PCCPS-PWM based vehicle-network high frequency resonance suppression method

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Abstract. In recent years, the safe and stable operation of electrified railways has attracted more and more attention. In particular, the stability of vehicle-grid coupling, which focuses on the phenomenon of vehicle-grid high frequency resonance (HFR), has become a hot research topic. Based on the instability mechanism of vehicle-grid coupling, and from the perspective of grid-side converter modulation strategy, measures to suppress HFR are further proposed. Based on the improvement of commonly used modulation strategies, Periodic Control Carrier Phase-Shift Pulse Width Modulation (PCCPS-PWM) is proposed, this solves the HFR problem caused by the switching characteristic frequency harmonics caused by the inaccurate phase shift angle between the grid-side converters. And it is verified by Matlab simulation and hybrid electric train sets.

1. Introduction
Nowadays, most trains adopt Carrier Phase-Shift Pulse Width Modulation, which is relatively simple and easy to be realized. It has the ability to eliminate the characteristic frequency harmonics of train switch, thus avoiding the occurrence of high-frequency resonance phenomenon in vehicle-network system[1]. But in practice, high frequency resonance still exists, the main reason is that carrier phase shift pulse width modulation has higher requirements on phase shift Angle. If the phase shift Angle of the train is not accurate during the running process, the characteristic frequency harmonics of the switch cannot be effectively cancelled. Especially for some types of trains, there is no synchronization line between multiple grid-side converters, which makes it difficult to correct the phase shift Angle in real time. As a result, the phase shift reference of each grid-side converter is different, which fails to achieve the effect of harmonic cancellation[2-3]. Thus, the high-frequency harmonic generated by the train is injected into the traction network and causes the high-frequency resonance phenomenon of the vehicle-network. For this reason, this paper proposes Periodic Control Carrier Phase-Shift Pulse Width Modulation (PCCPS-PWM) which is different from traditional Carrier Phase-Shift Pulse Width Modulation (CPS-PWM), which effectively reduced high-frequency resonance in the vehicle network system.

2. Modulation strategy based on PCCPS-PWM
PCCPS-PWM modulation strategy is mainly divided into two parts, namely carrier synchronization strategy and periodic control carrier phase-shift angle correction.
2.1. Carrier synchronization strategy

Since there is no synchronous line connection between different converters, the carrier phase shift Angle between different "bridge arms" of converters at the different grid sides is variable. Even if the phase shift Angle is set before the operation of the converter, the crystal vibration in different control boards is different and there is some deviation in timing. A long time operation will lead to the change of phase shift Angle, which cannot achieve the purpose of fixing phase shift Angle to suppress the switching subharmonic[4]. So, carrier synchronization strategy is very important.

Only the grid side voltage is the same between different converters, so the grid voltage $E_s$ is adopted as the synchronous signal. However, $E_s$ is sinusoidal AC signal, so it is not easy to select the reference point of synchronization between different converters. Therefore, the voltage signal $E_s$ is input into the hardware synchronous circuit, and the sinusoidal AC signal is converted into the square wave synchronous signal through the voltage comparator, and then the ECAP module in DSP captures the rising edge of the square wave, and generate the interruption, so as to enter the interruption for the synchronization between different converters. Its schematic diagram is shown in figure 1. In addition, ECAP has a counter inside, which can record the time when the interrupt is generated until the actual execution of the carrier phase shift program, so that the carrier period correction can be obtained more accurately and the phase shift correction Angle can be precisely corrected.

![Figure 1. Schematic diagram am of square wave](image)

2.2. Periodic control carrier phase-shift angle correction

The phase shift Angle of each converter module is set by setting the carrier phase shift register before the current converter at the grid side sends pulse. In order to prevent the instability of ac current caused by the carrier phase mutation during operation, the register value cannot be changed at will after the grid side converter pulses. Take the hybrid electric locomotive as an example: three marshals, two moves and a tow, two converters in total, each converter has two converter modules, and the phase shift Angle is 0°, 90°, 45°, 135°, respectively. Figure 2 is used to analyze periodic control carrier phase-shift angle correction strategy.

![Figure 2. Schematic diagram of periodic control carrier phase-shift angle correction strategy](image)

Phase correction is based on periodic control and take the power frequency as a period. The grid-side converter of the hybrid power EMU adopts a switching frequency of 1 kHz, so there are 20 carriers in one power frequency cycle. During each power frequency period, the error phase of the carrier should be evenly distributed among the 20 carriers and the carrier phase can be modified and fixed by modifying the period of these 20 carriers.

As shown in figure 2, the phase of each carrier is fixed at 0°, 90°, 45°, 135°, before the grid-side converter sends a pulse. After the pulse is sent, due to the different crystal oscillators of the control board
in different converters, the originally set phase will change. For example, the carrier originally fixed at 0° may be on the left side of the zero-crossing point, which is lagging, or on the right side, which is leading. This requires that this error phase is equally distributed to 20 carriers, and their periods are modified to make the carrier phase fixed at 0° in the next power frequency cycle. Next, we will discuss the specific situations according to the phase shift angle:

2.2.1. Phase shift angle is 0°

Figure 3. Schematic diagram of periodic control carrier phase-shift angle correction strategy (Phase shift angle is 0°)

The corresponding calculation formula is:

\[ T'_{PRD} = T_{PRD} \times \frac{20 \times 2}{T_{error}} \]  

Among them, \( T_{ERROR} \) is the error between the actual carrier and the reference carrier at the moment of the grid voltage zero crossing.

2.2.2. Phase shift angle is not 0°

Figure 4. Schematic diagram of periodic control carrier phase-shift angle correction strategy (Phase shift angle is not 0°)

The corresponding calculation formula is:

\[ T'_{PRD} = T_{PRD} + \frac{T_{error}}{20 \times 2} \]  

Periodic Control Carrier Phase-Shift Angle Correction Strategy can be shown in table 1, and the strategy is also applicable to N converter modules.
Table 1. Periodic control carrier phase-shift angle correction strategy

| Phase-shift angle | Rise and fall zone flag | Sign of difference | Lead/Lag | Carrier period |
|-------------------|-------------------------|--------------------|----------|----------------|
| Phase shift angle is 0° | Fall | Positive | Lag | Decrease |
|                   | Rise | Positive | Lead | Increase |
|                   | Rise | Negative | Lag | Decrease |
| Phase shift angle is not 0° | Fall | Carrier number is 0 | Lag | Decrease |
|                   | Carrier number is 1 | Lead | Increase |

3. Simulation and Experiment

In order to verify PCCPS modulation strategy, build a grid-side converter simulation model and experimental platform, simulation and experimental parameters related to Table 2 [5-6]. The simulation and experiment are carried out for two converters, that is, four converter modules.

Table 2. Simulation and experimental parameters

| parameters | Value |
|------------|-------|
| Voltage on primary side of on-board traction transformer | AC 25 kV |
| Voltage on the secondary side of on-board traction transformer | AC 900 V |
| Rated voltage of DC side | 1650 V |
| Maximum AC current | 511 A |
| AC current rating | 360 A |
| Inductance on the grid side | 2.08 mH |
| DC support capacitor | 4 mF |
| Secondary resonance inductance | 0.359 mH |
| Secondary resonant capacitor | 7.06 mF |
| Switching frequency | 1KHz |

3.1. Simulation results

The simulation mainly verifies the effectiveness of the PCCPS modulation strategy to suppress the harmonics of the switching characteristic frequency. To simulate the operation of two converters and four converter modules at rated power, the phase shift angles of the four carriers are 0°, 90°, 45°, 135°, respectively. Using the PCCPS modulation strategy, the amplified waveforms of the AC current is1~is4 on the 900V side are shown in figure 5. If the PCCPS modulation strategy is not used, the sawteeth of the four current waveforms should be completely coincident[7]. However, it can be seen from the figure that is1~is4 waveforms form sawtooth wave under carrier phase shift control. This shows that there is a phase difference between the carriers of these four converter modules, so as to realize phase shift control.
Next, a comparison is made before and after the PCCPS modulation strategy is adopted by the network-side converter to illustrate the effectiveness of the strategy. Figure 6 shows the THD of the AC current on the primary side of the on-board traction transformer when this strategy is adopted, and its value is only 1.05%.

When the PCCPS modulation strategy is not used, the AC current THD on the primary side of the on-board traction transformer is shown in figure 7, and its value is as high as 9.09%.

It can be seen from the simulation that the PCCPS modulation strategy proposed in this paper can greatly reduce the switching frequency harmonics, thereby reducing the total current THD to a very low level.
3.2. Experimental waveform

First, verify that the PCCPS modulation strategy can make the system run stably. PCCPS adjusts the phase of the carrier relatively slowly, and has little effect on the switching pulse. Therefore, it can meet the requirements of AC current stability. At the same time, the phase shift angle is fixed, through harmonic cancellation, the purpose of reducing the switching frequency harmonics is achieved.

![Waveforms of AC current $i_{s1}$~$i_{s4}$ when PCCPS is running at no load](image)

**Figure 8.** Waveforms of AC current $i_{s1}$~$i_{s4}$ when PCCPS is running at no load

When the grid-side converter is running under load, it can also maintain stability, and the harmonic content is very small, which fully meets the requirements. Our country’s completely self-developed hybrid EMU adopts this PCCPS modulation strategy. Figure 9 is a diagram of field test:

![Harmonic test of hybrid EMU](image)

**Figure 9.** Harmonic test of hybrid EMU

The rated current of the primary side of the on-board traction transformer of this hybrid EMU is 51.2 A, since the current transformer on the hybrid EMU is 250:1, the AC current that can be measured on the secondary side is only 0.2048 A, and its THD cannot be directly measured. The primary side of the transformer is not convenient for measurement due to structural reasons, so a 150-turn coil is connected in series with the wire of the secondary side of the transformer to amplify the current to facilitate measurement. At this time, the measurable current value on the secondary side of the current transformer is 30.72 A under rated conditions.

When the hybrid EMU is running at rated power, if only the carrier phase shift angle is set before the grid-side converter sends the pulse, and PCCPS is not used, the measured harmonic content distribution is shown in figure 10(a); If PCCPS is used, the measured harmonic content distribution is shown in figure 10(b):
Compared with the above figure, it can be clearly seen that when the PCCPS strategy is not adopted, although the carrier phase shift angle is set before the grid-side converter sends the pulse, the switching subharmonic content is still high, such as the 37th, 39th, 41th and 43th times (Adopt unipolar frequency doubling modulation, so the characteristic subharmonics are twice the switching frequency). Therefore, the total THD is relatively high, which does not meet the requirement of THD<2.5 under rated conditions; If the PCCPS strategy is adopted, the content of the 37~43rd odd harmonics is very low, and the total THD is only 1.41%, which fully meets the requirements. This proves the feasibility and effectiveness of the PCCPS modulation strategy.

4. Conclusion
PCCPS-PWM optimizes the traditional carrier phase shift strategy, detects the phase shift Angle in real time, and makes the phase shift Angle more accurate, so as to effectively eliminate the characteristic subharmonics and reduce the pollution caused by harmonics to the power grid. In the case that there is no synchronous line between multiple traction systems of the same train, this paper provides a method to correct the carrier phase-shift Angle accurately and stably by fine-tuning the PWM carrier period based on the zero crossing of network pressure as a reference.

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