Research on Three-level Rectifier Neutral-Point Voltage Balance Control in Traction Power Supply System of High Speed Train

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Abstract:-For the neutral-point(NP) voltage balance problem of three-level PWM rectifier in high speed train traction power supply system, in this paper, a method for controlling the neutral point voltage of three level rectifier is proposed, which is based on the method of carrier amplitude conversion. By analyzing the effect of the change of the carrier amplitude on the neutral point potential, the sinusoidal pulse width modulation (SPWM) mode of the carrier amplitude transform is introduced into the control of the single phase three level pulse rectifier. The control of the neutral point voltage is achieved by the modulation of triangle carrier amplitude. Pulse conversion and carrier frequency shift are used in the control of high speed train traction and regenerative braking. At last, the Algorithm was applied to the traction condition and regenerative braking condition control of CRH2 (CHINA RAILWAY HIGH-SPEED). Compared to the transient direct current method that used in high speed train now, adding the pulse conversion and carrier amplitude shift control to the NP voltage control system have better ability to balance the NP voltage under the traction condition and regenerative braking condition. But in the condition of transform traction condition to regenerative braking condition, control method with amplitude shift is proved to be better, which illustrated the validity and superiority of carrier amplitude shift control.

Key words: High-speed Train; Three-level Rectifier; NP Voltage Balance; Carrier Amplitude Shift

1 Introduction

NP voltage balance in high-speed train is a key point to ensure the train running safely and stably. Train traction drive system requires three level NPC pulse rectifier to work bi-directionally. Fig. 1 is the main circuit diagram of a power unit on CRH2. while in traction condition, the rectifier operates in the rectification state, which gets energy from power grid. while in regenerative braking condition, it works in inverter state, which could transfer the energy that collected from brake to the power grid. Single phase three-level PWM rectifier works as AD-DC transformation in EMU traction drive system, but the imbalance of neutral point voltage is the inherent problem of diode clamp converter[1][2]. For that, scholars in various countries have done different researches. Literatures[3][4][5] used three-level space vector PWM(SVPWM) algorithm m to control the NP voltage through adjusting the reflecting time of redundant small vector. Literatures[6][7] raised that through injecting zero sequence signals to balance the NP voltage. These two methods are not only of great computational complexity, but also the realization of the process is complex. They both considered single phase rectifier only, but didn't realize the control effect of inverter control, and the train regenerative braking condition needs the converter works in inverter state. Currently, except the way to balance the neutral point voltage mentioned above, there are also method of optimizing the topology[8]. This method needs to improve the hardware, of which the cost is too high. Modular capacitor voltage balancing control method[9], this method is to control the average voltage actually, the control precision is not enough.

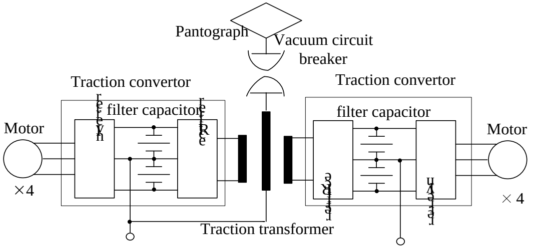


Fig.1. A main circuit diagram of a power unit

The reason to the imbalance of neutral point potential is analyzed in Section 2. In Section 3, the transient direct current control method is used to control the single phase three-level PWM rectifier of high speed train. This paper aimed at the imbalance of NP voltage in the high-speed train, and used NP voltage balance control method of pulse conversion(see in Section 4) to make research. the method can meet the requirement of balance neutral point voltage in traction condition, but the control method can't maintain the balance of the NP voltage in the traction switch to the regenerative mode. Further more, frequent pulse switching will increase the switching frequency of the switch, which will shorten the service life of the device. Therefore, adding carrier amplitude shift[10][11] method (see in Section 5)to the traction, braking and the switch of two kinds of working conditions of high speed train, through change the magnitude of the carrier, keeps the phase constant to balance the NP voltage, and this way have succeed and achieved good results. Finally, using Matlab/Simulink simulated, and compared with the pulse conversion control method. The simulation results show that this method applying into the traction condition, regeneration condition and the switch between two kinds of working conditions in high-speed train, both have a good ability to balance the NP voltage. The last section points the main conclusions of this paper.

2 Analysis of NP voltage of single phase three-level PWM rectifier in high speed train

What shown in Fig. 2 is the topological structure of single phase three-level diode-clamped PWM rectifier in CRH2 EMU[12].

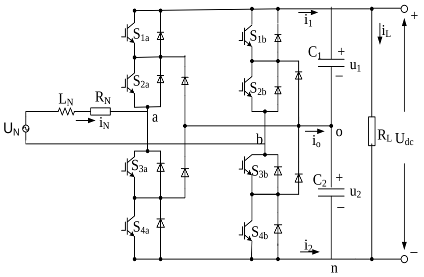


Fig.2 The main circuit of single phase three-level PWM rectifier

As we can see, R_N, L_N are grid side resistance and inductance respectively, R_L is equivalent load resistance, C_1 and C_2 are DC side support capacitors, and $S_{1a} \sim S_{4b}$ are IGBT power elements. In traction condition, grid side power factor is close to 1, showing positive resistance characteristic. Regenerative braking condition net side power factor is close to -1, showing negative resistance characteristic. The conduction situation of each bridge leg is shown as follows.

$$S_i = \begin{cases} 1, & S_{1i} = S_{2i} = 1 \\ 0, & S_{2i} = S_{3i} = 1 \\ -1, & S_{3i} = S_{4i} = 1 \end{cases} \quad i = a, b \tag{1}$$

According to the formula, each bridge leg equals to a switch, and each switch has three kinds of states 1, 0, -1. Three-level rectifier equivalent circuit[12] is shown in Fig.3

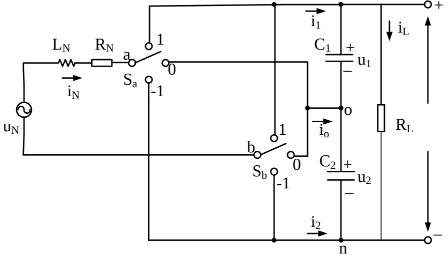


Fig.3 Three-level rectifier equivalent circuit

Each bridge leg of three-level rectifier main circuit has three conduction states 1,0,-1, totally 9 working modes. Each mode of working condition is shown in Table 1, 1 and 0 reflect the on and off of the switch, u_1, u_2 are the voltage of capacitor C_1 and C_2.

Table 1 Voltage of each working mode

S_a	S_b	u_{ao}	u_{bo}	u_{ab}	Mode
1	1	u_1	u_1	0	0
1	0	u_1	0	u_1	1
1	-1	u_1	$-u_2$	$u_{1+}u_2$	2
0	1	0	u_1	$-u_1$	3
0	0	0	0	0	4
0	-1	0	$-u_2$	u_2	5
1	1	$-u_2$	u_1	$-u_1-u_2$	6
1	0	$-u_2$	0	$-u_2$	7
1	1	$-u_2$	$-u_2$	0	8

Three-level rectifier covert working mode according to formula(1), the input voltage u_{ab} is shown in Fig. 4. There are five kinds of states to equivalent sine wave, they are $\pm u_{dc}, \pm\frac{u_{dc}}{2}$,0.

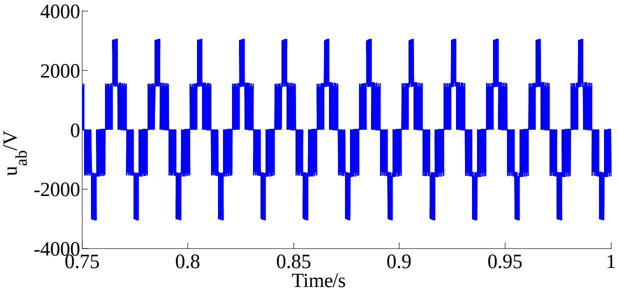


Fig.4 Rectifier input voltage

The imbalance of NP voltage will cause current distortion of AC side, produce low order harmonic which will cause the Train generate torque ripple of the traction motor, and influence the speed regulation performance. the lifetime of the power electrolytic capacitor is shortened, so that efficiency of the power converter is degraded and high power factor can not be achieved. We can see in Table 1 that in mode 1,3,5,7, only one of u_{ao}, u_{bo} is zero. At this point, the grid side voltage source is charging to one of the capacitor and another capacitor is discharged through the load. Current is injected into the neutral point.

The current that is injected into the neutral point $i_o = -C_1\frac{du_1}{dt} + C_2\frac{du_2}{dt}$, because $C_1 = C_2 = C$, then got

$$i_o = -C\frac{d\vartriangle u}{dt} \tag{2}$$

$$\vartriangle u = u_1 - u_2 = -\frac{1}{C}\int i_0 dt \tag{3}$$

According to (3), we can see the basic reason that causes the inequality of two output voltage is the imbalance charge and discharge of two capacitors in DC side.

3 Transient direct current control of high speed train

At present, the three level of the CRH2 multiple units train is the instantaneous direct current method, the outer loop is the voltage loop and the inner loop is current loop. The deviation between actual voltage u_{dc} and given voltage u_{dc}^* is used as the input of PI regulation. After the output of the PI regulation is synchronized with the input voltage sync signal, we can get the reference current component i_{N1}^*. By calculation the voltage and the current of intermediate DC link, we can get the effective component of the given current i_{N2}^*. Then the given output current i_N^* equals i_{N1}^* plus i_{N2}^*.

$$\begin{cases} i_{N1}^* = K_p(U_d^* - U_d) + 1/T_i\int(U_d^* - U_d)dt \\ i_{N2}^* = I_d U_d / U_N \\ i_N^* = i_{N1}^* + i_{N2}^* \\ u_{ab}(t) = u_N(t) - \omega L i_N^* \cos\omega t - R_N i_N^* \sin\omega t - K\left[i_N^* \sin\omega t - i_N(t)\right] \end{cases} \tag{4}$$

Where, K_p and T_i are the parameters of PI regulator, U_d^* is the given voltage of intermediate DC side, I_d, U_d are current and voltage of intermediate DC link respectively, K is proportional amplification coefficient, and ω is angular frequency of grid side voltage.

Fig.5 is PWM rectifier Simulink simulation, u_{ab}^* is the output of transient direct current control(Fig.6), which through SPWM modulation produce trigger pulse control the on-off of the rectifier's two bridge legs to achieve the effect of rectification.

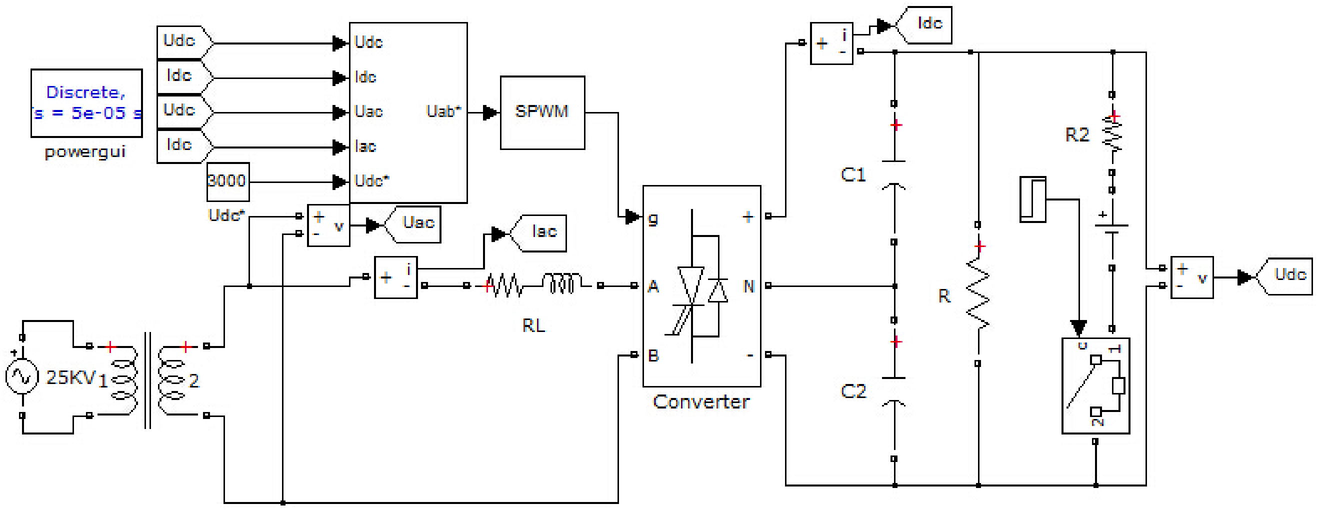


Fig.5 PWM rectifier simulation

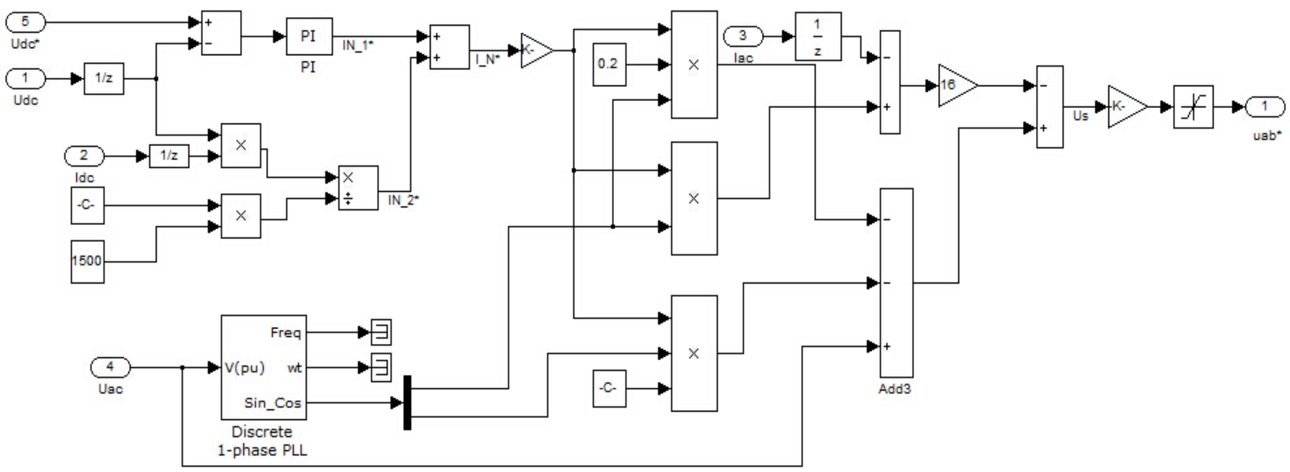


Fig.6 Transient direct current control simulation

The reference voltage of the CRH2 is 3000V, grid side voltage is 1500V, the frequency of single phase alternating current is 50Hz, and grid side inductance and resistance are $L_N = 0.002\text{H}$, $R_N = 0.2\Omega$ respectively, switch frequency $f_s = 1250\text{Hz}$. After 0.5s, the converter switch traction condition (rectifier) switch to regenerative braking condition (inverter).

Fig.7 is method of using transient direct current control. when there is no NP voltage control, the voltage of DC side tends to stable value 3000V after 0.2s and the fluctuation is less than 40V. After 0.5s the traction condition switches to regenerative braking condition again, and then state becomes steady after 0.5s. Fig.8 shows the voltage of two output capacitors, and the voltage deviation are more than 20V under two working conditions.

Transient direct current control method has good regulation ability to DC side voltage when traction, braking, and two kinds of operating conditions, but it don't achieve the balance of the upper and lower capacitor voltage.

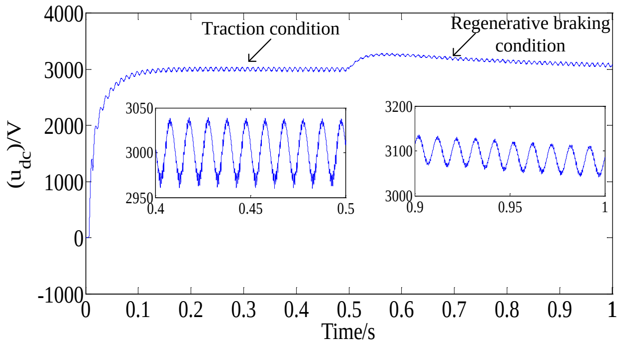


Fig.7 U_{dc} voltage waveform without NP voltage balancing control

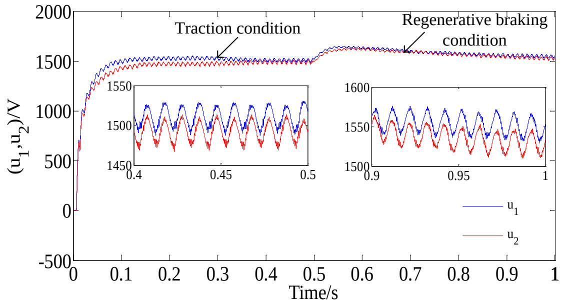


Fig.8 Capacitor voltages of the three-level rectifier without NP voltage balancing control.

4 Pulse conversion control of high speed train

In the researching progress, the method of balancing the NP voltage by pulse conversion is introduced[14]. Its principle is to transform the pulse combination of switch tube that leads to NP potential imbalanced to the pulse combination that is conducive to balance the NP potential. Table 1 shows that only when the pulse combination are (0,1), (1,0), (0,-1), (-1,0), there is $i_o \neq 0$. Among them, (1,0) and (0,-1) are redundant state each other, and state (-1,0) and (0,1) are redundant state each other too. Define the relational expression of pulse conversion as (5). Pulse conversion relation in traction condition (rectifier) is concluded in formula (6). Regenerative braking condition (inverter) is opposite.

$$W=(u_1-u_2)u_N i_N \tag{5}$$

$$\begin{cases} W>0\begin{cases}(1,0) & \Rightarrow & (0,-1)\\ (0,1) & \Rightarrow & (-1,0)\end{cases}\\ W<0\begin{cases}(0,-1) & \Rightarrow & (1,0)\\ (-1,0) & \Rightarrow & (0,1)\end{cases}\end{cases} \tag{6}$$

While $u_1-u_2>0$, $u_N>0, i_N>0$, to balance the NP voltage, we should discharge C_1 or charge C_2. So the pulse (1,0) should switch to (0,-1), and other conversions are similar.

Fig.9 is pulse conversion control simulation. If the voltage deviation is within the tolerance range of the comparator, then output is the original pulse. If the voltage deviation beyond the tolerance range of the comparator, then output is the converted pulse.

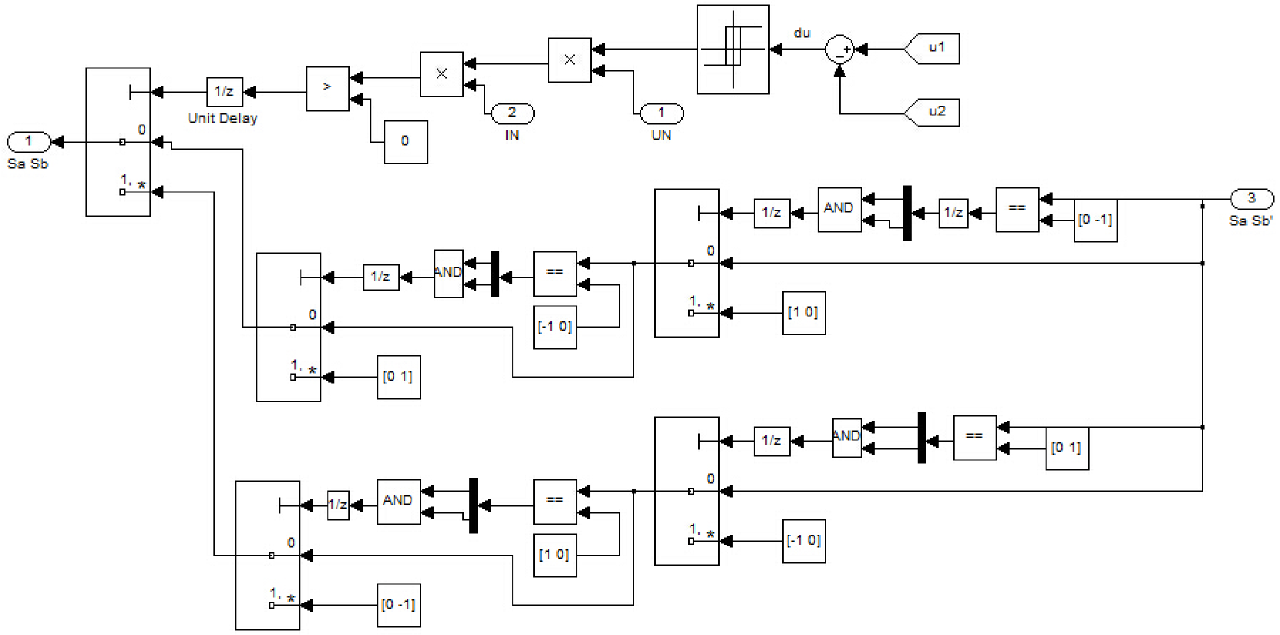


Fig.9 Pulse conversion control simulation

Fig.10 is U_{dc} voltage that added pulse conversion control. Under traction condition, after 0.3s, the DC side voltage tends to the stable value 3000V without more than 40V fluctuations. When the time is 0.5s, switch to regenerative braking mode. When the time is 0.8s, return to steady state. Fig.11 is the capacitor voltage that added pulse conversion control. In traction condition, when the time is 0.3s, the two capacitor voltages tends to be close to a given value 1500V, and reach a steady state. When the time is 0.5s, switch to regenerative braking mode. When the time is 0.8s, return to steady state. At the steady state, the deviation of the capacitor voltage is less than 20V. While in switching operating mode, the deviation is about 50V.

Compared with the transient direct current control method, after adding pulse conversion control to the system, the fluctuation of U_{dc} voltage is obviously decreased, and the problem of the capacitor voltage imbalance is improved obviously. While switching to the working conditions, the capacitor voltage deviation is still large. Besides, the control method of pulse conversion needs frequently switch the switch tube, the smaller the hysteresis width, the better the control effect, but accordingly, the switching frequency is higher, which will have an impact on the service life of hardware equipment. if increase the hysteresis width, we can't reach the ideal control accuracy.

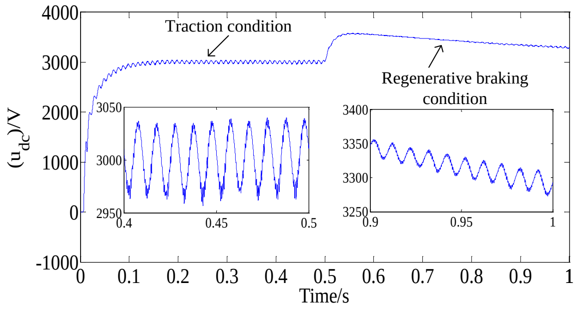


Fig.10 U_{dc} voltage of the three-level rectifier with pulse conversion control

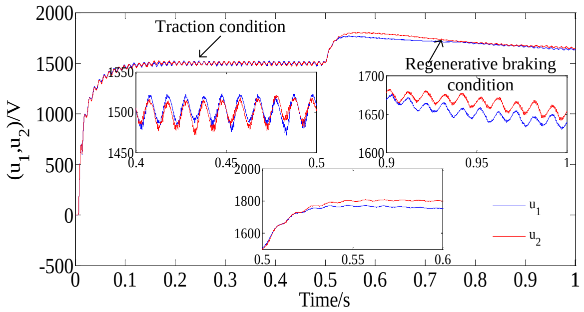


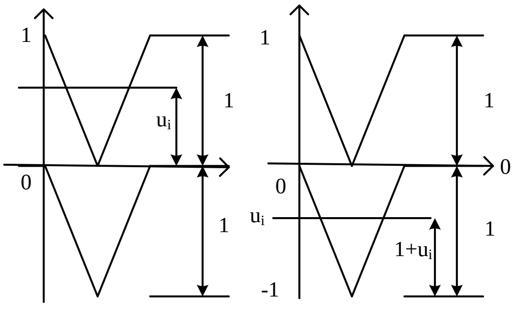
Fig.11 Capacitor voltages of the three-level rectifier with pulse conversion control

5 Carrier amplitude shift control of high speed train based on

Three level SPWM modulation is that comparison of carrier and modulation generates a trigger pulse, and the change of the carrier wave amplitude can change the neutral point current so as to influence the neutral point potential. Three-level SPWM modulated carrier can be expressed by (7)[15]

$$C_1=\begin{cases}\dfrac{2}{T_s}\times rem(t,T_s) & 0\le rem(t,T_s)<\dfrac{T_s}{2}\\ 2-\dfrac{2}{T_s}\times rem(t,T_s) & \dfrac{T_s}{2}\le rem(t,T_s)<T_s\end{cases}$$
$$C_2=\begin{cases}\dfrac{2}{T_s}\times rem(t,T_s)-1 & 0\le rem(t,T_s)<\dfrac{T_s}{2}\\ 1-\dfrac{2}{T_s}\times rem(t,T_s) & \dfrac{T_s}{2}\le rem(t,T_s)<T_s\end{cases} \quad (7)$$

Where C_1, C_2 are upper and lower carrier, $T_s=1/f_s$ is the carrier period, rem is remainder function. The duty ratio of '0' state in a carrier period is shown in Fig.12 and (8).



(1)$u_i\ge0$ (2)$u_i<0$

Fig.12 Duty ratio of the 0 state

$$D_{iO}=\begin{cases}1-u_i, & u_i\ge 0\\ 1+u_i, & u_i<0\end{cases}\quad i=a,b \qquad (8)$$

Where $u_a=u_{ab}^*=-u_b$, u_{ab}^* are modulation wave.

The duty ratio of working mode (1,0), (0,-1) is

$$D(1,0)=D(0,-1)=\begin{cases}u_a, & 0\le u_a<\dfrac{1}{2}\\ 1-u_a, & \dfrac{1}{2}\le u_a<1\end{cases} \qquad (9)$$

The duty ratio of working mode (0,1), (-1,0) is

$$D(0,1)=D(-1,0)=\begin{cases}-u_a, & -\frac{1}{2}\le u_a<0\\ 1+u_a, & -1<u_a<-\frac{1}{2}\end{cases}\qquad(10)$$

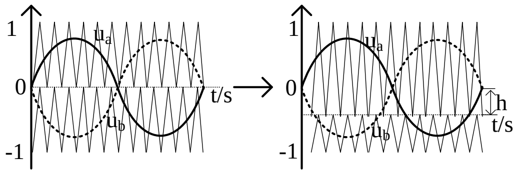
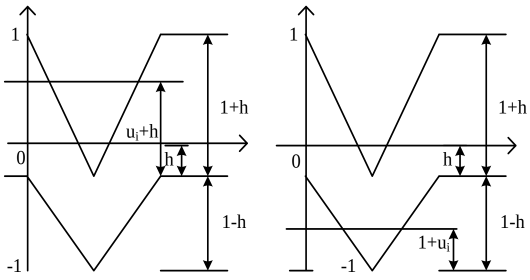


Fig.13 Amplitude shift SPWM modulation

Fig.13 shows the carrier Amplitude shift SPWM modulation scheme. Take $h=Km$ as the carrier amplitude change quantity, $K\in[-1,1]$ as amplitude shift coefficient, $m\in[0,1]$ as modulation ratio. While the carrier amplitude shift is h, we can see the 0 state of the bridge leg a,b in a carrier cycle duty ratio change to



(1)u_i≥-h (2)u_i<-h

Fig.14 The duty ratio of the 0 state after the amplitude changed

$$D'_{iO}=\begin{cases}\frac{1-u_i}{1+h}, & u_i\ge -h\\ \frac{1+u_i}{1-h}, & u_i<-h\end{cases}\qquad(11)$$

The duty ratio of working mode (1,0),(0, 1),(-1,0),(0,-1) respectively are

$$D'(1,0)=\begin{cases}\frac{1-u_a}{1-h}, & 1>u_a\ge h\\ 0, & u_a<h\end{cases}\qquad(12)$$

$$D'(0,1)=\begin{cases}\frac{1+u_a}{1-h}, & u_a\le -h\\ 0, & 1>u_a>-h\end{cases}\qquad(13)$$

$$D'(-1,0)=\begin{cases}\frac{1+u_a}{1+h}, & u_a\le -h\\ 0, & 1>u_a>-h\end{cases}\qquad(14)$$

$$D'(0,-1)=\begin{cases}\frac{1-u_a}{1+h}, & 1>u_a\ge h\\ 0, & u_a<h\end{cases}\qquad(15)$$

When $h=0$, we still use the original carrier modulation. When the carrier amplitude is changed($h\neq 0$), 0 state duty cycle and the four kinds of work modes that affect the NP potential changes all. And $D'(0,1)\neq D'(-1,0)$, $D'(1,0)\neq D'(0,-1)$, So the effect of adjusting the duty cycle can be achieved by changing the amplitude of the carrier. In a carrier cycle, the current flowing through the neutral point i_o that caused the NP potential imbalance, in the mode (1,0), (-1,0), $i_o=-i_L$ and in the mode (0,1), (0,-1), $i_o=i_L$. In a modulated wave period $(-\arcsin K, 2\pi-\arcsin K)$, the voltage difference of u_1 and u_2 could be expressed as

$$\Delta u=-\frac{1}{C}\int_{-\arcsin K}^{2\pi-\arcsin K} i_0\,dwt\qquad(16)$$

Where i_o is related to the duty ratio of each state. Changing the size of h can influence the regulation of the duty cycle, and achieve the effect of regulating NP voltage.

Fig.15 is control module diagram based on carrier amplitude shift, in which u_1,u_2 are the voltage across the capacitors C_1 and C_2. The voltage deviation is outputted by hysteresis controller to control the amplitude range of the carrier. The triangle carrier which the amplitude transforms compares with the modulation wave u_{ab}^*, then we can get the converter trigger pulse. Fig. 15 is the simulation diagram of carrier amplitude shift control

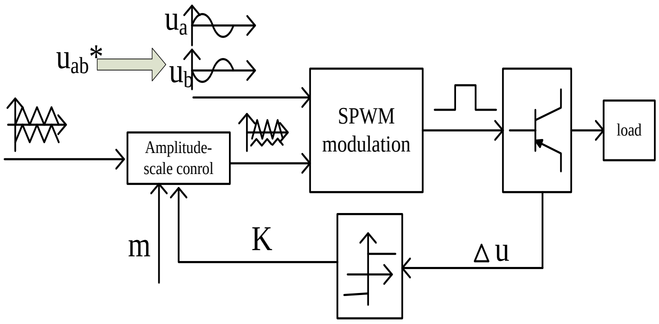


Fig. 15 Carrier amplitude shift control

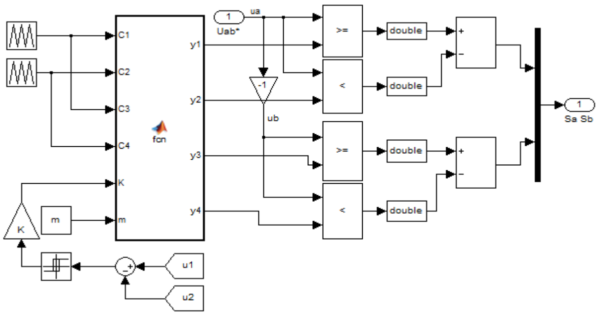


Fig. 16 The simulation diagram of carrier amplitude shift control

Fig.17 is U_{dc} voltage waveform of carrier amplitude shift control, under the traction condition, the voltage tends to be stable value 3000V after 0.3s, and the deviation is less than 30V. At the time 0.5s, after switching to regenerative braking mode, at the time 1s, voltage returns to the steady state, and the voltage deviation is less than 40V.

Fig.18 is the capacitor voltages of carrier amplitude shift control. In the condition of traction, barking and transformation between two conditions, the voltage deviations be controlled within 10V. Compared to the pulse conversion control, NP voltage deviation decreased significantly, and solved the problem of the large deviation when the working condition changes.

Fig.19 is the grid side voltage and current waveform of carrier amplitude shift control, u_N, i_N have the same phase under traction condition, and the power factor close to 1. u_N, i_N are appositive phase under regenerative braking condition, and the power factor is close to -1. The SIMULINK results are consistent with the theory. This control method improved the problem of the NP voltage imbalance without changing the other system performances.

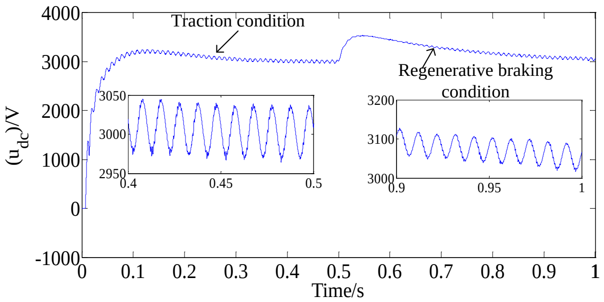


Fig.17 U_{dc} voltage of carrier amplitude shift control

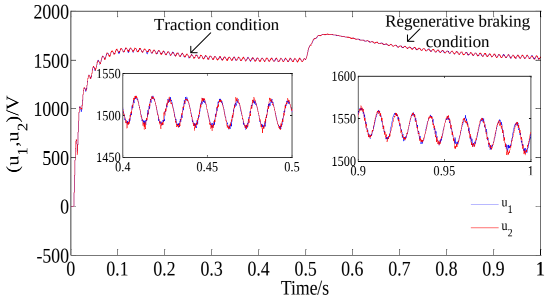


Fig.18 Capacitor voltages u_1 and u_2 using carrier amplitude shift method

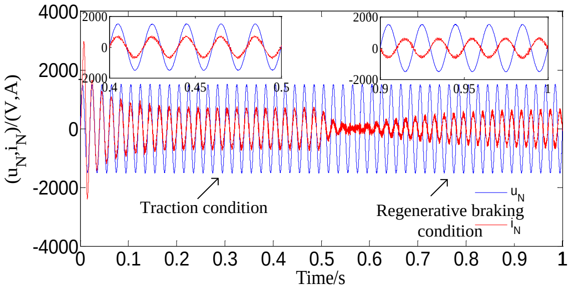


Fig.19 Grid side voltage and current of carrier amplitude shift control

Compared with the pulse conversion control, the carrier amplitude shift method don't need to switch the operation state of switch tube frequently. Without the limitation of the switching frequency, this method can achieve higher control accuracy in various operating conditions and the conversion of conditions.

Fig.20 shows the capacitor voltage deviation of using no NP voltage balance control, pulse conversion control and carrier amplitude shift method respectively. In terms of no NP potential control, the voltage deviation is large under traction condition. After 0.4, the deviation is about 30V. At the time 0.5s, the deviation increases while the traction mode switches to the regenerative braking condition. After the system is stable, the deviation is about 30V. The voltage deviation decreased significantly after added the NP potential control of pulse conversion, and the deviation is less than 20V under the traction condition when the system is stable. At the time of 0.5s, the voltage deviation reaches to 50V when the condition is switched. The deviation is controlled within 20V after the system is stable. After adding the NP control of the carrier amplitude shift, the voltage deviations are all controlled within 10V under traction and braking condition. There is no major fluctuation when the traction is switched to the regenerative mode within 0.5s.

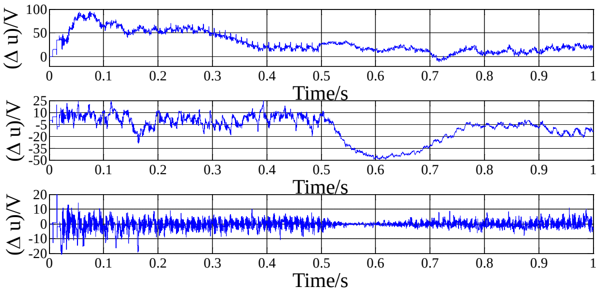


Fig.20 Capacitor voltage deviation under three control modes

Table 2 are the mean square error (MSE) of two capacitor voltages deviation of transient direct current control, pulse conversion and carrier amplitude shift control under traction and braking conditions respectively. Under the traction condition, the deviation is larger without NP voltage control, and the MSE is 21.77. The deviation is decreased after the addition of the pulse conversion control, the MSE is 7.79, and the control technique of pulse conversion achieved the effect of balance the NP potential in traction condition. the MSE decreased to 3.75 after added carrier amplitude shift control, which is significantly better than the first two control effects. In regenerative braking condition, the MSE is 8.23 without NP potential control. After adding the pulse conversion control, because the voltage deviation is large when operating mode changes. The MSE increased to 15.57, and it becomes1.98 after adding the carrier amplitude shift control. The problem of NP voltage unbalance is effectively solved. The control technique of the pulse conversion can reach a certain balance effect under the traction condition, but after switching to regenerative braking mode, the control effect is not good. The control method for carrier amplitude shift has the good ability to balance the NP voltage in both traction and braking conditions.

Table 2 The mean square error of the two capacitor voltages error deviation under all kinds of control method

Control methods	Conditions	**MSE**
Instant direct Current control	Traction	21.77
	Regenerative braking	8.23
Pulse Switching control	Traction	7.79
	Regenerative braking	15.57
Amplitude-Shift Control	Traction	3.75
	Regenerative braking	1.98

6 Conclusion

In this paper, CRH2 EMU converter is chose as the research object, the reason to the imbalance of neutral point potential is analyzed. Based on transient direct current control, a neutral point potential control method by adjusting the amplitude of the carrier is introduced. Comparing with the neutral point potential control method of pulse transformation, this method can not only balance the neutral point potential well while the system is stable, control the deviation of the two capacitor voltage within 10V, but also response fast and maintain neutral point potential balance when the system conditions changes. The mean square deviation of traction and regenerative braking condition are 3.75 and 1.98 respectively, which provide an effective method for solving the traction motor load torque ripple problem that caused by the imbalance of neutral point potential in the high speed train and ensure the good speed performance of the train.

The voltage deviation is controlled within 10V after adding the NP control of the carrier amplitude shift. The relationship between the carrier amplitude change quantity and voltage deviations will be studied in the future work in order to control NP voltage more accurately .

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