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Quantitative Calculation of Motor End Overvoltage and Analysis of Over Double Overvoltage Under High Frequency.

YANG Ying[1], MA Peng-cheng[2], PANG Shuo[3]

[123] School of Electrical and Mechanical Engineering and Automation, Shanghai University, Shanghai, China

Corresponding author:YANG Ying,yangying_h@163.com

Speaker:YANG Ying,yangying_h@163.com

Abstract

This essay conducts theoretical analysis and simulation verification on the mechanism and influencing factors of motor terminal overvoltage. Firstly, based on the theory of wave reflection, analyze the reflection process of voltage waves in transmission cables and the mechanism of overvoltage generation at the motor end. Then, based on the theory of distributed parameter transmission lines, the Thevenin equivalent circuit of the transmission cable is derived, and a theoretical model of the motor terminal voltage is obtained. Finally, based on the theoretical model of motor terminal voltage, the effects of motor terminal reflection coefficient, cable length, voltage rise time, and cable distribution parameters on motor terminal voltage are analyzed, with a focus on the problem of over double overvoltage caused by high switching frequency. Simulink simulation model of motor terminal voltage is established to verify the above analysis.

1 introduction

When the transient voltage change (dv/dt) of the output Pulse Width Modulation(PWM)voltage of the inverter is large or when a long cable is used to connect the inverter and the motor, the cable can no longer be simply regarded as a non-impedance wire, and its parasitic parameters need to be considered and analyzed by the theory of transmission line distribution parameters. Due to the mismatch between the characteristic impedance of the cable and the impedance of the motor, the voltage wave output by the inverter will produce obvious voltage reflection when it reaches the end of the motor, and the superposition of the reflected wave and the incident wave will generate overvoltage at the end of the motor and destroy the insulation of the stator winding of the motor [1-2].

Literature[3-5] analyzed the process of voltage wave propagation and reflection in the cable, explained the cause of the motor end overvoltage, showed that the motor end overvoltage is related to the transmission cable length, cable distribution parameters, inverter output voltage rise time and motor impedance, and gave the simulation waveform of the motor end overvoltage. Literature[6-7] studied the motor drive system connected by long cables. Through experimental testing of the motor insulation aging curve under different voltage amplitudes and frequencies, the rule of influence of overvoltage on motor insulation life was obtained. The results showed that the insulation life of motor winding rapidly decreased with the increase of voltage pulse amplitude and frequency. Literature[8] points out that cable length and voltage rise time have a great influence on motor overvoltage. As shown in Figure 1, for a silicon carbide (SiC) inverter with a voltage rise time of 50ns and a cable length of 40 feet, the motor overvoltage reaches twice of the DC bus voltage. Today, the voltage rise time of Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) is less than 10ns, even if the transmission cable between the inverter and the motor is short. It will also produce obvious overvoltage phenomenon at the motor end.

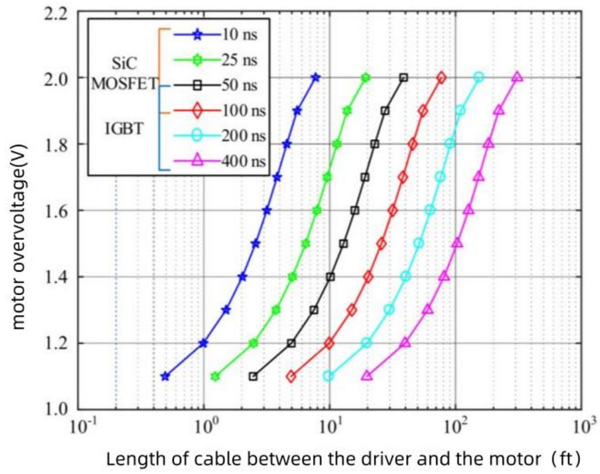

Fig.1. Motor overvoltage under different cable lengths and voltage rise times

The above are the motor end overvoltage analysis when the initial voltage is zero, so the motor end overvoltage will not exceed twice the bus voltage, but with the increase of switching frequency, the motor

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end overvoltage may far exceed twice the bus voltage. This paper gives the theoretical calculation of the motor overvoltage, analyzes the causes of the double overvoltage, and gives simulation verification.

2 Theoretical model of motor terminal voltage

2.1 Distributed parameter transmission line equivalent circuit

In the motor drive system shown in Figure 2, U_{dc} is the bus voltage, C_{bus} is the bus capacitance, and the PWM wave output by the three-phase inverter propagates in the transmission line in the form of traveling wave. When the incident wave propagates to the end of the motor along the uniform transmission line, the characteristic impedance of the transmission line does not match the load impedance, the uniformity is destroyed, and the incident wave will reflect at the end of the motor.

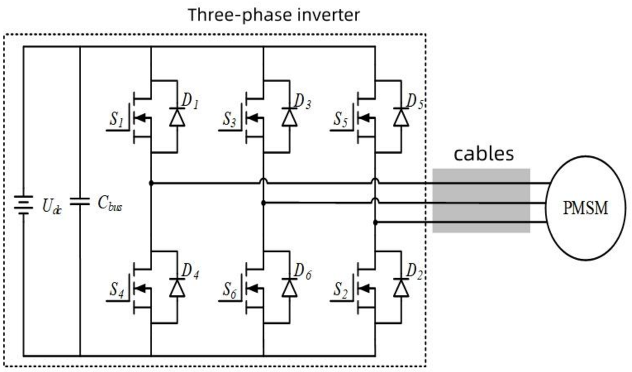

Fig.2. Motor Drive Systems

The distributed parameter circuit model of a uniform transmission line is shown in Figure 3, where u and i are the voltage and current at x meters away from the starting end, respectively.

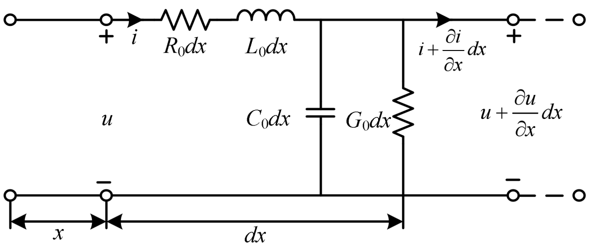

Fig.3. Distributed Parameter Circuit Models for Uniform Transmission Lines

Ignoring R_0 and G_0 at high operating frequency, can be obtained

$$\begin{cases} -\dfrac{\partial u}{\partial x} = L_0 \dfrac{\partial i}{\partial t} \\ -\dfrac{\partial i}{\partial x} = C_0 \dfrac{\partial u}{\partial t} \end{cases} \tag{1}$$

The general solution of this equation is

$$\begin{cases} U(x,s) = A_1 e^{-\sqrt{L_0C_0}sx} + A_2 e^{\sqrt{L_0C_0}sx} = A_1 e^{-s\frac{x}{v}} + A_2 e^{s\frac{x}{v}} \\ I(x,s) = \dfrac{dU}{sL_0dx} = \sqrt{\dfrac{C_0}{L_0}}\left(A_1 e^{-\sqrt{L_0C_0}sx} - A_2 e^{\sqrt{L_0C_0}sx}\right) = \dfrac{1}{Z_C}\left(A_1 e^{-s\frac{x}{v}} - A_2 e^{s\frac{x}{v}}\right) \end{cases} \tag{2}$$

Where, $A_1 e^{-s\frac{x}{v}}$ is the forward traveling wave of voltage and $A_2 e^{s\frac{x}{v}}$ is the reverse traveling wave of voltage. Where A_1 and A_2 are integral terms containing s, v is the traveling wave velocity, and x is the distance from the beginning.

Make the inverter output voltage $U_{i(s)}$, that is

$$U(0,s) = U_i(s) \tag{3}$$

The voltage equation is

$$U(0,s) = A_1 + A_2 = U_i(s) \tag{4}$$

1) When the end of the distributed parameter transmission line is open, when $I(l,s)=0$ the open voltage at the end of the instant transmission cable is

$$U_{eq}(l,s) = \frac{2e^{-\tau s}}{1+e^{-2\tau s}} U_i(s) \tag{5}$$

2) When the terminal of the transmission line with distributed parameters is short-circuited,when $U(l,s)=0$ the short-circuit current at the end of the instant transmission cable is

$$I(l,s) = \frac{1}{Z_C}\frac{2e^{-\tau s}}{1-e^{-2\tau s}} U_i(s) \tag{6}$$

The equivalent impedance of the transmission cable is

$$Z_{\mathrm{eq}} = \frac{U(l,s)}{I(l,s)} = \frac{1-e^{-2\tau s}}{1+e^{-2\tau s}} Z_C \tag{7}$$

The equivalent circuit at the end of the transmission cable (motor side) can be derived by the formula as shown in Figure 4.

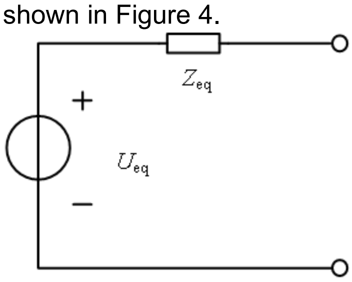

Fig.4. Distributed parameter transmission cable Thevenin equivalent circuit

2.2 Mathematical description of motor end voltage

According to the equivalent circuit of the distributed parameter transmission cable, when the motor impedance is Z_2, the mathematical expression of the motor terminal voltage is

$$U_m(s) = \frac{Z_2}{Z_2 + Z_{\mathrm{eq}}} U_{\mathrm{eq}}(s) \tag{8}$$

By U_{eq}, Z_{eq} and motor end reflection coefficient is

$$N_m = \frac{Z_2 - Z_C}{Z_2 + Z_C} \tag{9}$$

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The terminal voltage of the motor is obtained

$$U_m(s)=\frac{(1+N)e^{-\tau s}}{1+Ne^{-2\tau s}}U_i(s)=\frac{(1+N)e^{-s\frac{l}{v}}}{1+Ne^{-2s\frac{l}{v}}}U_i(s) \quad (10)$$

The motor terminal voltage recursion time domain equation is shown in equation (11).

$$u_m(t)=(1+N)\cdot u_i(t-\tau)-N\cdot u_m(t-2\tau) \quad (11)$$

When $(2k-1)\tau < t \le (2k+1)\tau$,The motor terminal voltage is

$$u_m(t)=(1+N)\sum_{i=0}^{k-1}\left\{(-N)^i u_i\left[t-(2i+1)\tau\right]\right\} \quad (12)$$

Where k is a positive integer. According to equation (12), the terminal voltage oscillation frequency of the motor is 4τ.

3 Analysis of the influence of voltage rise time and cable length on terminal voltage

The following analyzes the influence of voltage rise time and cable length on the motor terminal voltage.

In fact, the inverter output PWM voltage pulse is not an ideal step signal, and its rise takes a certain time. The output voltage of the inverter is shown in Formula (13).

$$u_i(t)=\begin{cases}\frac{t}{t_r}U_{dc} & 0<t\le t_r\\ U_{dc} & t>t_r\end{cases} \quad (13)$$

U_{dc} is the bus voltage, t_r is the inverter output voltage rise time, where $2(m-1)\tau < t_r \le 2m\tau$ and m is a positive integer.

When $t=t_r+\tau$, the motor terminal voltage achieved the maximum.

$$u_{\max}=(1+N)U_{dc}\left\{\sum_{i=1}^{m-1}\left[(-N)^i\frac{t_r-2i\tau}{t_r}\right]+1\right\} \quad (14)$$

Including $2(m-1)\tau < t_r \le 2m\tau$

As can be seen from equation (14), when $t_r \le 2\tau$, the maximum voltage of the motor end is $(1+N)U_{dc}$. With the increase of voltage rise time, the maximum voltage of the motor terminal gradually decreases from (1+N)Udc, and finally approaches the bus voltage U_{dc}. 2τ is the voltage critical rise time t_{r0}, that is

$$t_{r0}=2\tau=2l/v \quad (15)$$

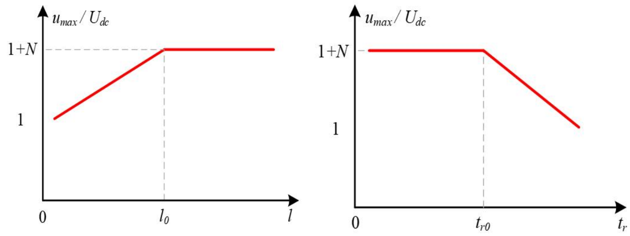
According to equation (15), the critical voltage rise time is related to the length of the transmission cable and the propagation speed of the voltage wave, and the critical length of the transmission cable is defined as

$$l_0=v\tau=vt_r/2 \quad (16)$$

The influence of cable length and voltage rise time on the maximum voltage at the motor end is shown in Figure 5. The analysis shows that:

1) When the transmission cable length is less than the critical length, the maximum voltage of the motor end increases with the increase of the cable length, and is less than $(1+N)U_{dc}$, when the cable length is greater than the critical length, the maximum voltage of the motor end reaches $(1+N)U_{dc}$, and no longer increases with the increase of the cable length, but the increase of the cable length will extend the voltage traveling wave propagation time in the cable. Increase the oscillation time of motor end overvoltage.

2) When the voltage rise time is greater than the critical time, the maximum voltage of the motor end decreases with the increase of the voltage rise time. When the voltage rise time is less than the critical time, the maximum voltage at the motor end reaches $(1+N)U_{dc}$. As can be seen from equation (16), when the voltage rise time decreases, the critical length of the cable also decreases, and the phenomenon of over-voltage at the motor end is more likely to occur.



(a)Influence of cable length (b)Influence of voltage rise time

Fig.5. The influence of cable length and voltage rise time on the maximum voltage of motor terminal

4 Simulation verification and double overvoltage problem

4.1 Simulation verification

The figure 6 shows the simulation waveform of the motor terminal voltage under different voltage rise times when the transmission cable length is 20m. The simulation conditions are as follows: bus voltage 50V, motor impedance 4000 Ω , inverter impedance 5 Ω , transmission cable length 2km, distributed inductance L_0 is 1mH /km, distributed capacitance C_0 is 13nF /km, damping resistance R_0 is 0.05Ω /km.The transmission speed of the voltage wave in the cable is $v=1/\sqrt{L_0\times C_0}=2.77\times10^8$ m/s .According to equation (15),the voltage critical rise time t_{r0} is 144ns.When the voltage rise time is 50 ns and 100 ns, the maximum voltage at the motor end is $(1+N)U_{dc}$=93V when the voltage rise time is less than the voltage critical rise time. When the voltage rise time is 200 ns and 500ns, it has exceeded the critical rise time. According to the deduced formula(14), the maximum voltage of the motor terminal is 70.6V and 57.1V respectively, and the trend is to decrease with the increase of the voltage rise time. The simulation results show that when the voltage rise time exceeds three times the critical rise time (six times the voltage transfer time), the maximum voltage of the motor end is significantly suppressed.

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The figure 7 shows the simulation waveform of the motor end voltage of the transmission cable of different lengths when the voltage rise time is 100ns. According to equation (16),the critical length of transmission cable l0 is 13.85m.When the length of the transmission cable is 6m and 10m, it is less than the critical length, and according to equation (14),the maximum end voltage of the motor is 56.8V and 70.7V respectively .and the trend is to increase with the increase of the cable length. When the transmission cable length is 20m and 50m, it has exceeded the critical length, and the motor terminal voltage reaches a maximum of 93V and does not increase, its value is equal to $(1+N)U_{dc}$. The longer the transmission cable is, the smaller the oscillation frequency and the longer the transmission time to steady state. The simulation results are consistent with the theoretical analysis.

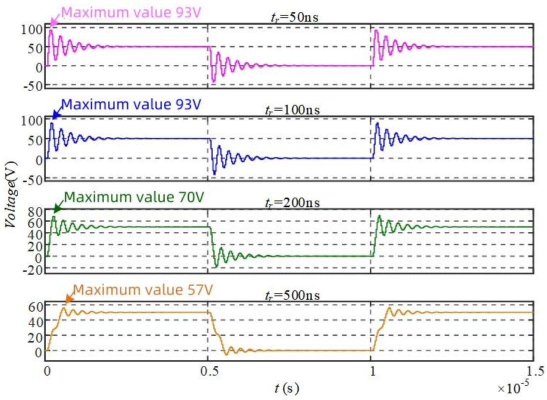

Fig.6. The waveform of motor terminal voltage under different voltage rise time

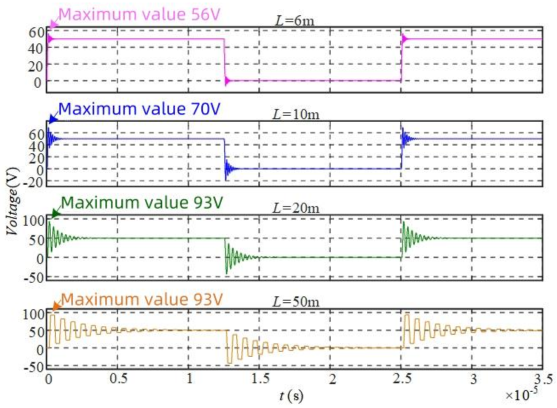

Fig.7. Motor end voltage waveform under different transmission cable lengths

4.2 Analysis of over double overvoltage at high frequency motor end

In theory, the maximum voltage of the motor end will not exceed twice the output voltage amplitude of the inverter. However, in the actual operation of the motor, sometimes there will be an overvoltage of more than twice the amplitude. Figure 8 shows the simulation waveform of the voltage of the motor end and the inverter end line. Among them, the bus voltage is 200V, the switching frequency is 100kHz, the transmission cable length is 25m, 0.025s reaches the given speed of 3000r/min, and the rated load is added abruptly for 0.04s. As can be seen from Figure 8, the maximum voltage of the motor terminal line is about 800V, which reaches 4 times the output voltage of the inverter, resulting in serious overvoltage phenomenon.

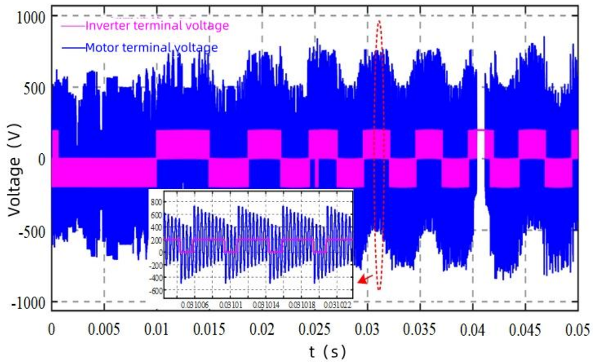

Fig.8. Simulation results of over twice overvoltage at motor end

The motor overvoltage is formed by the superposition of the incident voltage and the reflected voltage, and the reflected voltage continuously reflects and attenuates at the motor end and the inverter end, and the motor end voltage oscillates and attenuates accordingly, and is finally equal to the inverter end voltage. With the increase of switching frequency, the output voltage pulse width of the inverter decreases gradually. As shown in Figure 8, when the output voltage of the inverter is abruptly changed to 200V, the voltage of the motor terminal line still oscillates at a relatively large value. At this time, the motor end not only has the incident voltage and reflected voltage at the current time, but also superimposes the initial voltage value, and the motor end voltage exceeds 2 times the inverter end voltage. If the switching frequency continues to increase, the PWM voltage pulse width is small enough, the motor terminal voltage is the incident wave and the reflected wave of multiple stages, and the value will exceed 3 or 4 times the inverter terminal voltage, which has a huge impact on the motor winding insulation.

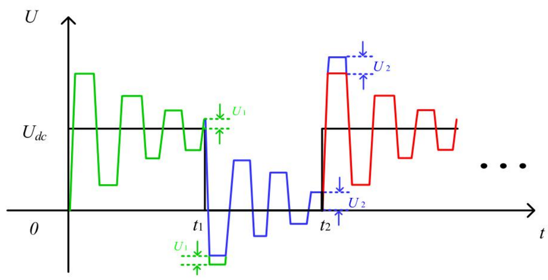

Fig.9. Schematic Diagram of Overvoltage Superposition

Formula (12) is the motor terminal voltage calculation formula when the initial voltage is zero. When the switching frequency is increased, the oscillation period is shortened, and the motor end voltage cannot be

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completely attenuated before the next voltage pulse arrives, so the motor end voltage has an initial value. Assuming that the initial voltage value is $u_{m0(t)}$, then the motor end voltage is

$$u_m(t) = u_{m0}(t) + (1+N)\sum_{i=0}^{k-1}\left\{(-N)^i u_i\left[t-(2i+1)\tau\right]\right\} \quad (17)$$

Where, $(2k-1)\tau < t \le (2k+1)\tau$, the initial voltage value $u_{m0(t)}$ is

$$u_{m0}(t) = N\sum_{i=0}^{k-1}\left\{(-N)^i u_i\left[t-(2i+1)\tau\right]\right\} \quad (18)$$

The voltage waveform of the motor terminal with the inverter switching frequency f_s of 5kHz, 25kHz, 50kHz and 100kHz is shown in Figure 10. The line voltage frequencies are 10kHz, 50kHz, 100kHz and 200kHz respectively. The bus voltage U_{dc} is 50V, the voltage rise time is 10ns, the transmission cable length is 150m, the distributed inductance L_0 is 1mH/km, the distributed capacitance C_0 is 13nF/km, and the motor impedance is 4000Ω.The reflection coefficient of the motor terminal calculated according to the working condition is N=0.86, and the voltage transmission speed in the cable is v=2.77 × 10^8m/s. One way transmission time τ = 541.5ns. When the switching frequency is 50kHz and the duty cycle is 50%, the line voltage high level period is 5μs. According to formula (18), the initial voltage value of the motor end is

$$u_{m0}(t) = N\sum_{i=0}^{k-1}\left\{(-N)^i u_i\left[t-(2i+1)\tau\right]\right\} = 0.47U_{dc} \quad (19)$$

When the voltage pulse comes again, according to equation (17), the terminal voltage of the motor is 2.33U_{dc}=116.5V, and the simulation results are consistent with the theoretical analysis. As can be seen from Figure 10, with the increase of switching frequency, the voltage pulse width narrows, the reflected voltage does not decay in enough time, and the multi-stage reflected voltage is superimposed, resulting in the maximum voltage of the motor end.

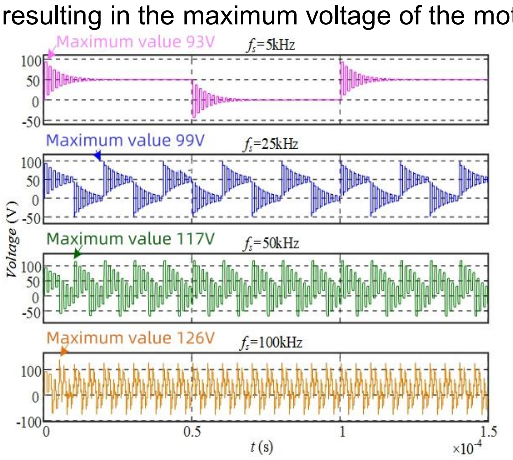

Fig.10. Motor terminal voltage simulation waveform under different switching frequency

Therefore, when the cable length is determined, the high switching frequency is the main reason why the motor end voltage exceeds twice the bus voltage.

5 Summary

In this essay, based on the wave reflection theory, the generation mechanism of motor end overvoltage is analyzed. Then, based on the distributed parameter transmission line theory, the Thevenin equivalent circuit of transmission cable is calculated, and the mathematical model of motor end overvoltage is given. Combined with the mathematical model, the effects of reflection coefficient, voltage rise time, cable length and distribution parameters on the motor end voltage are analyzed respectively. The results show that short voltage rise time or long cable will aggravate the motor end overvoltage, and high switching frequency is the main reason for the motor end overvoltage. When the voltage rise time exceeds six times the transmission time, there will be no obvious overvoltage at the motor end. In this paper, Simulink is used to establish simulation to verify the above analysis.

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