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

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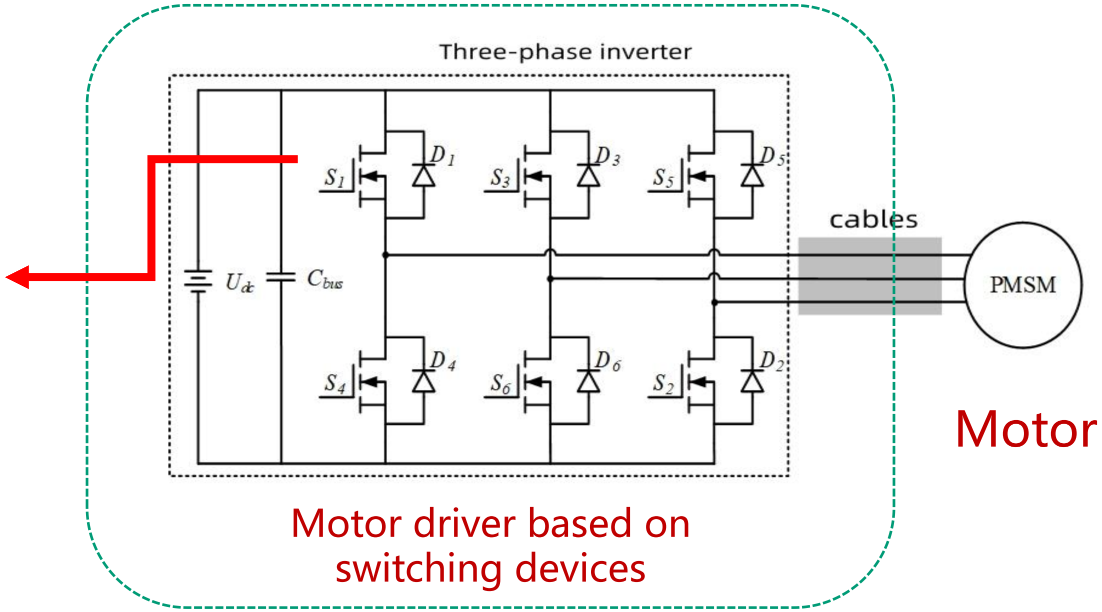
Research background

1.Research background

GaN HEMT



Motor

Motor driver based on switching devices

- ➢ High transient voltage (dv/dt)
- ➢ High transient current (di/dt)

- ➢ **Fast switching speed**
- ➢ **High switching frequency**
- ➢ **High power density**
- ➢ **Low loss**

GaN devices have obvious advantages

- ➢ **Design of driving circuit under high dv/dt**
- ➢ **Motor end overvoltage**
- ➢ **Shaft current**
- ➢ **High-frequency problem**

It also brings new problems

Research theme：motor end overvoltage suppression

- **Theoretical model of motor terminal voltage**

→

① To solve the distributed parameter transmission line equivalent circuit

② Mathematical description of voltage of the motor

- **Analysis of influencing factors of motor terminal voltage**

→

① Voltage rise time

② Cable length

- **Simulation verification and double overvoltage problem**

→

① Simulation of motor terminal voltage under different voltage rise time

② Motor end voltage waveform under different transmission cable lengths

③ Analysis of over double overvoltage at high frequency motor end

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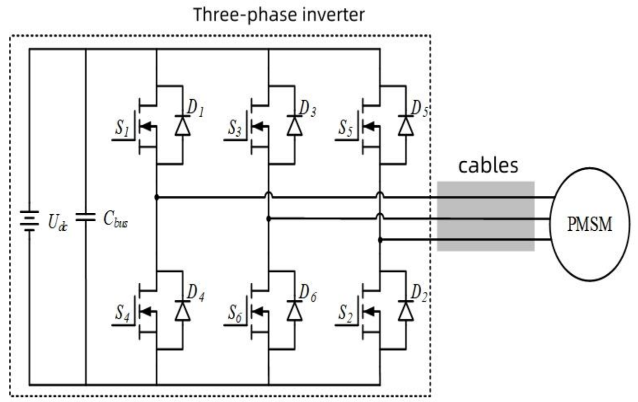
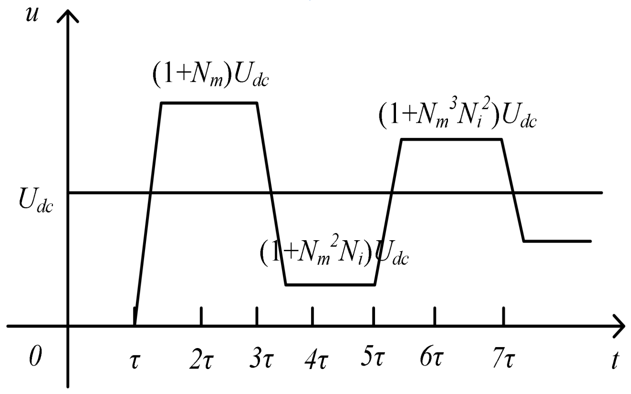
Theoretical model of motor terminal voltage

2.Theoretical model of motor terminal voltage

Research objective: To analyze the influencing factors of overvoltage and provide theoretical basis for overvoltage suppression

Principle of wave reflection





The motor does not match the cable impedance

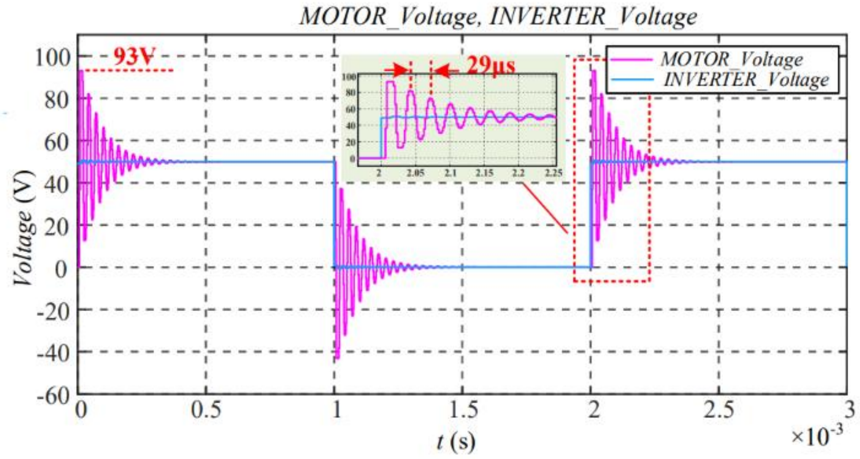
Voltage wave reflection

Motor overvoltage

Oscillation period: 4τ (τ is the travel time)

Maximum voltage: It has to do with the reflection coefficient

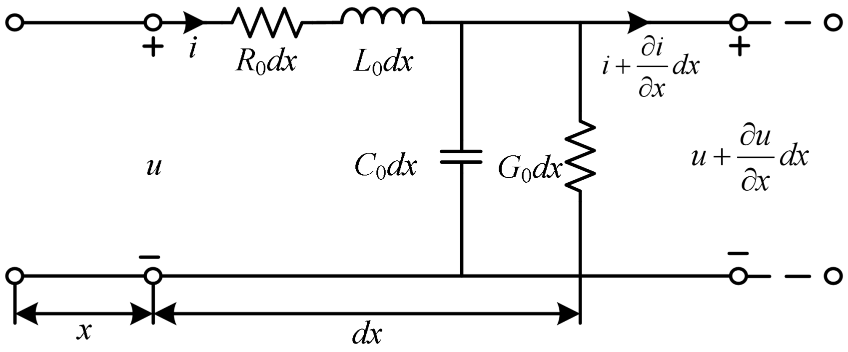
The bus voltage is 50V, the motor impedance is 4000Ω, the inverter impedance is 5Ω, the transmission cable length is 2km, the distributed inductance L_0 is 1mH/km, the distributed capacitance C_0 is 13nF/km, and the damping resistance R_0 is 0.05Ω/km. The calculated reflectance coefficients of motor end N_m and inverter end N_i are 0.86 and −0.96, respectively, and the voltage wave transmission time τ is 7.21μs.



2.Theoretical model of motor terminal voltage

Research objective: To analyze the influencing factors of overvoltage and provide theoretical basis for overvoltage suppression

Distributed parameter transmission line theory



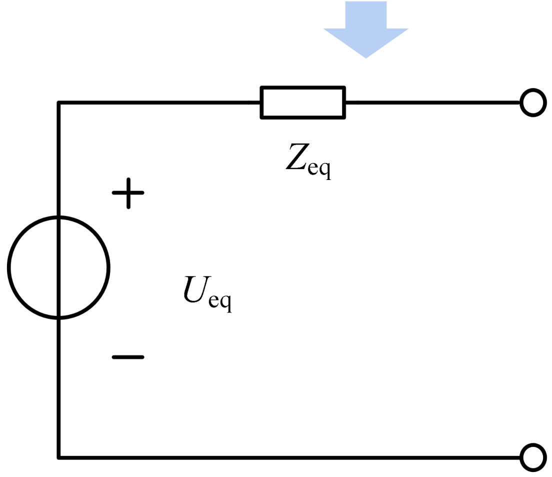
$$\begin{cases} -\dfrac{\partial u}{\partial x} = \cancel{iR_0} + L_0\dfrac{\partial i}{\partial t} \\ -\dfrac{\partial i}{\partial x} = \cancel{G_0 u} + C_0\dfrac{\partial u}{\partial t} \end{cases}$$

Theoretical model of motor terminal voltage

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

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

$$(2k-1)\tau < t \le (2k+1)\tau$$



Motor terminal over-voltage influencing factors

- Motor reflection coefficient N
- Cable length l
- Voltage wave transmission speed in the cable v(cable distribution parameter)
- Inverter output voltage U_i (voltage rise time)

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Analysis of influencing factors of motor terminal voltage

3.Analysis of influence factors of motor end overvoltage ---Cable length and Voltage rise time

In fact, the inverter output PWM voltage pulse is not an ideal step signal, and its rise takes a certain time.

Inverter output voltage is:

$$u_i(t) = \begin{cases} \frac{t}{t_r} U_{dc} & 0 < t \le t_r \\ U_{dc} & t > t_r \end{cases} \qquad 2(m-1)\tau < t_r \le 2m\tau$$

When $t = t_r + \tau$, the maximum motor end voltage is obtained:

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

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

According to the formula, the maximum voltage of the motor terminal is (1+N)U_{dc}. With the increase of voltage rise time, the maximum voltage of the motor terminal gradually decreases from (1+N)U_{dc}, and finally approaches the bus voltage U_{dc}. 2τ is the voltage critical rise time t_{r0}, that is

$$t_{r0} = 2\tau = 2l / v$$

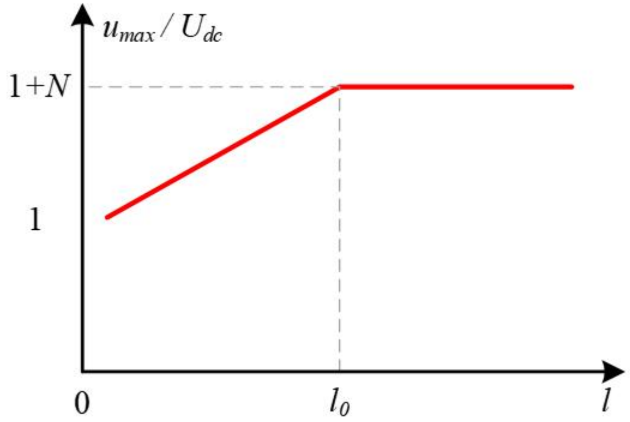
The critical voltage rise time is related to the length of the transmission cable and the propagation speed of the voltage wave, and the critical length of the transmission cable is defined as:

$$l_0 = v\tau = vt_r / 2$$

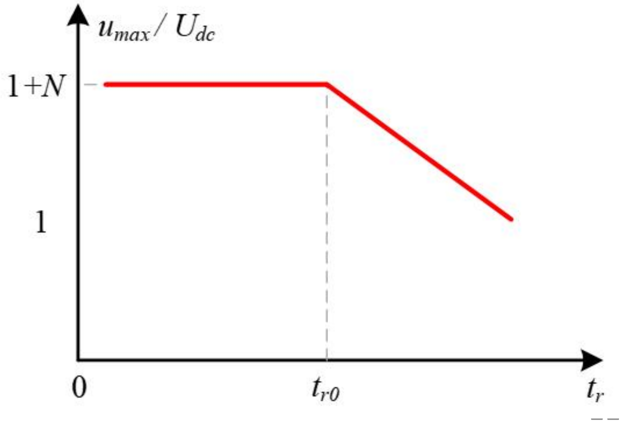
3.Analysis of influence factors of motor end overvoltage
---Cable length and Voltage rise time

The effect of cable length and voltage rise time on the maximum voltage at the motor end is shown in the figure below. The analysis shows that:

- 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 at the motor end reaches $(1+N)U_{dc}$ and no longer increases with the increase of the cable length.**



- 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 $(1+N)U_{dc}$.**



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Simulation verification and double overvoltage problem

4.Simulation verification and double overvoltage problem

Simulation verification

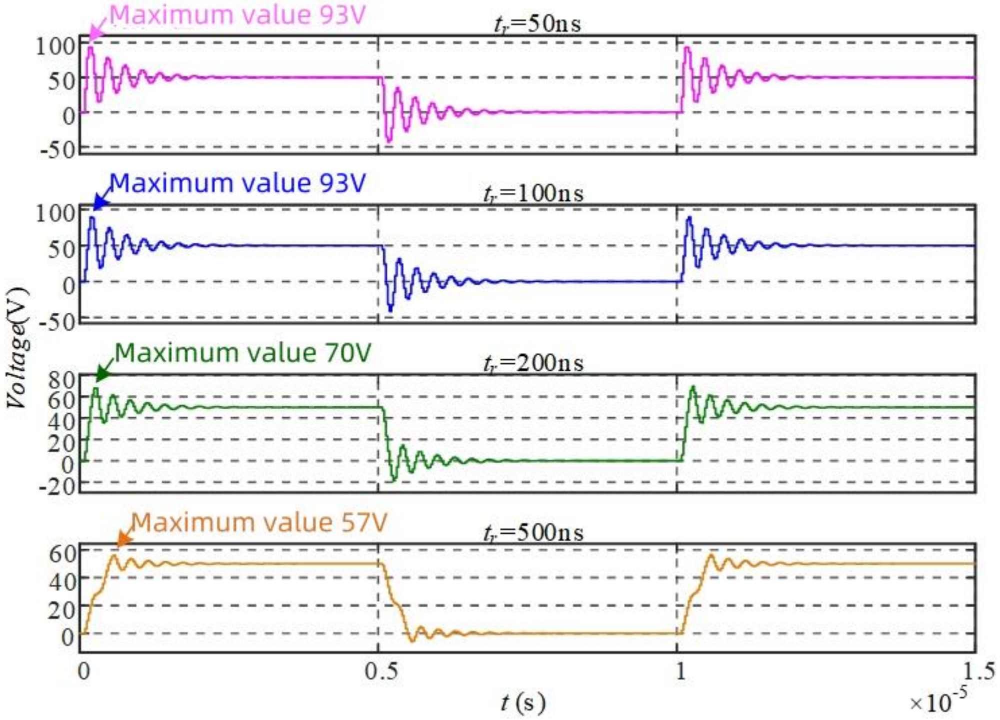
Simulation condition
bus voltage is 50V, motor impedance is 4000Ω, inverter impedance is 5Ω, distributed inductance L_0 is 1mH/km, distributed capacitance C_0 is 13nF/km, damping resistance R_0 is 0.05Ω/km.

The speed at which voltage waves are transmitted in a cable is

$$v = \frac{1}{\sqrt{L_0 \times C_0}} = 2.77 \times 10^8 \text{ m/s}$$

According to the formula $t_{ro} = 2\tau = 2l/v$ The voltage critical rise time **tr_0=144ns** is obtained.

The simulation results show that the motor terminal voltage decreases with the increase of voltage rise time.
When the voltage rise time exceeds three times the critical rise time (six times the voltage transfer time), the maximum voltage at the motor end is significantly suppressed.



When the transmission cable length is constant the simulation waveform of motor terminal voltage under different voltage rise time

4.Simulation verification and double overvoltage problem

Simulation verification

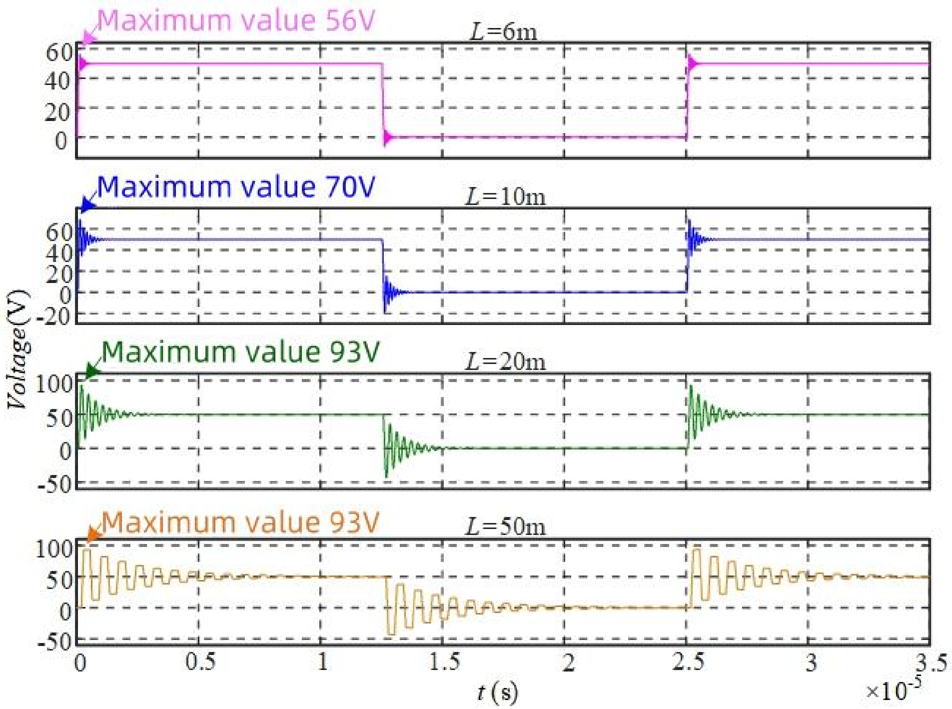
Simulation condition

bus voltage is 50V, motor impedance is 4000Ω, inverter impedance is 5Ω, distributed inductance L_0 is 1mH/km, distributed capacitance C_0 is 13nF/km, damping resistance R_0 is 0.05Ω/km.

According to the formula $l_0 = v\tau = vt_r/2$,the critical length of transmission cable **l_0=13.85m**.

The simulation results show that the motor terminal voltage increases with the increase of cable length.
When the transmission cable length is 20m or 50m, it exceeds the critical length, and the maximum terminal voltage of the motor reaches 93V and does not increase. The value is equal to $(1+N)U_{dc}$.

The longer the transmission cable, the smaller the voltage oscillation frequency and the longer the time to steady state. The simulation results are consistent with the theoretical analysis.



When the voltage rise time is constant the simulation waveform of motor end voltage of transmission cables of different lengths

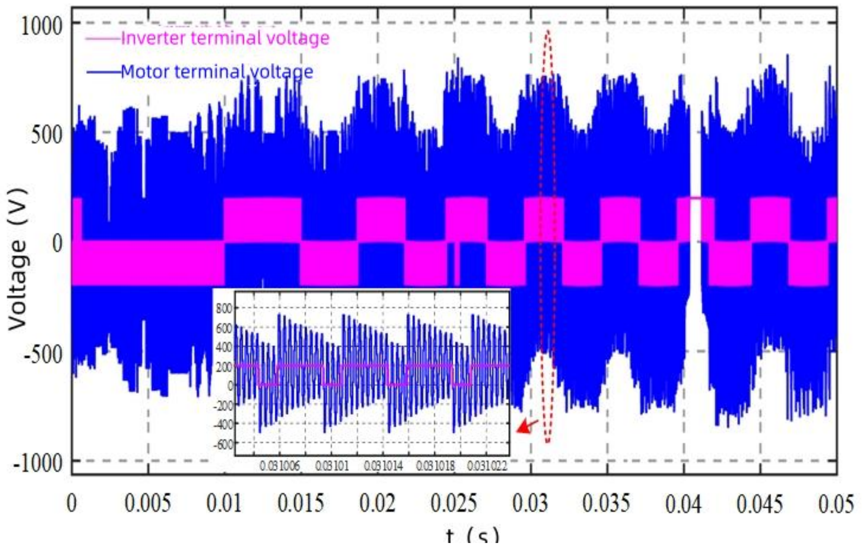
4.Simulation verification and double overvoltage problem

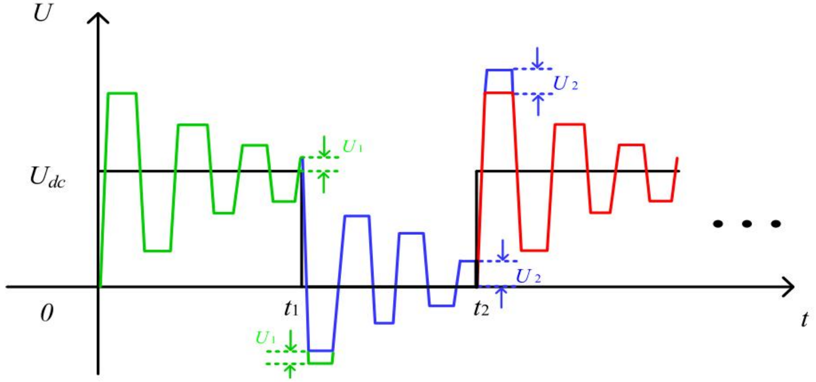
Analysis of over double overvoltage at high frequency motor end

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.

With the increase of the switching frequency, the output voltage pulse width of the inverter gradually decreases. If the switching frequency continues to increase, the PWM voltage pulse width is small enough, and the motor terminal voltage is the overlapping of the incident wave and the reflected wave of multiple stages, and its value will exceed 3 or 4 times the inverter terminal voltage, which has a huge impact on the motor winding insulation.

The DC bus voltage is 200V, the switching frequency is 100kHz, and the cable length is 25m. As can be seen from the figure, **the maximum voltage of the motor terminal line is about 800 V, reaching 3-4 times the output voltage of the inverter, resulting in serious overvoltage phenomenon, affecting the insulation performance of the motor and even affecting the stability of the system.**





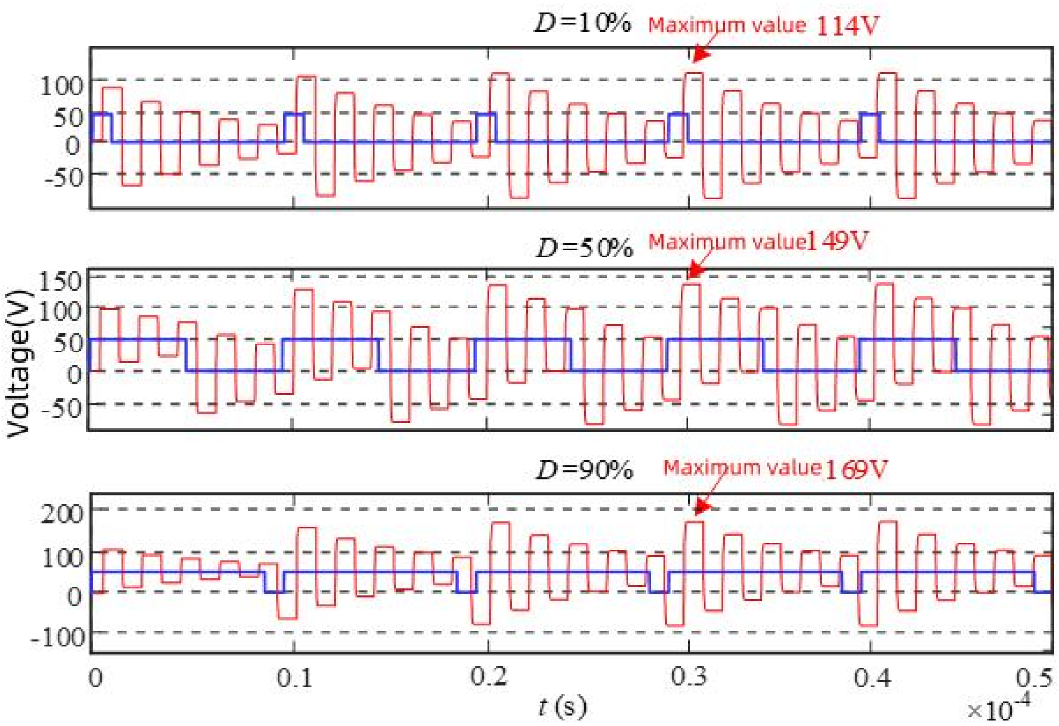
4.Simulation verification and double overvoltage problem

Analysis of influence of Duty ratio on overvoltage

As can be seen from the previous page, the overvoltage attenuation period generated by the high level voltage pulse is the entire PWM cycle. The attenuation time of low-level voltage is determined by the duty cycle ratio, the duty cycle is low, the low level time is long, the resulting overvoltage oscillation attenuation time is long, and the overvoltage oscillation amplitude is small at the end of one cycle. On the contrary, the unattenuated overvoltage amplitude will be superimposed to the next cycle, resulting in an increase in the overvoltage oscillation amplitude. Therefore, the phenomenon of overvoltage is related to the PWM duty cycle.

In a PWM cycle, the attenuation time of low level pulse is shorter than that of high level pulse, so the incomplete attenuation of low level overvoltage pulse is the main reason for more than twice the overvoltage at the motor end.

The bus voltage Udc is 50V, the cable length is 15m, and the switching frequency is 100kHz. The overvoltage phenomenon at different duty ratios is shown in the figure.



Simulation diagram of load side overvoltage with different duty cycle

4.Simulation verification and double overvoltage problem

Analysis of over double overvoltage at high frequency motor end

When the motor end voltage is 50% duty cycle, the motor end overvoltage is as follows, where t is the line voltage high level time, then the switching frequency is 1/4t.

$$(1+N+N^{\frac{t/\tau}{2}}+N^{\frac{2t/\tau}{2}}+N^{\frac{3t/\tau}{2}}+N^{\frac{4t/\tau}{2}}+\ldots)U_{dc}>3U_{dc}$$

When the bus voltage is 50V, the voltage rise time is 10ns, the transmission cable is 15m, and the distributed inductance and capacitance are 2.5mH and 60nF respectively, the characteristic impedance of the cable is 200Ω, the motor end impedance and the inverter impedance are 4000Ω and 5Ω respectively.
At this time, the motor end reflection coefficient is 0.91, and the inverter reflection coefficient is approximately -1.
When the above parameters are used, **the switching frequency f that makes the motor end overvoltage reach three times the output voltage of the inverter can be obtained**

$$f=\frac{1}{8\tau\log_N(\frac{2-N}{3-N})}$$

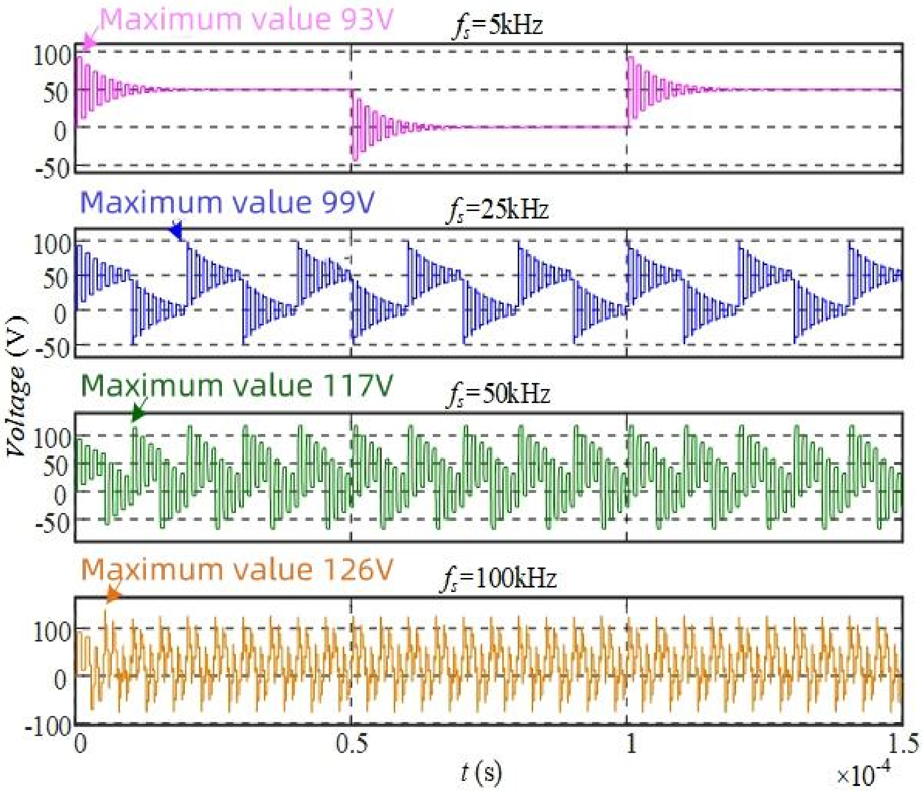
$$=\frac{1}{8\times\frac{15}{8.5\times10^7}\times\log_{0.91}(\frac{2-0.91}{3-0.91})}=1.026\times10^5\,\mathrm{Hz}$$

4.Simulation verification and double overvoltage problem

Analysis of over double overvoltage at high frequency motor end

As can be seen from the figure, with the increase of switching frequency, the maintenance time of high voltage pulse becomes shorter, the reflection voltage does not have enough time attenuation, and the superposition of multi-stage reflection voltage makes the motor end voltage gradually increase. When the switching frequency reaches 102kHz, the motor end overvoltage reaches 3 times the output voltage of the inverter.

When the cable length is determined, the high switching frequency is the main reason that the motor end voltage exceeds twice the bus voltage.



Motor terminal voltage simulation waveform under different switching frequency

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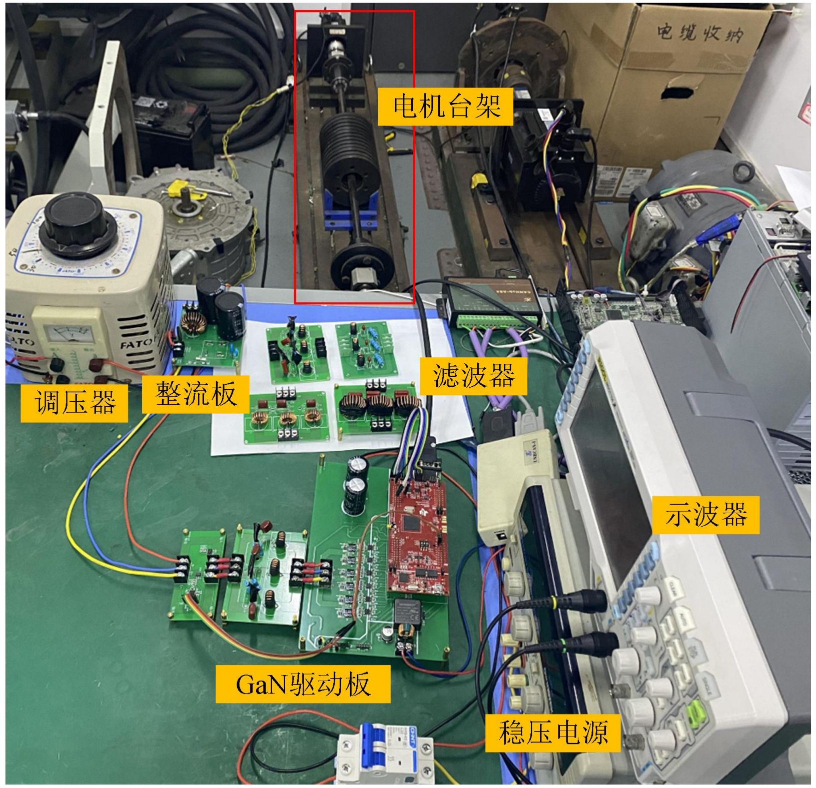
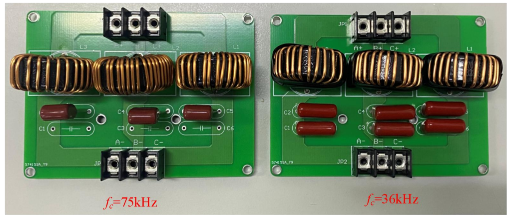
Experimental verification and summary

5. Contents and conditions of systematic experiments

Experimental platform



dv/dt filter



A sine wave filter

Experimental content

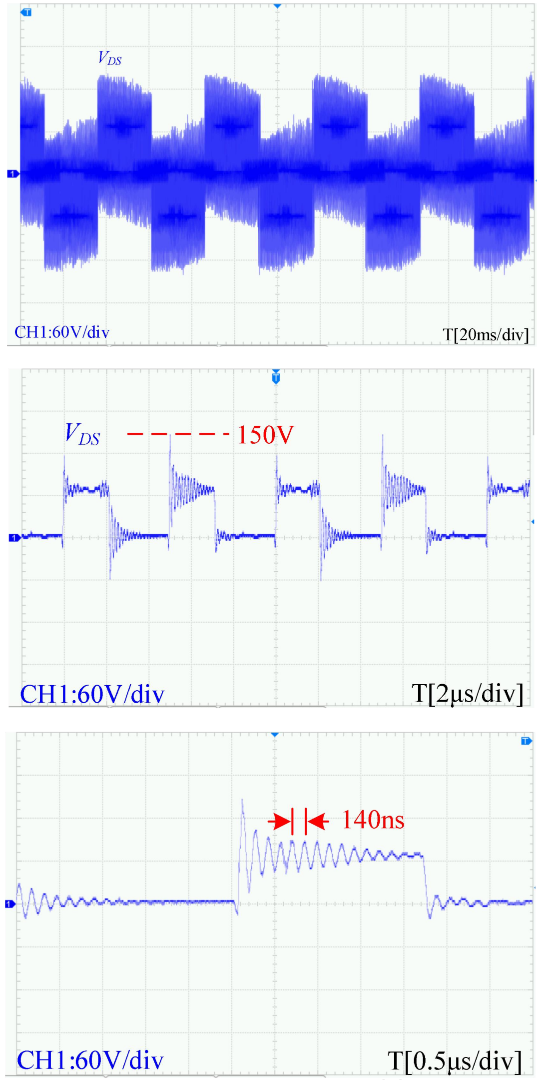
- Motor end overvoltage phenomenon
- Verification of system resonance suppression with LC filter
- The dv/dt filter suppresses the motor end overvoltage
- GaN HEMT motor drive system performance test

Experimental condition

- Bus voltage 60V
- Switching frequency 100kHz
- Given speed 500rpm
- The inverter is connected to the motor by a 17AWG cable with a length of 3m

Test the line voltage 10cm from the motor end

Motor terminal voltage



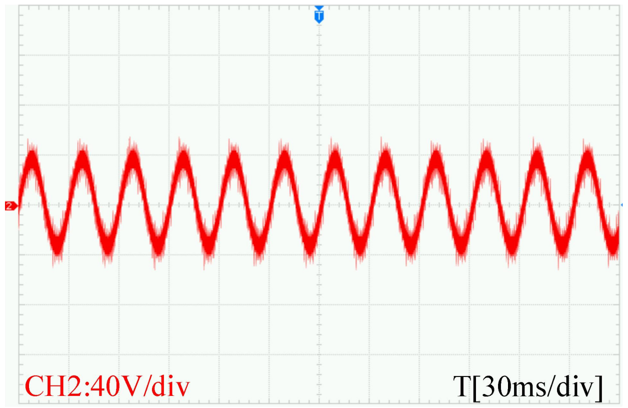
5.The filter suppresses the motor terminal voltage

Sine-wave filter:
Verify overvoltage suppression and system stability

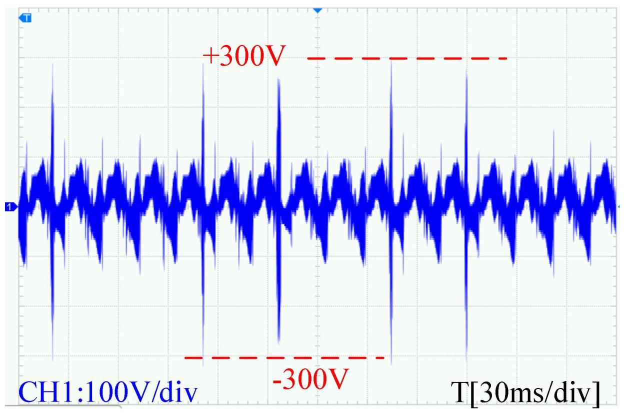
Experimental condition

- Bus voltage 60V (regulated power supply)
- Switching frequency 100kHz
- The given speed is 300rpm
- Carrier count midpoint current sampling
- Filter parameters :100uH, 200nF, 44nF

Motor terminal voltage test results



Filter cut-off frequency 36kHz



Filter cut-off frequency 75kHz

When the delay time of digital control system is Ts and the resonant frequency is 36kHz, the system is stable. When the resonant frequency is 75kHz, the resonance phenomenon occurs. The effectiveness of suppressing LCL resonance based on digital control combined with filter design is verified

5. Summary and prospect

Summary

☐ Thevenin equivalent circuit of transmission cable is derived, and the theoretical model of motor terminal voltage is obtained.

☐ According to the theoretical model of motor end voltage, the analysis shows that short voltage rise time or long cable will aggravate the motor end overvoltage.

☐ The overvoltage caused by high switching frequency is mainly analyzed. When the cable length is determined, the high switching frequency is the main reason that the motor terminal voltage exceeds twice the bus voltage.

☐ Simulink simulation model of motor terminal voltage was established for verification.

Prospect

☐ At high switching frequency, the system delay is considered, and the necessary delay compensation is added to the control to further improve the control bandwidth of the system.

☐ For the inductance parameter variation of soft saturation filter, the three phase asymmetry caused by it can be deeply analyzed.

☐ In some cases, the current sensor is in front of the filter, and the mathematical model of the controlled object should be reconsidered.

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