L. L. MENG, W. DAI

ISSN 0543-5846
METABK 64(1-2) 65-68 (2025)
UDC:621-181-537.315:621.315.2:669.011.005:658.53=111

RESEARCH ON MOTOR OVERVOLTAGE ISSUES IN METALLURGICAL ENVIRONMENTS USING THREE-LEVEL INVERTERS

Received – Primljeno: 2024-04-25
Accepted – Prihvaćeno: 2024-08-10
Original Scientific Paper – Izvorni znanstveni rad

Industries such as nuclear power plants and underground mining are characterized by space constraints,forcing the use of long-wire cables to power motors.The impedance mismatch between long-wire cables and motors leads to overvoltage phenomena at motor terminals,especially when the cable length is long or the transmission frequency is high. In this paper by analyzing the expressions of the peak voltage at the motor terminal of the two-level and three-level inverters,we explain the mechanism of the three-level inverter to suppress the overvoltage at the motor terminal,and build the inverter-long-line cable-motor system for simulation to verify the correctness of the conclusion.

Keywords: motor over-voltage, long cable, metallurgical environments, three-level inverter motor

INTRODUCTION

With the development of power electronics technology, motor drive systems are increasingly used in the industrial sector. However, overvoltage issues at the motor end due to long-line cable connections can lead to insulation damage in motors[1]. Therefore, overvoltage protection and suppression in motor drive systems have become important research areas. The literature[2] identifies the fundamental cause of overvoltage phenomena as the impedance mismatch between long-line cables and motors. To address this issue, many researchers have proposed overvoltage suppression methods from different perspectives, such as improved control algorithms[3], optimization of cable parameters, and additional filters. However, these methods have certain limitations in practical applications, such as cost, size, and loss. Therefore, seeking an effective and practical method for suppressing overvoltages at the motor end has significant[4] engineering importance. Metallurgical equipment such as rolling mills and extrusion presses frequently encounter extreme working conditions and high load fluctuations[5], necessitating efficient and reliable motor drive systems. Through a comparative analysis of the time-domain expressions of two-level and three-level inverters, it was found that three-level inverters exhibit superior voltage suppression capabilities when addressing the issue of impedance mismatch caused by long cable lengths. This enhanced voltage control not only reduces the risk of motor insulation damage but also significantly lowers maintenance and replacement costs due to motor failures. Simulation results have confirmed the stability and reliability of three-level inverters in harsh metallurgical environments characterized by high temperatures and dust, ensuring continuity in the production process and long-term operation of the equipment.This paper will compare the time-domain expressions for the peak overvoltages at the motor end with two-level and three-level inverters, analyze the mechanism by which three-level inverters suppress motor end overvoltages, and validate their correctness and effectiveness through simulation and experimentation.

ANALYSIS OF OVERVOLTAGE AT THE MOTOR END WITH TWO-LEVEL AND THREE-LEVEL INVERTERS

The accurate establishment of a high-frequency mathematical model for long-line cables is extremely important for analyzing overvoltage at the motor end. According to the uniform transmission line theory, the voltage and current at any point on the transmission line vary with time and distance, thus a distributed parameter model for long-line cables is established. R_0, G_0, L_0, C_0 representing the resistance, conductance, inductance, and capacitance per unit length of the long-line cable. Under high-frequency conditions, $R_0 \ll \omega L_0$, $G_0 \ll \omega C_0$. Therefore, the long-line cable can be considered as a lossless transmission line.

The fundamental cause of overvoltage at the motor end when driving motors over long distances with variable frequency drives is the mismatch between the motor's equivalent impedance and the characteristic impedance of the long-line cable. To analyze the voltage reflection phenomenon at the motor end, it is necessary to establish a high-frequency mathematical model of the motor. Establish the distributed parameter model of the cable and the high-frequency mathematical model of the motor, as shown in Figure 1. Where, L_0, C_0 repre-

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W. Dai, LL. Meng,(E-mail: mengll@ncst.edu.cn), North China University of Science and Technology, Heibei, Tangshan, China.

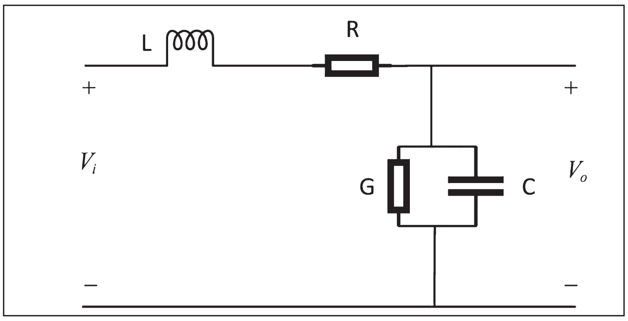

Figure1 High-Frequency Model of Long-Line Cable

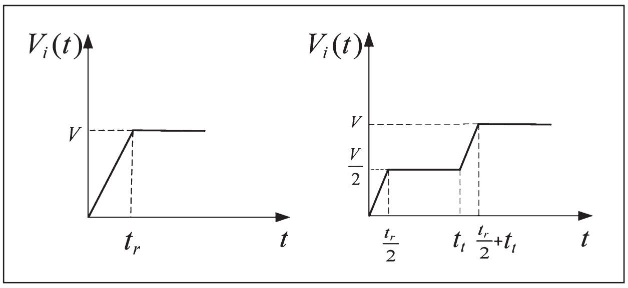

Figure 2 Output Pulse Wave of Two-level Inverter and Output Pulse Wave of Three-level Inverter

sent the inductance and capacitance per unit length of the cable, respectively. Assume that the motor is in an open-circuit condition.

As shown in Figure 2, the PWM wave output from the two-level inverter can be represented as:

$$V_{i2}(t)=\frac{V}{t_r}\cdot t\cdot u(t)-\frac{V}{t_r}\cdot(t-t_r)\cdot u(t-t_r) \qquad (1)$$

Where: V represents the DC bus voltage, $u(t)$ represents the unit step function.

Applying the Laplace transform to Equation (1) yields:

$$V_{i2}(s)=\frac{V}{t_r}\frac{1}{s^2}(1-e^{(-st_r)}) \qquad (2)$$

For the circuit in Figure 1, the voltage transfer function is:

$$H(s)=\frac{V_{O2}(s)}{V_{i2}(s)}=\frac{\frac{1}{LC}}{s^2+\frac{R}{LC}s+\frac{1}{LC}}=\frac{\omega^2}{(s+\sigma)^2+\sigma^2} \qquad (3)$$

Where, $\omega=\sqrt{\frac{1}{C_0L_0}}$, $\sigma=\frac{R}{2L}$.

$$\begin{aligned}V_{O2}(s)&=\frac{V}{t_r}\cdot\frac{1}{s^2}\cdot\frac{\omega^2}{(s+\sigma)^2+\sigma^2}(1-e^{-st_r}) \qquad (4)\\&=V^{'}(s)-V^{"}(s)\end{aligned}$$

The above expression represents two identical responses, with the second response being a time shift relative to the first. Therefore, by simplifying the $V^{'}(s)$, the overall time-domain response can be obtained. Performing the inverse Laplace transform, the time-domain response is obtained as:

$$V^{'}(t)=\frac{V}{t_r}\cdot(t-\frac{e^{-\sigma t}}{\omega}\sin\omega t)\cdot u(t) \qquad (5)$$

$$V^{"}(t)=\frac{V}{t_r}[(t-t_r)-\frac{e^{-\sigma(t-t_r)}}{\omega}\sin\omega(t-t_r)]\cdot u(t-t_r) \qquad (6)$$

The total time-domain response of the two-level inverter motor terminal voltage is:

$$V_{o2}(t)=V[1-e^{-\sigma t}\frac{\sin(\omega t_r/2)}{(\omega t_r/2)}\cos\omega(t-t_r/2)] \qquad (7)$$

$$V_{o2.\max}\approx V[1+\frac{\sin(\omega t_r/2)}{(\omega t_r/2)}] \qquad (8)$$

Indicates the maximum overvoltage at the motor end of a two-level inverter, voltage amplification factor at the motor end of a two-level inverter:

$$\alpha_2=\frac{V_{o2.\max}}{V}=1+|\frac{\sin(\omega t_r/2)}{(\omega t_r/2)}|=1+|\frac{\sin\theta}{\theta}| \qquad (9)$$

$$\theta=\frac{\omega t_r}{2}=\frac{t_r}{2\sqrt{L_0C_0}}=\frac{vt_r}{2l} \qquad (10)$$

In Equation (10) $v=l/\sqrt{L_0C_0}$ represents the propagation speed of the pulse wave in a cable of specified length.

Overvoltage Analysis at the Motor End with Three-level Inverters:

$$\begin{aligned}V_{i3}(t)&=[\frac{V}{t_r}t\cdot u(t)-\frac{V}{t_r}(t-\frac{t_r}{2})u(t-\frac{t_r}{2})+\frac{V}{t_r}(t-t_t)u(t-t_t)-\frac{V}{t_r}(t-t_t-\frac{t_r}{2})u(t-t_t-\frac{t_r}{2})] \qquad (11)\\&=\frac{V}{t_r}[t\cdot u(t)-(t-\frac{t_r}{2})u(t-\frac{t_r}{2})]+\frac{V}{t_r}[(t-t_t)u(t-t_t)-(t-t_t-\frac{t_r}{2})u(t-t_t-\frac{t_r}{2})]\\&=V_{c1}(t)+V_{c2}(t)\end{aligned}$$

$$V_{c1}(t)=\frac{V}{t_r}[t\cdot u(t)-(t-\frac{t_r}{2})u(t-\frac{t_r}{2})] \qquad (12)$$

$$V_{c2}(t)=\frac{V}{t_r}[(t-t_t)\cdot u(t-t_t)-(t-t_t-\frac{t_r}{2})u(t-t_t\frac{t_r}{2})] \qquad (13)$$

Applying the Laplace transform to Equation (11) yields:

$$\begin{aligned}V_{i3}(s)&=\frac{V}{t_r}[\frac{1}{s^2}-\frac{1}{s^2}e^{-\frac{t_r}{2}s}+\frac{1}{s^2}e^{-t_ts}-\frac{1}{s^2}e^{-(t_t+\frac{t_r}{2})s}] \qquad (14)\\&=\frac{V}{t_r}\frac{1}{s^2}[1-e^{-\frac{t_r}{2}s}+e^{-t_ts}-e^{-(t_t+\frac{t_r}{2})s}]\end{aligned}$$

Referring to the analysis process for overvoltage at the motor end with two-level inverters, the complex frequency domain overvoltage at the motor end with three-level inverters can be obtained as:

$$V_{o3}(s)=\frac{V}{t_r}\frac{1}{s^2}[1-e^{-\frac{t_r}{2}s}+e^{-t_ts}-e^{-(t_t+\frac{t_r}{2})s}]\cdot\frac{\omega^2}{(s+\sigma)^2+\sigma^2} \qquad (15)$$

Performing the inverse Laplace transform yields the time-domain expression:

$$V_{o3}(t)=V\{1-\sin c(\theta^{'})\cdot e^{-\sigma(t-t_t)}\cos\frac{\omega t_t}{2}\cdot\cos(\omega t-\theta^{'}-\frac{\omega t_t}{2})\} \qquad (16)$$

Amplification factor:

$$\begin{aligned}\alpha_3&=\frac{V_{o3}}{V}=1-\sin c(\theta)\cdot\cos\frac{\omega t_t}{2}\cdot\cos(\omega t-\theta-\frac{\omega t_t}{2}) \qquad (17)\\&=1+|\sin c(\theta)\cdot\cos\frac{\omega t_t}{2}|\end{aligned}$$

For a typical system, the PWM pulse rise time is $t_r = 0{,}1\mu s$, the level transition time is $t_t = 3\times10^{-4}s$, the distributed inductance of the long-line cable is $L_0 = 8{,}68\times10^{-4}\ H/km$, the distributed capacitance is $C_0 = 1{,}34\times10^{-8}\ F/km$, and the length is $l = 300\ m$, by substituting these parameters into Equations (9) and (15), the calculations yield:

Voltage amplification factor at the motor end of a two-level inverter:

$$\alpha_2 = 1 + \frac{\sin\theta}{\theta} \approx 2 \tag{18}$$

Voltage amplification factor at the motor end of a three-level inverter:

$$\alpha_3 = 1 + |\sin c(\theta)\cdot\cos\frac{\omega t_t}{2}| \approx 1.5 \tag{19}$$

Comparing Equations (9) and (15), it can be observed that when the input PWM wave is two-level, the maximum voltage at the motor end is twice the DC bus voltage. However, when the input is three-level, the maximum voltage at the motor end is influenced by the level transition time, manifesting as an overlay of oscillatory waves from one level state to the next. As the number of levels increases, the level transition time decreases, making the waveform overlay more pronounced, and thus more effectively suppressing overvoltages at the motor end. From Equation (19), it is known that the voltage amplification factor at the motor end for a three-level inverter is 1,5, which is significantly lower compared to the two-level inverter's motor end voltage amplification factor.

SIMULATION VALIDATION

To verify the correctness of the above conclusions, simulation models of PWM single-phase and three-phase drive systems are constructed in MATLAB/SIMULINK. A ramp signal superimposed to generate PWM pulses with a slope is used, and the pulse rise time is considered. Since the distributed parameters of the cable and the characteristic impedance of the motor are already fixed, the simulation experiment explores only the impact of the number of levels on the overvoltage at the motor end. In the simulation, the DC bus voltage for both two-level and three-level inverters is the same. The simulation parameters are as follows: DC bus voltage is 100 V, inverter operating frequency is 10 kHz, motor characteristic impedance R = 3 000 Ω, PWM pulse rise time $t_r = 0{,}1\mu s$, level transition time $t_t = 3\times10^{-4}s$, distributed inductance of the long-line cable, $L_0 = 8{,}68\times10^{-4}\ H/km$ distributed capacitance $C_0 = 1{,}34\times10^{-8}\ F/km$, $l = 300\ m$.

When the DC bus voltage is 100 V, the traditional two-level inverter motor-side voltage waveform is shown in Figure 3, and the voltage peak is very large, which can be up to 2 times the DC bus voltage. The three-level inverter motor-side voltage waveform is

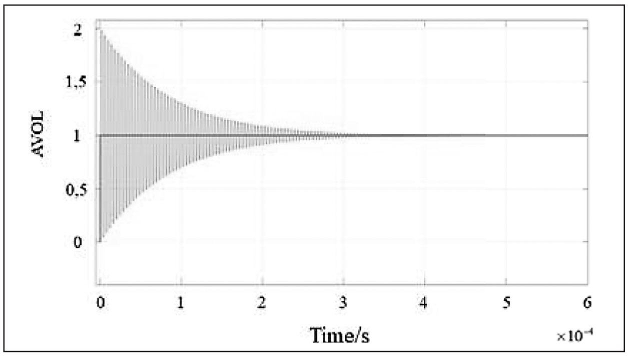

Figure 3 Simulated waveform of motor terminal voltage at two levels

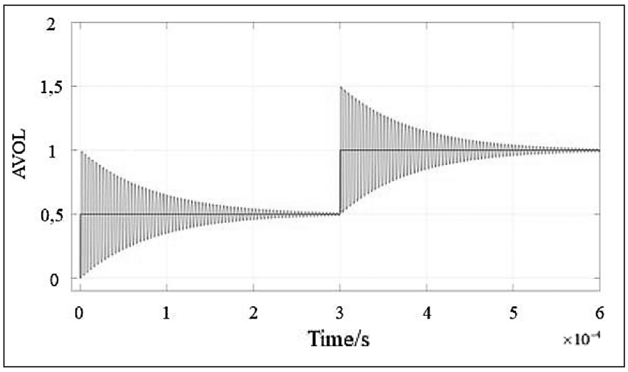

Figure 4 Simulated waveform of motor terminal voltage at three levels

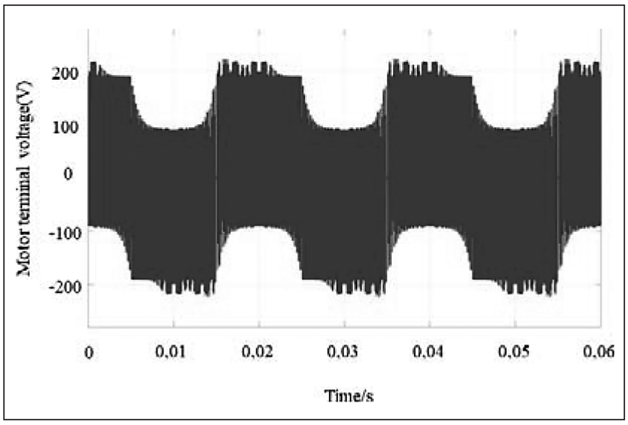

Figure 5 Two level inverter motor terminal line voltage waveform

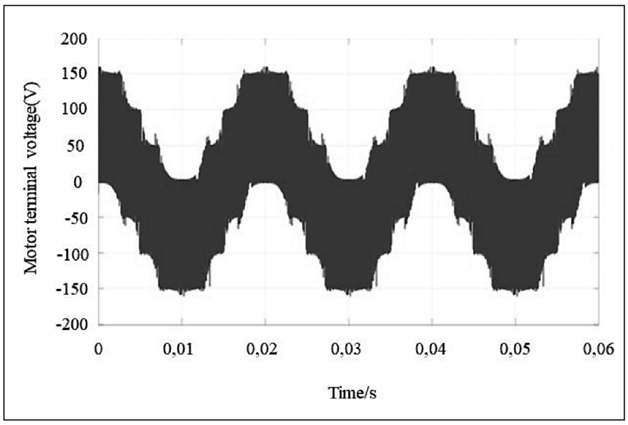

Figure 6 Three level inverter motor terminal line voltage waveform

shown in Figure 4 with a voltage peak of 1,5 times the DC bus voltage. Figure 5 and Figure6 shows the motor terminal voltage in the three-phase drive system using two-level and three-level inverters, respectively, and from the waveforms, it can be seen that its voltage amplification is basically the same as the simulation results of the single-phase drive system.

CONCLUSION

By establishing the drive system model of inverter-long-wire cable-motor, the mathematical expressions for the peak voltage at the motor terminal line when two-level inverter and three-level inverter are used are deduced on the basis of which the increase in the number of levels is proposed to reduce the amplitude of the voltage jump. And the waveforms of inverter terminal line voltage and motor terminal line voltage are obtained through simulation and experiment, which confirm that the three-level inverter can play a good suppression effect on motor terminal overvoltage.

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Note: The responsible translator for English language LL. Meng - North China University of Science and Technology, China