Analysis on the Common-mode Voltage and its Effects of a Marine SPWM Frequency Conversion Speed Regulation System

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Abstract. The AC frequency conversion speed regulation technology has been used widely in the ship field for its excellent operating and control characteristics, whereas it can also bring out negative effects such as the common-code voltage on the drive system. The analysis is made on the common-mode voltage of the SPWM frequency conversion speed regulation system, including its generation mechanism, spectrum features, negative effects and suppression methods, which provides beneficial reference and enlightenment for the improvement of the SPWM frequency converter technical performance as well as the equipment maintenance and management.

1. Introduction

With the rapid development of the technology of power electronics, automatic control and computers, as well as the ever-growing demands for safety, maneuverability and automatics, the comprehensive performance of the AC frequency conversion speed regulation technology has been greatly improved and widely applied in the ship field as well[1].

The SPWM (Sinusoidal Pulse Width Modulation) frequency conversion speed regulation system is applied in the air-conditioners and refrigerating plant of a vessel, which has superior drive and control characteristics. Meanwhile, the frequency converters can have influence on motor efficiency, temperature rise, noise, vibration, cooling, insulation, etc., which may give rise to problems such as bearing failure, winding insulation breakdown and electromagnetic interference (EMI). Some phenomena are related to the common-code voltage caused by the frequency converters. In the marine low-voltage frequency conversion speed regulation system, the common-code voltage is usually neglected for its amplitude is not large. However, it can reduce the reliance of the system and influence the normal functioning, and it’s necessary to analyze and discuss it.
The frequency conversion speed regulation simulation system is established by use of the software MATLAB based on the system structure, the mathematical model and the modulation parameters of the SPWM frequency converters of the air-conditioner and refrigerating plant. Combined with the simulation results, the generation mechanism, the influencing factors, the side effects and the suppression methods are analyzed, which bears great realistic significance to the technical innovation and equipment maintenance and management.

2. Overview of a marine frequency conversion speed regulation system

The vessel servo motors of the air-conditioners and refrigerating plant have changeable working conditions, frequent start-ups, and demands for the precision of auto valves openness, so the frequency conversion speed regulation system is adopted, equipped with several kinds of voltage type, AC-DC-AC, SPWM frequency converters. As Figure 1 shows, the bipolar control mode is adopted in the inverter circuit of the frequency converter. In the half cycle of the modulated sinusoidal wave, the triangular carrier wave is continuously changing between the positive and negative poles, and the SPWM wave is also changing between the positive and the negative. N times of the modulated wave frequency can be modulated to acquire the desired SPWM waveform[2].

![Figure 1. Bipolar SPWM control mode waveform](image)

The frequency conversion drive system structure is shown in Figure 2, in which a two-level, voltage type, AC-DC-AC frequency converter is adopted, consisting of three parts, i.e., the rectifying circuit, the intermediate circuit (DC-Link) and the inverter circuit. The rectifying circuit is composed of uncontrollable diodes, the DC-Link comprises of two capacitors connected in series, and the inverter circuit contains three legs and six high-frequency switches.

First of all, the rectifier changes the fundamental frequency AC into DC, then the electricity is filtered by the DC bus capacitors, and lastly DC is changed into AC whose frequency and voltage can be modulated[3]. The inverter switch tubes are driven to opening and turnoff by means of the control pulses emitted by the chips according to some algorithm, making the inverter output a group of pulse sequences whose pulse width can be modulated, which takes the place of the sinusoidal wave AC voltage equivalently. The aim of frequency conversion speed regulation can be acquired by modulating the width and period of the pulses. Unlike the triple-phase fundamental frequency AC power supply, there exists a high-frequency common-code voltage between the triple-phase winding neutral point and the DC bus voltage in the star-connected motor fed by the SPWM frequency converter.
3. Analysis on the common-code voltage of the SPWM frequency converter

If the motor is fed by a symmetrical triple-phase fundamental frequency AC power supply, the vector sum of the triple-phase voltages is always zero at any moment. Though the output triple-phase voltages of the frequency converter are distributed by phase difference 120° between each other under the SPWM control mode, the vector sum of the three voltages is not zero, and that is to say, there exists the common code, which is exactly the root cause of the effects such as shaft voltage and shaft current. The control strategies and technical means are searched for to eliminate the common-code voltage by analyzing its essential properties.

3.1. Generation mechanism of the common-code voltage

The common-code voltage is the voltage to earth of the motor triple-phase star-connected stator winding neutral point. To the completely symmetrical star-connected stator winding, the sum of \( i_U, i_V \) and \( i_W \) is similar to zero, and thus

\[
U_{CM} = \frac{(U_U + U_V + U_W)}{3}
\]  

In the above formula, \( U_{CM} \) is the motor terminal common-code voltage produced by the converter, and \( U_U, U_V \) and \( U_W \) are the triple-phase phase voltages outputted by the frequency conversion power supply system, namely, the voltages to earth of the triple-phase stator terminal.

If the motor power supply is symmetrical triple-phase sinusoid AC and the sum of \( U_U, U_V \) and \( U_W \) is zero, the common-code voltage \( U_{CM} \) is zero. However, in the SPWM frequency conversion power supply system there are many kinds of switching opening and turnoff states, and as a result the sum of the triple-phase voltages outputted by the frequency converter is not zero. Namely, the common-code voltage varies periodically with time instead of being zero.

The voltage-clamped neutral point O in the frequency converter intermediate DC-Link is set as the system reference point. When the SPWM mode is adopted, the six switch tubes of the upper and lower legs of the inverter are driven to opening and turnoff, causing the frequency converter to output a series of pulses with equal amplitude but unequal width which are equivalent to the sinusoid AC. The upper and lower switch tubes of the same leg cannot open at the same time to prevent the leg penetrating. If ‘0’ and ‘1’ are represented as the turning on of the upper switch tubes and the lower ones of the same leg respectively, there are three on-off actions at any moment, which sums up to \( 2^3 = 8 \)
kinds of combinations. The switch tube states of the three legs and their corresponding common-code voltages are shown in Table 1.

| Switch tubes of the leg | S_A | S_B | S_C | Common-code voltage U_CM |
|------------------------|-----|-----|-----|--------------------------|
| S_1                    | 0   | 0   | 0   | -U_d/2                   |
| S_2                    | 0   | 0   | 1   | -U_d/6                   |
| S_3                    | 0   | 1   | 0   | -U_d/6                   |
| S_4                    | 0   | 1   | 1   | U_d/6                    |
| S_5                    | 1   | 0   | 0   | -U_d/6                   |
| S_6                    | 1   | 0   | 1   | U_d/6                    |
| S_7                    | 1   | 1   | 0   | U_d/6                    |
| S_8                    | 1   | 1   | 1   | U_d/2                    |

In the above Table 1, U_d is the voltage of the frequency converter intermediate DC Link bus. According to Table 1 we can conclude

\[ U_{CM} = \pm U_d/2 \quad S_1, S_8 \] (2)

\[ U_{CM} = \pm U_d/6 \quad \text{the other switch combinations} \] (3)

As we can see, the voltage to earth of the motor stator winding neutral point at any moment is not zero, and that is to say, there is always a nonzero common-code voltage, which presents step transitions and whose amplitude has relations to the DC bus voltage U_d. The rise time of the switch tubes is only several hundred ns as usual, and the four numerical values \( \pm U_d/2 \) and \( \pm U_d/6 \) will hop quickly with the opening and turnoff states of the switch tubes. As a result, the common-code voltage has a high dv/dt (the change rate of the output voltage), intensely impacts the motor drive system, and is regarded as a kind of high-frequency signal for its amplitude jump frequency is 6 times of the frequency conversion switching frequency.

3.2. Spectrum features of the common-code voltage

If the original phase angle of the modulation wave is 0, the Fourier series expansion of the output triple-phase voltages of the SPWM frequency converter is:

\[ U_1 = \frac{U_d}{2} \left\{ \sin(\omega_1 t) + \sum_{n=1}^{\infty} \left( \frac{4}{n\pi} \right) \sin \left[ \frac{an\pi}{2} \sin(\omega_1 t + \frac{n\pi}{2}) \right] \right\} \] (4)

\[ U_2 = \frac{U_d}{2} \left\{ \sin(\omega_1 t + 120^\circ) + \sum_{n=1}^{\infty} \left( \frac{4}{n\pi} \right) \sin \left[ \frac{an\pi}{2} \sin(\omega_1 t + 120^\circ + \frac{n\pi}{2}) \right] \right\} \] (5)

\[ U_3 = \frac{U_d}{2} \left\{ \sin(\omega_1 t + 240^\circ) + \sum_{n=1}^{\infty} \left( \frac{4}{n\pi} \right) \sin \left[ \frac{an\pi}{2} \sin(\omega_1 t + 240^\circ + \frac{n\pi}{2}) \right] \right\} \] (6)

In the mathematical expression, \( a \) is the modulation depth of the frequency converter; \( \omega_1 \) is the angle frequency of the frequency converter modulation wave; \( \omega_s \) is the angle frequency of the frequency converter carrier wave.
Equations (4)~(6) are the sum of the two parts. One is the angle frequency \( w_1 \) of the fundamental component, and the other is the harmonic component. Substitute the three equations into Equation (1), and then the Fourier expression of the common-code voltage \( U_{CM} \) can be acquired by means of the Bessel function.

\[
U_{CM} = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{U_d}{2n\pi} J_0 \left( \frac{an\pi}{2} \right) \cos(n\omega_1 t) + \\
3 \sum_{n=1}^{\infty} J_1 \left( \frac{an\pi}{2} \right) \{ \cos(k\omega_1 + n\omega_d t) + \cos(k\omega_1 - n\omega_d t) \} \] 
\quad n = 1, 3, 5,..., \quad k = 6l, l = 1, 2, 3,... \tag{7}
\[
U_{CM} = 3 \sum_{n=2}^{\infty} (-1)^{n+1} \frac{U_d}{2n\pi} J_1 \left( \frac{an\pi}{2} \right) \{ \sin(k\omega_1 + n\omega_d t) + \sin(k\omega_1 - n\omega_d t) \} \] 
\quad n = 2, 4, 6,..., \quad k = 6l - 3, l = 1, 2, 3,... \tag{8}

In the equation, \( J_k \) is the k-order Bessel function.

Because the common-code voltage of the frequency conversion system is mainly generated at the end of the inverter, the inverter is simplified and regarded as a DC-AC inverter bridge for the convenience of simulation in Figure 3. The inverter bridge is packaged in the '3 PHASE SPWM INVERTER', whose DC side is connected with 514V DC power supply with the 2000Hz carrier wave frequency.

![Figure 3. Simplified inverter](image)

In the inverter bridge sub-module, connect the negative pole voltages of the triple-phase U, V and W and the calculated common-mode voltage signal to the oscilloscope, which is shown in Figure 4.
Run the simulation and get four signal curves in Figure 5. The first is the common-code voltage curve, and the last three are U, V and W triple-phase voltage curves respectively. The common-code voltage generated by the inverter is a 4-order trapezoidal waveform corresponding to different on-off combinations, whose amplitude values coincide with Equations (2) and (3).

Consequently the spectrum diagram shown in Figure 6 can be acquired.
Based on the analysis on Chart 6 and combined with Equations (7) and (8), on condition that a sinusoidal wave is used as the modulation wave and a triangle wave as the carrier wave the amplitude-frequency characteristics of SPWM frequency converter system common-code voltage are shown as follows.

1. The amplitude of the fundamental component (namely, the angular frequency \(\omega_1\) component) is 0, and that is, the common-code voltage does not include the component whose frequency equals to the modulation wave frequency.

2. There exists harmonic wave at the odd times of the carrier wave frequency \(w_s\), whose amplitude is \(\frac{4}{n\pi}J_n\left(\frac{an\pi}{2}\right)\).

3. There does not exist harmonic wave at the even times of the carrier wave frequency \(w_s\).

4. The exists harmonic wave at the angular frequency \((nw_s+k\omega_1)\) and \((nw_s+k\omega_1)\), and that is, the amplitude is \(\frac{12}{n\pi}J_l\left(\frac{an\pi}{2}\right)\) when \(n=1,3,5\ldots\), \(k=6l\), \(l=1,2,3\ldots\) or when \(n=2,4,6\ldots\), \(k=6l+3\), \(l=1,2,3\ldots\) The harmonic wave is divided into groups according to the units \((nw_s+k\omega_1)\) and \((nw_s+k\omega_1)\), and each group is distributed around the bilateral location \(\pm k\omega_1\) of \(nw_s\) as the center with their amplitudes symmetrically attenuating on both sides.

5. The harmonic wave amplitude of the common-code voltage does not change with the carrier wave frequency value, but moves correspondingly with the carrier wave frequency. The maximum harmonic wave amplitude is at one time of the carrier wave frequency.

From the above we can conclude that in Chart 2 besides fundamental component the AC-DC-AC SPWM frequency converter common-code voltage contains high-order harmonic wave relevant to the carrier wave frequency, which can disturb the power supply system, load and adjacent equipment, influence the normal work of motors and reduce the overall reliability of the system.

4. Effect Analysis on the Common-Code Voltage

Because of the instantaneous asymmetry of SPWM frequency converter triple-phase output voltages, the common-code voltage produced by the motor terminals is jumping with the opening and turnoff states of the switch tubes, has characteristics of high-frequency dv/dt and high-amplitude
voltage pulse features, and brings about negative effects on the AC frequency conversion speed 
regulation system, which mainly include three aspects as follows.

Firstly, the common-code voltage involves a great deal of high-order harmonic component, which 
flows into the stator lamination through the parasitic capacitance between the stator winding and the 
stator core, and generates eddy inside the stator core. As a result, the motor heat loss is increased, the 
insulation aging is accelerated, and the work efficiency is reduced, which can influence the operating 
performance and life of the motor.

Secondly, under the action of high-frequency common-code voltage the parasitic capacitance inside 
the motor forms a low impedance common-code passage, which produces a potential difference 
between the two rotation shaft ends or the shaft and the bearing, i.e., the shaft voltage. An electric 
shock may happen if the motor earth is bad. There exists a layer of a stable insulating lubricating oil 
film between the shaft and the bearing outer ring. When the shaft voltage comes up to a certain value 
and exceeds the film insulation strength, the film will be punctured and the shaft current is produced. 
Under normal circumstances, harmful shaft current can arise if the shaft voltage reaches 500mV, 
which results in bearing electro erosion and failure, increases noise, vibration and mechanical wear, 
and influences the reliability and the service life of the motor. The higher SPWM frequency converter 
carrier wave frequency is, the greater the shaft voltage value and the shaft current value are, the more 
harmful to the equipment safety it is.

Lastly, under the action of exceedingly high turn-off dv/dt and high-frequency pulsation 
common-code coupling effect may appear inside the motor. High-frequency common-code voltage 
flows into the earth through the electrostatic coupling between the stator winding and the grounding 
shell, then gives rise to harmonic interference by flowing back to the power grid through the 
grounding conductor, thus causes strong common-code electromagnetic interference (EMI), brings 
about security device malfunction, and results in reducing the system reliability as well as increasing 
the failure rate.

5. Countermeasures against the Common-code Voltage

Because the hazards above are caused under the influence of the common-code voltage, the 
damages to the motor and the power grid can be reduced in terms of the sources by restraining the 
common-code voltage effectively. The usual countermeasures against the negative effects of the 
common-code voltage are listed as follows.

(1) Traditional methods: The motor rotation shaft is installed with a grounding electric brush, 
which provides a low impedance parallel path from the rotation shaft to the shell and makes the shaft 
current flow through the electric brush instead of the bearing to protect the bearing from damage. The 
bearing insulation is adopted to increase the current path impedance in order to prevent the shaft 
voltage between the shaft and the bearing from forming a loop and causing shaft current. A conductive 
bearing lubricant is utilized to reduce the shaft current. Electrostatic shielding is mounted between the 
stator and the rotator to eliminate the shaft current.

(2) Passive filtering method: According to the amplitude-frequency characteristics of the 
common-code voltage, passive filters such as common-code choke, common code transformer and 
common code suppressor are set on the converter output terminal[4]. The high-frequency 
common-code voltage are distributed in the vicinity of the multiple frequency of the carrier wave, and 
the motor electrical properties are maintained effectively by filtering some specific frequency bands.
(3) Active filtering method: Auxiliary power supplies such as a dual-bridge inverter and an active common-code noise canceller output a voltage waveform which is equal in value but has reverse phase compared with the common-code voltage. The wave can offset the common-code voltage effects to ameliorate the unsatisfactory output voltage.

(4) Reducing the carrier wave frequency: The SPWM pulse is theoretically a kind of high-frequency square wave, and consists of fundamental wave and high-order harmonic wave. If the carrier wave frequency is very high, more pulses will be emitted within the given cycle and more capacitive current will be induced among the rotator, the stator and the shell, which can cause the bearing easy to damage. Therefore, the carrier wave is adjusted to a proper scope to acquire superior driving performance.

(5) Software method: In respect of control strategies new modulation modes are introduced such as the space vector method, which controls the opening and turnoff states of the inverter switch devices to reduce the common-code voltage, and overcomes the defects of a gain in weight and volume and the reliability reduction caused by the added hardware [5].

6. Conclusion

The damage to the drive system caused by the frequency converter common-code voltage cannot be neglected. Aiming at a marine voltage type, AC-DC-AC, SPWM frequency converter drive system the dissertation analyzes the generation mechanism and the spectrum features of the common-code voltage, and carries out modeling and simulation. On the above basis the negative effects and usual suppression methods are summarized, which helps to optimize the original design of the SPWM frequency conversion system, reduce the supplementary load loss of the motor, increase the reliability and efficiency of the AC drive system, and improve the management of the frequency conversion drive apparatus.

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