Terminal Voltage Analysis according to Filter Types of Motor Drive System with Long Cables

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Abstract-- **This work starts with a comparison between Ansys simulation software (HFSS, Q3D, and Q2D) combined with circuit diagram simulation (Ansys circuit) and actual measurements for a longitudinally homogeneous unit length of cable and finally selects the most suitable simulation method Q2D combined with Ansys circuit. The finite element simulation modeling and the circuit simulation can effectively simulate the inverter-cable-motor system, which can be a key tool to solve the overvoltage phenomenon at the motor end. In this paper, firstly, through the finite element modeling of the power cable, a finite element model matching the characteristic parameters of the cable is obtained, a high-frequency motor model is established in the circuit, and the frequency response of the cable and the motor is obtained through experimental and simulation comparison. This confirms the validity of the finite element simulation. And through the inverter drive regulation analysis of switching frequency, duty cycle on the motor end overvoltage, and cable length and motor end relationship, accurate simulation modeling will provide an effective way to analyze the motor overvoltage phenomenon and help to better simulate the inverter-long cable-motor system.**

Index Terms-- **Long cable, finite element simulation, overvoltage, passive filters**

I. Introduction

When inverters and motors are far apart, they need to be connected with long cables. Voltage reflections occur when the PWM voltage from the inverter output is transmitted through long cables [1]. This causes the inverter voltage transmitted through the long cable to cause nearly twice as much overvoltage at the motor terminals, increasing the already high *dv/dt* amplitude. And in the PWM drive system, the PWM inverter output pulse will rise and fall in a very short period of time when the PWM inverter switching device is rapidly on and rapidly off, so there is a high voltage change rate *dv/dt* to make the inverter drive motor to produce a large shock [2]. This will cause insulation damage or even insulation breakdown of the motor or cable [3]. As a result, this shortens the service cycle of the motor and in severe cases can burn out the motor and cables.

Normally long cable-motor overvoltage analysis mostly uses transmission line theory to build a mathematical model and MATLAB to analyze the whole system in [4] and [5]. However, the cable model of MATLAB can only simulate the cable model by adding the transmission line model RLGC data. With the increasing demand for cable types in today's marketplace, the requirements for cable

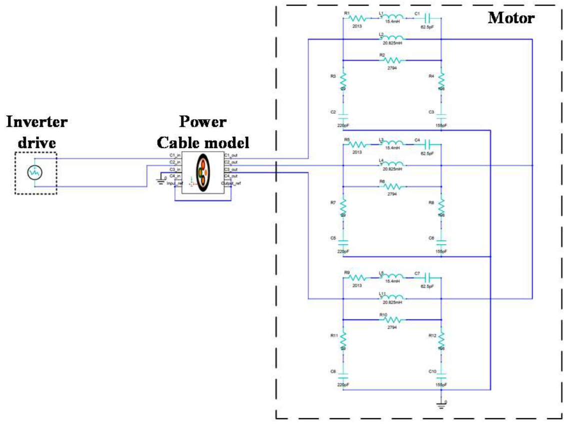


Fig. 1: Ansys Circuit of Inverter-cable-motor system model.

materials are becoming more accurate, and the finite element analysis of ANSYS can not only set the cable material but also directly obtain various characteristics of the cable, and then coupled with Ansys circuit, time domain frequency domain analysis function can be coupled to better simulate the inverter-long cable-motor system for more accurate simulation of motor end overvoltage phenomenon.

In this paper, a four-wire shielded cable modal is proposed in Section II. This model will connect the PWM inverter and filter to the high-frequency AC motor [6]. The transmission characteristics of each unit length of cable are also analyzed and compared by means of finite element method simulation, and the characteristics of the cable, inverter, and motor are studied in detail. Section III will analyze the motor terminal overvoltage phenomenon theoretically in terms of switching frequency, the different lengths, the different duty cycles, and the different rise times of the PWM inverter, and research the effect on the motor terminal voltage at different conditions through simulation. In Section IV, to reduce overvoltage at the motor terminal, two passive filter designs are used. The first filter is installed in the back of the inverter before the cable, this classical RLC filter can improve the rise time of the motor voltage to a large extent to reduce the overvoltage. And the second type of filter is installed before the motor, the reflection coefficient of the voltage wave is matched to the input impedance at the motor terminal to suppress overvoltage. The simulation was conducted to compare the effects of different types of filters before and after use and to verify the feasibility and effectiveness of the filters.

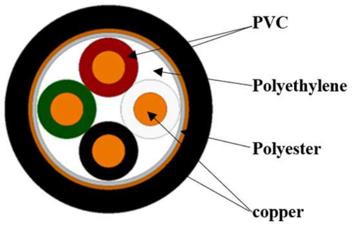


Fig. 2: Cable cross-section and material.

II. Modeling of the Shielded Cable

A. Format simulation and measurement of the cable section

A cross-linked polyethylene cable is considered in this research because of its high mechanical strength, good heat resistance, and good reliability of power transfer. For the cable, 4-mm^2 of the extent is selected and modeled. Fig. 1 shows the cross-section and material of the cable. As can be seen in the figure, the cable includes four wires with a shield.

A scattering parameter (S-parameter) [7] is used to describe the characteristics of the circuit in this paper. By modeling the cable in HFSS, Q3D, and Q2D software from Ansys, the S-parameter curves are obtained. Figs. 2 and 3 compare the impedance curves using different software for the cable length of 100 meters.

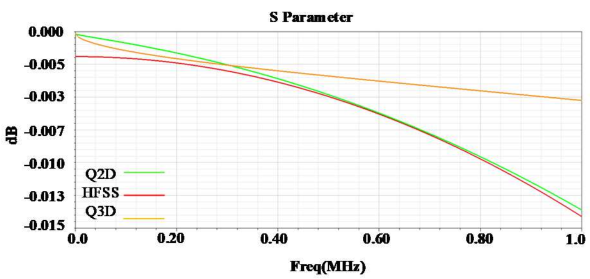


Fig. 3: Simulation results of S-parameter.

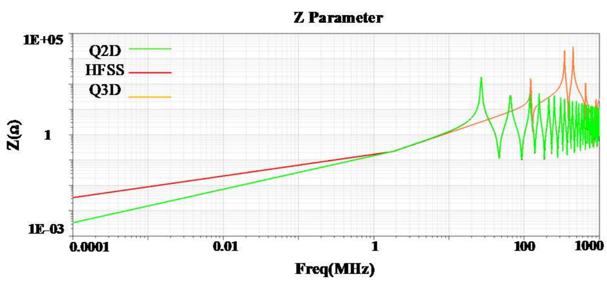


Fig. 4: Simulation results of Z-parameter.

In Fig. 2, the frequency range is selected between 100 Hz and 1 MHz In Fig. 3, it is chosen as 100 Hz and 1 GHz. According to the simulation results, the s-parameter curve of Q3D software is different from the other two simulations when the S-parameter and Z-parameter are obtained, and the Z-parameter curve starts from 1.8MHz and deviates greatly from Q2D and HFSS software. In contrast, HFSS and Q2D software is more stable. As Q2D software is more suitable for this article than other simulation methods, the cables are arranged symmetrically in cross-section and the symmetrical position is constant with respect to the long cable, the twisted shape inside the cables can be ignored, and the Q2D software is selected further analysis.

Since this paper focuses on the overvoltage phenomenon in differential mode (DM) mode, we compare the cable DM-OC impedance in Q2D simulation and actual measurement cases in Fig. 5 and motor DM impedance [8] in Fig. 6, Because one of the high-frequency motor models reported shows that 1 MHz the motor can be expected to be an open circuit [9]. respectively. The proposed cable and high-frequency motor models shown in Fig. 7 are in good agreement with the experimental results. The agreement between experiment and simulation can prove the feasibility of cable-motor system simulation for more accurate overvoltage analysis.

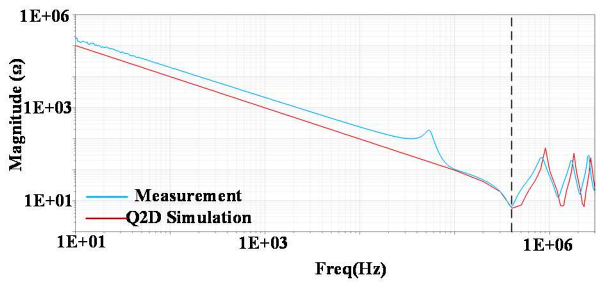


Fig. 5: 100m Cable (Q2D and Measurement) input impedance: DM-OC.

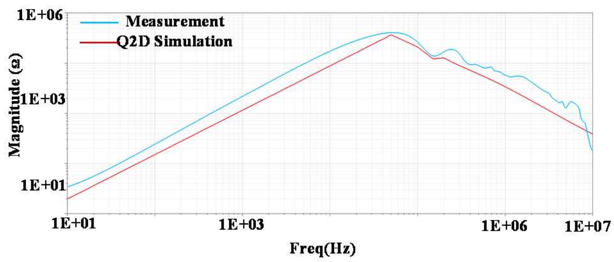


Fig. 6: High-frequency motor (Circuit and Measurement) DM impedance.

III. Simulation Results Using a Practical High-Frequency Motor Model

For verification, the simulation results with practical high-frequency motor and cable models are offered in this paper. In this study, a 3.7 kW induction motor is adopted. Fig. 7 shows the equivalent circuit of the high-frequency motor model. The parameters in the model are obtained by practical measurement. This model is combined with the three-phase inverter model implemented in the Ansys circuit. Different pulse duty cycles of the inverter drive: 0.5, 0.88. Switching frequency 2kHz 10kHz 20kHz. And lengths from 5m to 300m, the effect of a DC link voltage of 600V on the overvoltage at the motor terminals has been analyzed in various simulations as explained above.

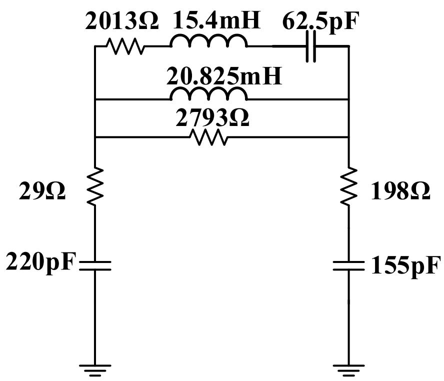
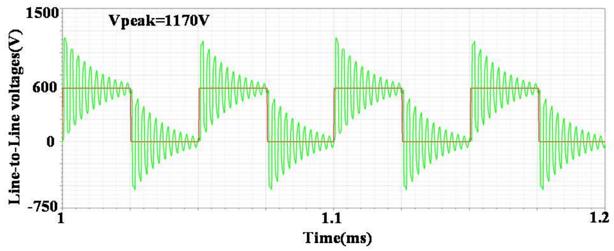


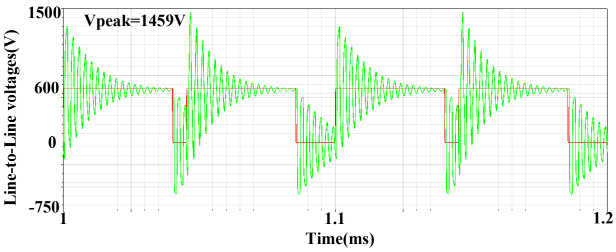
Fig. 7: parameters of the motor.

A. Effect of inverter drive duty cycle on motor terminal line voltage

Single-phase PWM drive and high-frequency motor and Q2D cable finite element model were established through Ansys circuit responsible for the simulation. The simulation parameters are set as follows: inverter output voltage pulse amplitude 600V, fundamental frequency 60Hz, switching frequency 10kHz, cable length 100m, duty cycle 0.5,0.88, and simulation waveform shown in Fig. 8.



(a)



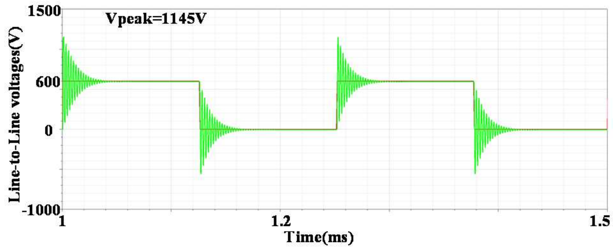
(b)

Fig. 8: Relationship between Duty Cycle and Motor Terminal Line Voltage(a):0.5. (b):0.88

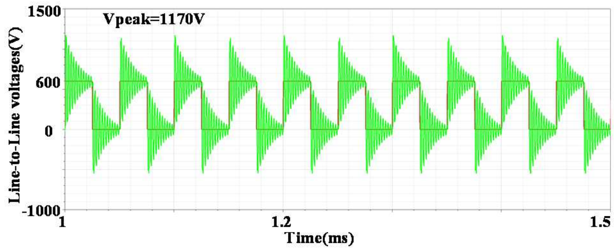
In Fig. 8, the switching mode of the PWM could affect the magnitude of the motor terminal voltage, from which it can be seen that the motor terminal voltage could reach more than 200% of the PWM pulse voltage in the case of polarity reversal and pulse narrowing [10].

B. Effect of switching frequency on motor terminal line voltage

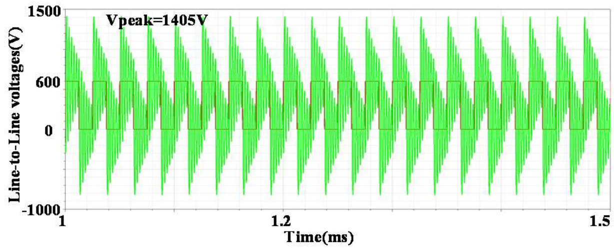
Single-phase PWM drive and high-frequency motor and ANSYS Q2D cable finite element model was established through Ansys circuit responsible for the simulation. The simulation parameters are set as follows: inverter output voltage pulse amplitude 600V, fundamental frequency 60Hz, cable length 100m, inverter rise time 150ns, duty cycle 0.5, switching frequency 2kHz 10kHz 20kHz, and simulation waveform shown in Fig. 9.



(a)



(b)



(c)

Fig. 9: Relationship between switching frequency and motor terminal line voltage (a):2kHz. (b):10kHz. (c):20kHz.

In Fig. 9, the effect on the overvoltage at the motor end is higher as the switching frequency increases, because the oscillation generated by the rising edge of the PWM pulse starts before the oscillation generated by the falling edge of the pulse ends as the switching frequency increases. This leads to a double reflection that can cause the voltage at the motor terminals to exceed two times.

C. Effect of cable length on motor terminal line voltage

Single-phase PWM drive and high-frequency motor and Q2D cable finite element model were established through Ansys circuit responsible for the simulation. The simulation parameters are set as follows: inverter output voltage pulse amplitude 600V, fundamental frequency 60Hz, duty cycle 0.5, switching frequency 10kHz, cable length 5m-300m, and simulation waveform shown in Fig. 10.

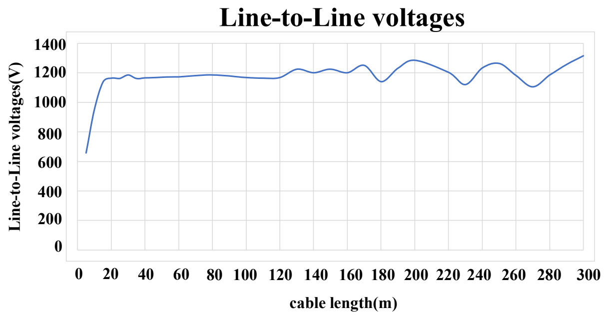


Fig. 10: Relationship between different cable lengths and motor terminal line-to-line voltage.

The simulation is carried out with different lengths of cables to observe the effect of different lengths of cables on the overvoltage at the motor terminal. It can be seen in Fig. 10 that with the increase in cable length, the motor terminal voltage is not always a rising state, before 20m the motor terminal voltage becomes a rising trend, after 20m it tends to stabilize, around 120m as the cable length increases, the cable damping component appears to dominate in a specific length section, and the motor terminal voltage repeats the trend of falling and rising again.

IV. Passive Filter Design

A. Modeling design of RLC filters for overvoltage suppression

Since it is a uniform transmission line, the characteristic impedance of the long cable is 39Ω by HFSS TDR simulation. The high-frequency pulses generated by the PWM are propagated between the motor and the long cable. According to the transmission line theorem, if the impedance at the motor terminal is equal to the characteristic impedance of the cable, the reflection coefficient at the motor end is 0. The incident wave energy will be completely absorbed by the resistor so that no electrical reflection occurs on the cable. This situation is known as perfect matching. Therefore, to minimize the voltage reflection energy, the impedance must be matched at high-frequency conditions, so the filter resistance should be chosen to be equal to the characteristic impedance of the cable, i.e., $R_f = Z_0 = 39\ \Omega$. The structure of the two filters in this paper is shown in Fig. 11. has been proposed in [11], [12] the purpose is to reduce the *dv/dt* of the PWM output voltage, the overvoltage, and high-frequency oscillation on the motor side. where R_f is the filter resistance and L_f is the filter inductance. C_f is the filter capacitance.

Assuming that the reflection at the motor end is a complete reflection, then there is the function (1). where H(s) is the filter transfer function, R_f, L_f, and C_f are the resistance, inductance, and capacitance of filters respectively; $\mathcal{E}$ is the damping factor (2), ω_n is the natural oscillation frequency of the filter, (3) based on the relationship between $\mathcal{E}$ and the unit step response rise time t_r=1µs. From equation and $\mathcal{E}$, L_f, C_f must satisfy (4) and (5).

$$H(s) = \frac{(R_f/L_f)s + 1/(L_f C_f)}{s^2 + (R_f/L_f)s + 1/(L_f C_f)} = \frac{2\varepsilon\omega_n s + \omega_n^2}{s^2 + 2\varepsilon\omega_n s + \omega_n^2} \quad (1)$$

$$\varepsilon = (R_f/2)\sqrt{C_f/L_f} \quad (2)$$

$$\omega_n^2 = 1/(C_f L_f) \quad (3)$$

$$t_r \le 0.78/\omega_n \quad (4)$$

$$L_f C_f \ge (t_r/0.78)^2, L_f \ge (R_f t_r)/1.56, C_f \ge \frac{t_r}{0.78} \times \frac{2}{R_f} \quad (5)$$

It is important that the filter inductance and the filter capacitance should be minimized as much as possible because the larger the value the greater the loss. Through the formula, we can know the minimum value of the filter parameters L_f and C_f is not only related to the filter resistance R_f but also to the rise time t_r. The unit step response rises time t_r =1 µs. The total filter capacitor is used to extend the rise time of the motor terminal voltage to suppress overvoltage at the motor end. The filter inductance is used to set the percentage of voltage overshoot.

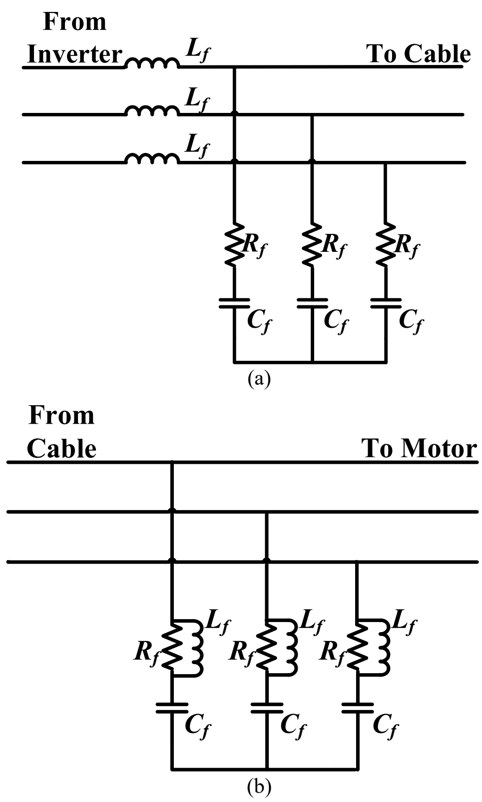


Fig. 11: (a) Inverter output RLC Filter. (b) Motor Terminal RLC Filter.

TABLE I

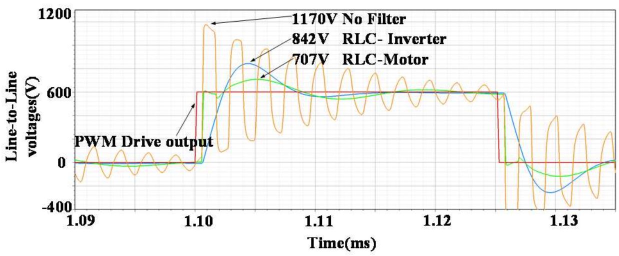
FILTER PARAMETER

Type	R_f(Ω)	L_f(µH)	C_f(nF)
1	39	50	70
2	39	100	70
3	39	50	210

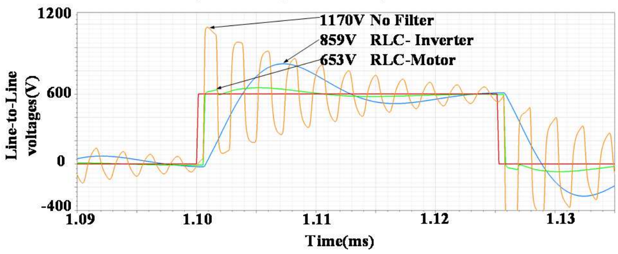
B. Simulation results

In terms of the problems with long cable drive systems, the simulated overvoltage results of the two passive filters and without filters are plotted the parameters for the experiments are summarized in Table 1. And the parameters of the inverter output filter RLC and the motor terminal filter RLC will always be the same, and we will substitute the simulation for three different parameter values (Type1 2 3).

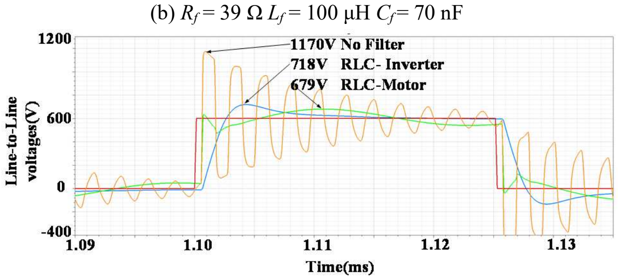
In Fig. 12(a), the line-to-line voltage curve for the case of Type 1 using L_f= 50 μH C_f=70 nF, With the two filters connected, the analog waveform of the overvoltage at the motor end is effectively suppressed. The voltage at the motor end dropped from 1170V to 707V after the motor RLC filter device, effectively reducing the overvoltage by nearly 40 %, and the voltage at the motor end dropped from 1170V to 842V after the inverter output RLC filter device, reducing the overvoltage by nearly 28 %. Type 1 is the method that is close to the minimum value. If the parameters of the filters are further modified, the overshoot can be reduced even further. As can be seen from Type 2 of Fig. 12(b), the motor terminal voltage drops to 653V, and the inverter output voltage rises to 859V at the motor RLC device with constant filter resistance capacitance L_f =100 μH. As shown in Type 3 of Fig. 12(c), in the case of constant filter resistance L_f= 50 μH C_f= 210 nF, both filter devices under the voltage overshoot by less than 20 % [13], both achieve the best results. But the capacitance value is too large, making higher costs and an increase in losses.



(a) R_f = 39 Ω L_f = 50 μH C_f = 70 nF



(b) R_f = 39 Ω L_f = 100 μH C_f = 70 nF



(c) R_f = 39 Ω L_f = 50 μH C_f = 210nF

Fig. 12: Line-to-Line voltages at motor terminals for each different filter type and peak voltage:(a). (b). (c).

V. Conclusions

For the overvoltage problem at the motor end caused by the long cable drive of the inverter, this paper is based on the transmission line theory to verify the effectiveness of the proposed two passive filter design methods, Ansys circuit was used for simulation. The high-frequency inverter-cable-motor model is derived and applied to finite element software for simulation, which also accurately explains the overvoltage phenomenon and is verified by simulation.

Inverter output RLC Filter can mitigate the voltage stress, presenting adequate attention and setting time.

Motor Terminal RLC Filter the motor has the lowest overvoltage, but the voltage pulse rise time is still very short. A voltage pulse rise time that is too short leads to wave reflections and common mode currents inside the machine windings.

It is demonstrated that the designed filter effectively reduces the overvoltage amplitude and suppresses the *dv/dt*. At the same time, the developed model provides a reference for testing another filter The model is also used as a reference to verify the design of other filters.

Acknowledgment

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