance of the cable by affecting the distributed inductance and capacitance per unit length, ultimately impacting the motor terminal overvoltage amplitude. For the three-core cable structures widely applied in practical engineering, the electromagnetic field distribution is highly complex. However, based on the parametric sweep function of ANSYS Q2D, the distributed parameters under different conductor radii and spacings can be accurately extracted, thereby obtaining the variations in distributed inductance and capacitance as functions of conductor spacing or radius, as illustrated in Figures 13 and 14.

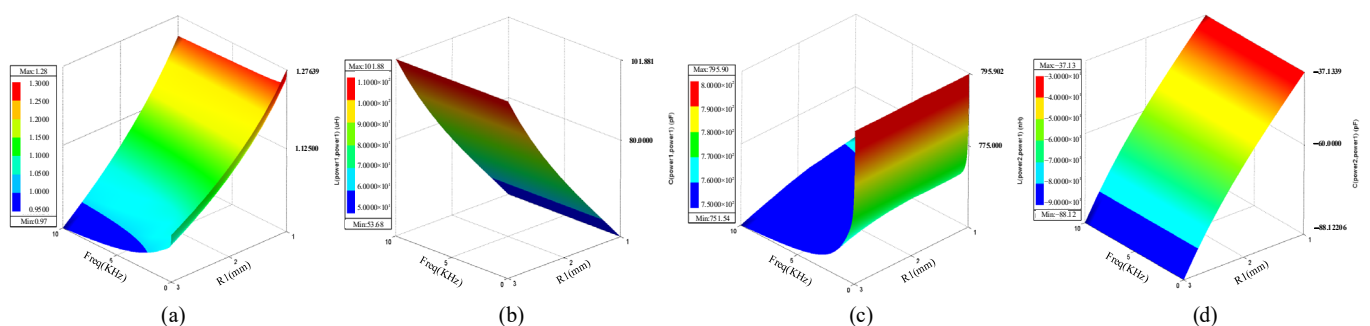


Figure 13. Parametric sweep distribution maps for conductor radius: (a) self-inductance per unit length; (b) mutual inductance per unit length; (c) capacitance to ground per unit length; (d) mutual capacitance per unit length. (Note: The local dark regions are visual shading shadows from the 3D rendering and do not represent out-of-bound data).

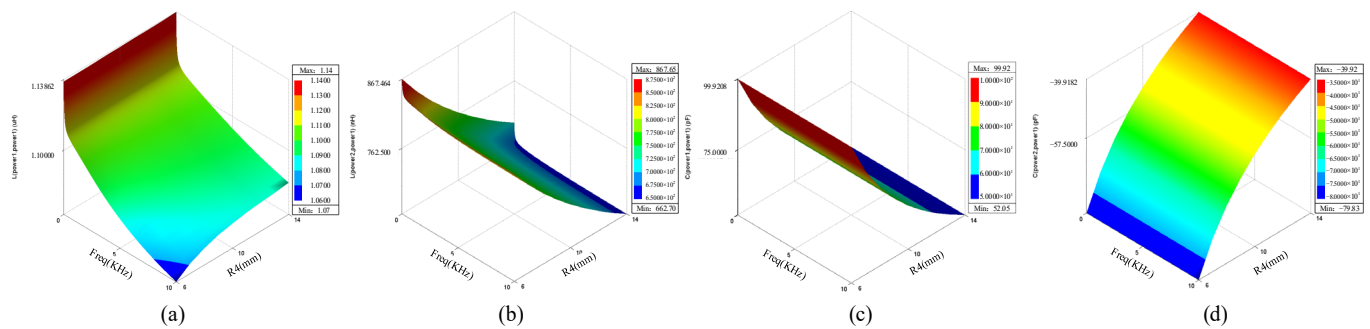


Figure 14. Parametric sweep distribution maps for conductor spacing: (a) self-inductance per unit length; (b) mutual inductance per unit length; (c) capacitance to ground per unit length; (d) mutual capacitance per unit length. (Note: The local dark regions are visual shading shadows from the 3D rendering and do not represent out-of-bound data).

As illustrated in Figure 13, when the conductor radius expands from 1.0 mm to 2.6 mm, the per-unit-length self-inductance exhibits a rising trend, whereas the mutual inductance gradually decreases. Conversely, because the increased radius narrows the physical gap between the conductor surfaces, the electric field coupling is significantly enhanced, causing both the per-unit-length mutual capacitance and capacitance to ground to present a distinct upward trend.

Figure 14 details the dependence of the distributed parameters on the conductor spacing ranging from 6 mm to 14 mm. As the conductor spacing widens, the per-unit-length self-inductance scales up, while the mutual inductance reduces due to the weakened magnetic flux coupling between the cores. Concurrently, the elongated electric field paths weaken the capacitive coupling, thereby prompting a clear downward trend in both the mutual capacitance and capacitance to ground.

The extracted parameters were imported into the transmission line model in Figure 5. The resulting normalized overvoltage values are listed in Tables 3 and 4.

Table 3. Correspondence between conductor radius and normalized overvoltage.

Conductor Radius (mm)	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6
Normalized Overvoltage Value	1.391	1.412	1.399	1.431	1.419	1.410	1.420	1.415	1.401

Table 4. Correspondence between conductor spacing and normalized overvoltage.

Conductor Spacing (mm)	6	7	8	9	10	11	12	13	14
Normalized Overvoltage Value	1.312	1.308	1.311	1.309	1.310	1.307	1.311	1.308	1.310

As tabulated in Tables 3 and 4, the impact of these internal geometric variations on the terminal transient is quantitatively evaluated. When the conductor radius increases significantly from 1.0 mm to 2.6 mm, the normalized overvoltage merely fluctuates within a narrow range of 1.39–1.43 pu, yielding a maximum deviation of only 0.04 pu. Similarly, when the conductor spacing widens from 6 mm to 14 mm, the normalized overvoltage is strictly confined near 1.31 pu, with a negligible variation of less than 0.005 pu. These small changes, underlined by the precise data, indicate that geometry tuning alone is much less effective than changing cable length or pulse rise time, as the inherent parameter trade-offs maintain a highly robust characteristic impedance (further detailed in Section 4.1).

4. Discussion

4.1. Wave Reflection Mechanisms and Parameter Sensitivity Analysis

The transient motor terminal overvoltage is fundamentally governed by transmission-line reflection theory [20]. At the high-frequency range excited by steep PWM pulses, the motor presents a much higher input impedance than the cable ($Z_L \gg Z_0$), causing the reflection coefficient $\Gamma = (Z_L - Z_0)/(Z_L + Z_0)$ to approach unity and potentially double the superimposed terminal voltage relative to the incident wave amplitude [15].

By comprehensively synthesizing parametric simulation results, a distinct hierarchical order of influence among the operational and structural factors emerges, proving that operational variables play a dominant role in overvoltage severity. Specifically, both the pulse rise time (t_r) and the cable length (l) simultaneously act as the twin primary determinants governing the transient stress, whereas the structural geometric parameters remain strictly secondary. On the one hand, shortening t_r from 2 μ s to 0.1 μ s causes the terminal peak voltage to jump sharply from 1.35 pu to 2.08 pu, representing a substantial voltage rise of 0.73 pu that exceeds twice the nominal base voltage with noticeable overshoot. On the other hand, as l escalates from 25 m to 200 m, the normalized overvoltage increases by an even more pronounced 0.87 pu (from 1.25 pu to 2.12 pu), indicating a conspicuous escalation in insulation degradation risk.

In stark contrast, the variations induced by the cross-sectional geometry of the cable are practically inconsequential. Altering the conductor radius (r) across a wide evaluation range from 1.0 mm to 2.6 mm yields a maximum peak voltage fluctuation of merely 0.010 pu (approximately 2.9%). Similarly, widening the conductor spacing (d) from 6.0 mm to 14.0 mm induces an even more negligible variation in only 0.005 pu (about 0.4%) in the overvoltage amplitude. This quantitative contrast firmly demonstrates that fine-tuning the internal structural design of the cable provides a negligible mitigation effect compared to the critical adjustment of the twin operational parameters.

The distinct variance in parameter sensitivity can be elucidated by the underlying electromagnetic coupling and transmission mechanisms. As the cable length scales up, the wave propagation time elongates relative to the pulse rise time, allowing the incident and reflected traveling waves to superimpose more constructively until reaching a saturation plateau dictated by Γ . Concurrently, the pulse rise time t_r acts as the primary governor of the high-frequency harmonic contents injected into the line. Shorter rise times correspond to severe high-frequency spectrum densities that intensify electromagnetic transient propagation, whereas longer rise times naturally suppress these high-frequency spectral components, pulling the terminal voltage back toward the nominal state.

In contrast, the characteristic impedance Z_0 of the cable exhibits robust tolerance against structural modifications. For the flat three-core symmetrical configuration investigated, fine adjustments to the conductor radius or insulation spacing only induce minor proportional shifts in the per-unit-length distributed inductance L and capacitance C simultaneously. Because Z_0 is defined by the square root of their ratio ($Z_0 = \sqrt{(R + j\omega L)/(G + j\omega C)} \approx \sqrt{L/C}$, which is a valid lossless approximation under the high-frequency condition $R \ll \omega L$ and inherently exhibits a logarithmic dependence on the geometry via $\ln(D/r)$), these simultaneous changes cancel each other out to a large extent, keeping Z_0 remarkably stable [21]. Consequently, the impedance mismatch at the motor-cable interface remains virtually unaltered, which explains why optimizing the internal geometric dimensions of the cable is an ineffective mitigation strategy compared to adjusting operational parameters.

It is worth noting that representing the high-frequency motor impedance as a simplified high-impedance termination in this study introduces certain simulation deviations. In reality, the complex turn-to-turn capacitance and frame inductance of the motor wind-

ings create frequency-dependent resonance characteristics. By omitting these parasitic networks, the current wideband model may over-attenuate or phase-shift higher-order high-frequency harmonics (in the MHz range), slightly underestimating the fine-grained high-frequency ringing superimposed on the voltage peaks.

However, this simplification does not fundamentally alter the core sensitivity conclusions of this work. The overvoltage phenomenon is primarily governed by the dominant traveling-wave reflections determined by the transient switching spectrum (associated with the high- dv/dt pulse edges), where the severe impedance mismatch between the cable characteristic impedance (Z_C) and the motor input impedance (Z_M) remains virtually unchanged. Because changing the structural geometry of the cable only induces minor, mutually canceling variations in distributed parameters without breaking this fundamental mismatch, the hierarchical order of sensitivity—where operational parameters (l and t_r) dominate over geometric tuning—remains robustly valid.

4.2. Comparison with Prior Literature and Engineering Implications

The strong dependence of terminal overvoltage on cable length and inverter dv/dt aligned well with classical long-cable VFD studies [22], confirming the validity of the proposed modeling framework. Compared with previous studies, however, the present work extends the analysis to a mining submersible pump PMSM drive by integrating geometry-dependent Q3D parameter extraction, experimental validation, and quantitative sensitivity evaluation within a unified framework.

Rather than proposing a new overvoltage suppression topology, the primary contribution of this work lies in establishing an engineering-oriented sensitivity ranking that quantitatively identifies the dominant factors governing motor terminal overvoltage. This ranking provides a practical basis for selecting effective mitigation strategies instead of relying solely on empirical experience.

Specifically, the results demonstrate that cable length and inverter PWM pulse rise time dominate the overvoltage behavior, whereas conductor radius and spacing have only a marginal influence. Consequently, engineering efforts should primarily focus on optimizing cable routing and coordinating inverter dv/dt before considering cable geometry optimization. This prioritization enables more efficient allocation of design resources during system planning and EMC optimization.

For applications where long transmission distances cannot be avoided, the sensitivity results further indicate that external mitigation measures, such as dv/dt filters, output filters, or terminal impedance matching networks, should be preferentially implemented. Although the present study does not propose a new suppression method, it provides the quantitative evidence required to determine when and where such mitigation techniques are most beneficial. Therefore, the proposed methodology complements existing overvoltage suppression research by supporting evidence-based engineering decision-making for long-cable PMSM drive systems.

4.3. Limitations and Future Work

Despite the high calibration accuracy achieved on the 20 m experimental platform, several limitations of the current study must be acknowledged, which also outline promising avenues for future research:

1. **Scalability of Field Verification:** The extended parametric extrapolations for longer cable lines are entirely simulation-based and lack direct field-site verification. To resolve this, future efforts will focus on conducting collaborative onsite field measurements in operating mining environments to validate the model's scalability under actual long-distance conditions.

2. Representing frequency-dependent cable parameters with fixed values at the carrier frequency (5 kHz) serves as an efficient engineering approximation but may under-represent complex MHz-scale transient spectrums. To refine this approximation, a frequency-dependent vector-fitting technique will be integrated in subsequent studies to dynamically update distributed parameters across the entire wideband spectrum. Additionally, conducting precise experimental measurements to capture the motor's high-frequency input impedance curves and the frequency-dependent dielectric properties of insulation materials remains a critical task for our future work to further improve the microscopic accuracy of the winding stress model.
3. Simplification of External Installation Environment: The current distributed parameter extraction simplifies the cable environment by assuming an isolated cable in an idealized air medium, omitting complex real-world installation conditions. In practical industrial sites, metallic boundaries such as steel cable trays or electromagnetic proximity coupling from adjacent parallel cables can alter the cable's capacitance to ground and mutual inductances. Investigating how these diverse external boundary conditions affect the parameter matrices and the resulting overvoltage transients will be systematically conducted in our future work.
4. Generalization of System Configurations: The current evaluation is restricted to a single specific PMSM power rating and cable family. Expanding the established modeling framework to a broader spectrum of high-voltage industrial configurations, various power ratings, and alternative geometric cable structures remains a critical task for our future research. Additionally, the current study maintains a constant motor load; investigating the dynamic effects of load fluctuations and varying motor torque profiles on the transient overvoltage attenuation will be systematically conducted in our future work.

5. Conclusions

A wideband simulation framework was developed for a long-distance mining submersible pump PMSM drive by combining transmission-line modeling with Q3D-based parameter extraction. Parametric simulations and a relative sensitivity comparison were used to rank the influence of cable length, pulse rise time, and cable geometry on motor terminal overvoltage. The main conclusions are as follows:

1. Dominant impact of cable length and pulse rise time: Cable length and PWM pulse rise time were the most influential factors in the parametric study. Peak overvoltage increased with cable length and decreased with longer rise time.
2. Limited effect of cable geometry: Conductor radius and spacing caused only minor changes in normalized overvoltage compared with cable length and rise time.
3. Design priority: For EMC design and overvoltage mitigation, cable routing and inverter dv/dt coordination are more effective than fine cable-geometry tuning alone.

Overall, the simulation results suggest that cable length layout and inverter switching characteristics (dv/dt) should be prioritized over minor cable-geometry changes. The proposed modeling workflow provides a reproducible basis for further experimental validation and collaborative overvoltage suppression in industrial long-cable drives.

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Abbreviations

The following abbreviations are used in this manuscript:

VFD	Variable Frequency Drive
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
EMC	Electromagnetic Compatibility
IGBT	Insulated Gate Bipolar Transistor

References

- Chen, Y.; Zang, B.; Wang, H.; Liu, H.; Li, H. Composite PM Rotor Design and Alternating Flux Density Harmonic Component Analysis of a 200 kW High-Speed PMSM Used in FESS. *IEEE Trans. Ind. Appl.* **2023**, *59*, 1469–1480. [\[CrossRef\]](#)
- Wang, Q.; Zhao, X.; Yang, P.; Hua, W.; Buja, G. Effects of Triangular Wave Injection and Current Differential Terms on Multiparameter Identification for PMSM. *IEEE Trans. Power Electron.* **2024**, *39*, 2943–2947. [\[CrossRef\]](#)
- Dorn-Gomba, L.; Ramoul, J.; Reimers, J.; Emadi, A. Power Electronic Converters in Electric Aircraft: Current Status, Challenges, and Emerging Technologies. *IEEE Trans. Transp. Electr.* **2020**, *6*, 1468–1664. [\[CrossRef\]](#)
- de Paula, V.C.; de Paula, H. Employing DC Transmission in Long Distance AC Motor Drives: Analysis of the Copper Economy and Power Losses Reduction in Mining Facilities. In Proceedings of the 2015 IEEE Industry Applications Society Annual Meeting, Addison, TX, USA, 18–22 October 2015; pp. 1–7.
- Dzhankhotov, V.; Pyrhönen, J. Passive LC Filter Design Considerations for Motor Applications. *IEEE Trans. Ind. Electron.* **2013**, *60*, 4253–4259. [\[CrossRef\]](#)
- Smochek, M.; Pollice, A.F.; Rastogi, M.; Harshman, M. Long Cable Applications from a Medium-Voltage Drives Perspective. *IEEE Trans. Ind. Appl.* **2016**, *52*, 645–652. [\[CrossRef\]](#)
- Liu, Z.; Skibinski, G.L. Method to Reduce Overvoltage on AC Motor Insulation from Inverters with Ultra-Long Cable. In Proceedings of the 2017 IEEE International Electric Machines and Drives Conference (IEMDC), Miami, FL, USA, 21–24 May 2017; pp. 1–8.
- Xiong, H.; Zhang, J.; Von Jouanne, A. Control of Variable Frequency Drive PWM to Mitigate Motor Overvoltage Due to Double Pulsing in Reflected Wave Phenomenon. In Proceedings of the 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, USA, 23–27 September 2018; pp. 6563–6570.
- Jiang, Y.; Wu, W.; He, Y.; Chung, H.S.-H.; Blaabjerg, F. New Passive Filter Design Method for Overvoltage Suppression and Bearing Currents Mitigation in a Long Cable Based PWM Inverter-Fed Motor Drive System. *IEEE Trans. Power Electron.* **2017**, *32*, 7882–7893. [\[CrossRef\]](#)
- Naranyanasamy, B.; Sathyanarayanan, A.S.; Luo, F.; Chen, C. Reflected Wave Phenomenon in SiC Motor Drives: Consequences, Boundaries, and Mitigation. *IEEE Trans. Power Electron.* **2020**, *35*, 10629–10642. [\[CrossRef\]](#)
- Sadoughi, M.; Fateh, F.; Mirafzal, B. Overvoltage Stress on AC Motor Winding Insulations Driven by Fast-Switching Inverters: A Study. In Proceedings of the 2024 IEEE Kansas Power and Energy Conference (KPEC), Manhattan, Kansas, 25–26 April 2024; pp. 1–6.
- Wu, X.; Ji, Y.; Li, C.; Xu, Y.; Zou, J.; Tian, L.; Chen, S.; Ma, Z.; Han, Y. Review and New Expansion of the Active Damping Strategy of the PMSM Drive System with LC Sine Wave Filter. *CES Trans. Electr. Mach. Syst.* **2025**, *9*, 268–288. [\[CrossRef\]](#)
- Tilea, I.; Munteanu, C. Motor Cable Electric Parameter Effects on the Overvoltage Phenomenon in Inverter Driven Motors. In Proceedings of the 2013 8th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 23–25 May 2013; pp. 1–6.

14. Wu, Y.; Choksi, K.; ul Hassan, M.; Luo, F. An Extendable and Accurate High-Frequency Modelling of Three-Phase Cable for Prediction of Reflected Wave Phenomenon. In Proceedings of the 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), Houston, TX, USA, 20–24 March 2022; pp. 944–950.
15. He, J.; Sizov, G.Y.; Zhang, P.; Demerdash, N.A.O. A Review of Mitigation Methods for Overvoltage in Long-Cable-Fed PWM AC Drives. In Proceedings of the 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, USA, 17–22 September 2011; pp. 2160–2166.
16. Xie, M.; Zheng, C.; Zhong, Y.; Gong, Z.; Wu, X.; Garcia, C.; Rodriguez, J. Dual-Objective Continuous-Set Model Predictive Control for PMSM With LC Filter. *IEEE Trans. Power Electron.* **2026**, *41*, 11893–11905.
17. Azadeh, Y.; Choksi, K.; Mirza, A.B.; Zhang, X.; Wu, Y.; Luo, F.; Haran, K.S. Cable and Motor Winding Impedance Interactions in Motor Drive Systems and Its Impact on HF Overvoltages. *IEEE Trans. Power Electron.* **2024**, *39*, 1244–1253. [[CrossRef](#)]
18. Narayanasamy, B.; Sathyanarayanan, A.S.; Deshpande, A.; Luo, F. Impact of Cable and Motor Loads on Wide Bandgap Device Switching and Reflected Wave Phenomenon in Motor Drives. In Proceedings of the 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, USA, 26–30 March 2017; pp. 931–937.
19. Azadeh, Y.; Mirza, A.B.; Choksi, K.; Zhang, X.; Luo, F.; Haran, K.S. dV/dt Impact on Turn-to-Turn Overvoltage Distribution in Motor Windings. In Proceedings of the 2023 IEEE Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMC + SIPI), Grand Rapids, MI, USA, 31 July–4 August 2023; pp. 579–584.
20. Xu, Y.; Yuan, X.; Ye, F.; Wang, Z.; Zhang, Y.; Diab, M.; Zhou, W. Impact of High Switching Speed and High Switching Frequency of Wide-Bandgap Motor Drives on Electric Machines. *IEEE Access* **2021**, *9*, 82866–82880. [[CrossRef](#)]
21. Sadoughi, M.; Sadasivan, A.; Howard, A.; Fateh, F.; He, J.; Mirafzal, B. Mitigating High-Frequency Overvoltage on Motor Windings: An Adaptive Approach. In Proceedings of the 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 29 October–2 November 2023; pp. 5170–5176.
22. Choksi, K.; Wu, Y.; Mustafeez-ul-Hassan; Luo, F. Evaluation of Factors Impacting Reflected Wave Phenomenon in WBG Based Motor Drives. In Proceedings of the 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), Himeji, Japan, 15–19 May 2022; pp. 736–740.

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