LETTER

Discordant Splitting Capacitance Drives System Bus Voltage Pulsation Suppression

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Abstract This paper analyzes the power decoupling performance of the mismatched split-capacitor half-bridge circuit, and reveals the mechanism of fundamental harmonic generation in the circuit through the mathematical model of the decoupling circuit established. In order to solve this problem, firstly, this paper proposes a control strategy of introducing DC bias coefficient on the basis of instantaneous voltage control of split capacitor C_1 . Secondly, using instantaneous voltage of capacitor C_1 as control quantity can better realize voltage tracking control effect, with fast response speed and simple control. Finally, the effectiveness of this control strategy is verified by experiments.

key words: Split capacitor structure, capacitance mismatch, PR control, instantaneous voltage control

Classification: Power devices and circuits, Circuits and hardware

1. Introduction

Permanent Magnet Synchronous Motor (PMSM) is widely used in the industry and household appliances due to its advantages of simple structure, convenient maintenance and high power density [1, 2]. The conventional PMSM driver requires a large capacity electrolytic capacitor to keep the bus voltage stable [3, 4]. However, it is easy to cause the failure of the drive system due to the shortcoming of short life and large volume of electrolytic capacitor [5, 6, 7, 8]. So, it is replaced by the thin film capacitor. This system is called Electrolytic Capacitor Less (ECL) driver. However, ECL motor drive systems suffer from higher torque ripple, lower grid quality, and lower efficiency due to the reduction of the DC-link capacitor [9, 10].

In order to solve the above problems, some scholars proposed a method of using active power decouples the circuits [11, 12, 13, 14]. According to the topological structures of the circuits, they can usually be divided into two categories, namely, parallel compensation circuits [15, 16, 17, 18] and series compensation circuits [19, 20]. The advantage of series compensation circuit is that it can be constructed with

low voltage components and only needs to deal with part of the ripple power. In this case, high conversion efficiency can be preserved. However, the DC link would be limited, and it is not suitable for working under the condition of high AC line. Yet, parallel decoupling often uses independent decoupling circuits in parallel on the DC-Link, which have the characteristics of high adaptability and flexible composition. The parallel decoupling is suitable for both rectification and inverter power flow directions. So, the parallel compensation circuit is widely used.

In order to improve the efficiency of power decoupling, The literature [21, 22, 23, 24] proposed a closed-loop feedback control method of DC bus voltage, which had a good effect in suppressing bus voltage ripple and improving decoupling accuracy. Literature [25] proposed a half-bridge decoupling circuit based on DC split capacitor as shown in Figure 1, which had several advantages of parallel decoupling circuit. In literature [26, 27], the power decoupling strategy of pulsating DC voltage feedback control was introduced. The control idea was using orthogonal transformation to reduce the secondary ripple voltage error of rectifier to primary ripple, and using proportional resonance controller to control the error and generate half-bridge circuit modulation signal. Literature [28] used a method applying direct power control to control the feedback DC pulsating voltage, which had the ability to suppress the harmonics in the DC voltage.

Fig. 1. Half-bridge power decoupling circuit

However, the premise of bus voltage control in the above literatures are $C_1 = C_2 = C_f$. In the actual operation state, the film capacitor would be affected by humidity, time effect and other factors, resulting in 20% capacitance offset. In the circuit, its fundamental wave amplitude can reach 100

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V, accounting for 5% of the system output power. It can be seen that the influence caused by capacitor deviation cannot be ignored [29, 30]. The variation of capacitor parameters will lead to a larger deviation between the compensated secondary power pulsation and the calculated power parameters; simultaneously generate other frequencies of harmonics. It will reduce the power decoupling performance, lead to capacitor voltage distortion, and make the original control difficult to effectively suppress the bus voltage fluctuation. For the problem of capacitance deviation, this paper analyzes the power decoupling performance of the half-bridge circuit when the capacitance deviation of the splitting capacitor occurs. By establishing the theoretical derivation of the decoupling circuit, it reveals the mechanism of generating a harmonic power in the circuit. To solve this problem, in this paper, a new control strategy is proposed, in which DC compensation is introduced on the basis of capacitor C_1 instantaneous voltage control to suppress the DC-Link fluctuations. This control strategy improves the stability of the system. Finally, the proposed control strategy is verified by experiments, and the results are consistent with the theoretical analysis.

2. Harmonic Analysis of Pulsating Power in Capacitance Deviation Decoupling Circuit

In the active power decoupling circuit shown in Fig. 1. The split capacitors C_1 and C_2 form a DC-Link capacitor, and the split point is connected with the midpoint of the bridge arm of the half bridge circuit composed of S_2 and S_3 through inductance L_f to form a decoupling loop.

When the circuit operates, the voltages of capacitors C_1 and C_2 complement each other, so as to realize no pulsation of DC-link voltage.

The grid voltage and current are defined as

$$\begin{aligned} u_g(t) &= U_g \sin(\omega t) \\ i_g(t) &= I_g \sin(\omega t) \end{aligned} \quad (1)$$

where U_g and I_g are the amplitudes of grid voltage and rectifier input current. Because the energy stored in the inductor is small, it can be ignored. The instantaneous input power P_{ac} at the AC side of the rectifier can be expressed as

$$\begin{aligned} P_g &= u_g(t)i_g(t) \\ &= \frac{U_g I_g}{2} - \frac{U_g I_g}{2} \cos(2\omega t) \end{aligned} \quad (2)$$

It can be seen from (2) that P_{ac} contains only secondary pulsation power and DC component.

In the decoupling circuit, the voltage references of the split capacitors are expressed as follows

$$\begin{aligned} u_{c1} &= U_{C1} + B \cos(\omega t + \theta) \\ u_{c2} &= U_{C2} + B \cos(\omega t + \theta) \end{aligned} \quad (3)$$

where U_{c1} and U_{c2} are the DC biases of the split capacitor voltages respectively, B is the amplitude of AC component of

split capacitor voltages, θ is the initial phase, ω is the angular frequency. The currents flowing through the capacitors are

$$\begin{aligned} i_{c1}(t) &= C_1 \frac{du_{c1}(t)}{dt} = \omega C_1 B \cos(\omega t + \theta) \\ i_{c2}(t) &= C_2 \frac{du_{c2}(t)}{dt} = -\omega C_2 B \cos(\omega t + \theta) \end{aligned} \quad (4)$$

According to Kirchhoff's Law (KCL), the current of inductor L_f in decoupling circuit can be obtained

$$i_{L_f}(t) = -(C_1 + C_2) \omega B \cos(\omega t + \theta) \quad (5)$$

Because the energy stored in inductor is small, the decoupling circuit power can be considered to be equal to the instantaneous power P_c of C_1 and C_2 , which can be expressed as

$$\begin{aligned} p_c(t) &= u_{c1}(t)i_{c1}(t) + u_{c2}(t)i_{c2}(t) \\ &= (C_1 U_{C1} - C_2 U_{C2}) \omega B \cos(\omega t + \theta) + \\ &\quad \frac{1}{2} (C_1 + C_2) \omega C_f B^2 \sin(2\omega t + 2\theta) \end{aligned} \quad (6)$$

where C_1 is equal to C_2 under ideal conditions. Therefore, the decoupling circuit can effectively absorb the pulsating power of the power grid. However, the capacitance values of C_1 and C_2 will change due to humidity, time effect and other factors, resulting in increased DC-Link fluctuation. In order to analyze the specific influence of capacitance deviation on the performance of decoupling circuit, capacitance deviation is set for capacitor C_1

$$\begin{cases} C_1 = mC_2 \\ C_2 = C_f \end{cases} \quad (7)$$

where C_f is the design capacitance and m is the deviation coefficient of split capacitance. It can be seen from (6) that the decoupling circuit contains primary pulsating power and secondary pulsating power in case of capacitance deviation. According to the power balance theory, the secondary power of the power grid is absorbed by the decoupling circuit, which means the quadratic terms of (6) and those of (2) are equal. The phase and amplitude of the AC component of the split capacitor voltages are further solved when $m \neq 1$.

$$\theta = \pm \frac{\pi}{2} + \frac{1}{2} \arctan t \frac{-U_g}{\omega L_1 I_g} \quad (8)$$

$$B = \sqrt{\frac{\sqrt{(U_g I_g)^2 + (\omega L_1 I_g^2)^2}}{\omega(1+m)C_f}} \quad (9)$$

It can be seen from (8) and (9) that when the capacitance values deviate, the phases of split capacitors C_1 and C_2 remain unchanged, but the amplitudes change.

When the capacitance is equal, the power balance relationship of the circuit is

$$P_g = P_m + P_c \quad (10)$$

where P_m is the instantaneous power of the motor. When the capacitance values are offset, it can be further seen from (6) that the original power balance relationship is broken, and the circuit power balance relationship is

$$P_g = P_m + P_C + P_1 \quad (11)$$

where P_1 is the primary pulsating power derived from the capacitance deviation. Due to the capacitance deviation, the active power decoupling circuit cannot absorb the primary pulsating power. The primary pulsating power is transmitted to the DC side, resulting in DC-Link voltage fluctuation.

Fig. 2 is a voltage waveform under the condition of splitting capacitor $C_1 = 1.2C_2$ ($m = 1.2$) based on the conventional control strategy. It can be seen that the DC voltage includes the fundamental AC voltage component under the condition of capacitance deviation, which increasing the DC-Link voltage fluctuation.

Fig. 2. Simulation of traditional control in case of capacitance deviation. (a) Half bridge decoupling circuit waveform. (b) DC-link voltage spectrum

3. Split capacitor Control Strategy

Because of the capacitance deviation, the DC-Link voltage contains the primary pulsating power. In order to eliminate the primary pulsating power, this paper delays the pulsating power P_c of the decoupling circuit by 90 degree. Then, the P_c and the delayed signal are calculated by the orthogonal transformation matrix, so that the fundamental harmonic in the P_c is reduced to a DC component, and the second harmonic is reduced to a fundamental wave. The transformation matrix is as follows

$$T_r = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \quad (12)$$

According to (2) and (10), it can be concluded that the decoupling power P_c is equal to the pulsating power output by the power grid, and the capacitor power is based on the voltage, so the pulsating decoupling power P_c is reduced to the pulsating fundamental voltage U_c

$$U_c = \frac{1}{2} (C_1 U_{c1} - C_2 U_{c2}) \omega B + \frac{1}{2} (C_1 + C_2) \omega B^2 \cos(\omega t + \theta) \quad (13)$$

The DC coefficient of U_c is caused by capacitance deviation, and the fundamental wave is the power grid pulsation. Under the condition of equal capacitance, the error voltage U_c only contains the fundamental component. The voltage passes through PR controller to generate current reference value i_{Lf}^* , then, compared with the actual inductor current. Because the waveform of inductor current is sinusoidal, PR controller is used to adjust and then control the modulation signals S_2 and S_3 output.

Fig. 3. Diagram of the proposed control strategy

In order to suppress the fundamental harmonic caused by capacitance deviation, this paper introduces additional DC deviation, this paper introduces additional DC bias coefficient b to eliminate the DC component of the fundamental harmonic after order reduction. The relationship between the splitting capacitor voltages and the DC-Link voltage can be expressed as

$$\begin{cases} U_{C1} = (1 - b)U_{dc} \\ U_{C2} = bU_{dc} \end{cases} \quad (14)$$

U_{dc} is the average value of DC-Link voltage, b is the dc bias coefficient. Since the splitting capacitor voltages fluctuate between 0 and U_{dc} , the maximum and minimum capacitor voltages should meet the following relationship

$$\begin{aligned} U_{C1 \max} &= U_{c1} + B < V_{dc} \\ U_{C2 \min} &= U_{c2} - B > 0 \end{aligned} \quad (15)$$

Substitute (14) into (15) to obtain

$$bU_{dc} > B \quad (16)$$

Substitute (9) into (16) to obtain

$$\frac{U_g I_g}{\omega(1 + m)C_f} - b^2 U_{dc}^2 < 0 \quad (17)$$

The above formula is the unary quadratic inequality of DC bias coefficient b , and the extreme value of b can be expressed as

Fig. 4. ECL drive system of total control strategy.

$$b = \pm \sqrt{\frac{U_g I_g}{U_{dc}^2 \omega C_f (1 + m)}} \quad (18)$$

In this paper, the capacitance deviation coefficient is set as $m = 1.2$. According to (13), it can be seen that the DC bias is positive, so $b = +0.5$. The Specific control is shown in Figure 3.

The PR controller is used to realize i_{Lf} tracking i_{Lf}^* without static error and high-power operation of circuit, and its controller transfer function is as follows

$$G_{PR}(s) = K_P + K_R \frac{2\omega_c s}{s^2 + 2\omega_c s + \omega} \quad (19)$$

where K_P is the proportional coefficient, K_R is the resonance coefficient, ω_c is the cut-off frequency.

4. Experimental results

In order to verify the feasibility of the proposed control strategy, an experimental platform was built. The main component parameters of the ECL drive system are shown in Table I. The control part of the experimental circuit is realized in DSPACEDS1006 semi-physical simulation platform.

Table I. Key parameters of the ECL motor drive.

Parameters	Values
Inductance	2 mH
Switching frequency	10 kHz
Grid frequency	50 Hz
C_f	90 μ F
m	1.2
DC-link voltage	380 V
Rated power	0.4 kW
Rated torque	5N·m

Fig 4 shows the control scheme block diagram of the ECL motor driver, which includes PFC control, PMSM vector control and DC link instantaneous voltage stability control. Fig.5 and Fig.6 show the experimental wave-forms under the traditional control strategy and the proposed control strategy

respectively. The traditional control strategy can not eliminate the first harmonic caused by capacitance deviation, so the power grid current behind the power grid voltage. However, in this paper, the order reduction module is used to reduce the order of the first harmonic caused by capacity deviation to DC bias, and eliminate the bias through DC compensation link, and control the power grid current to track the power grid voltage. The results show that when the control strategy proposed in this paper is adopted, the grid voltage and current can be well controlled in phase, and the motor speed and torque are more stable.

(a)

(b)

Fig. 5. Experimental waveform of the motor drive system. $n = 1000$ rpm and $T_e = 5$ N·m (a) traditional ECL motor drives system. (b) the proposed ECL motor drives system.

It can be seen from Fig.7 that the voltage of the split capacitor under traditional control cannot be completely complementary, and the decoupling performance declines, resulting the

(a)

(b)

Fig. 6. Experimental waveform of motor torque T_m and three-phase motor currents i_a , i_b , i_c with the $n = 1000$ rpm, $T_e = 5$ N.m (a) traditional ECL motor drives system. (b) Proposed ECL motor drives system.

DC-Link voltage fluctuation of 90 V. However, the proposed control strategy can effectively control the split capacitor voltages complementary, and effectively restrain the fluctuation of bus voltage within 20V, with the suppression effect being improved by about 78%.

(a)

(b)

Fig. 7. Experimental waveform of split capacitor voltage and DC-link voltage. (a) traditional ECL motor drives system. (b) Proposed ECL motor drives system.

Fig.8 shows that the ac component of DC-link voltage is very small and can be ignored basically. The harmonic content of power grid current i_g meets the IEC 61000-3-2 standard. The experimental results accord with the theoretical analysis

and verify the effectiveness of the proposed optimal control structure.

(a)

(b)

Fig. 8. Experimental waveform of (a) spectrum of u_{dc} and (b) spectrum of i_g

5. Conclusion

In this paper, a new control method is proposed to suppress DC-Link fluctuation under capacitance deviation condition. Firstly, the harmonic analysis of capacitance bias split capacitor structure is proposed. Then, the power decoupling relation is used to eliminate the second harmonic in the system, and the fundamental wave caused by the capacitance deviation is eliminated by a given DC bias coefficient. Finally, the effectiveness of the proposed control strategy is verified by experimental results.

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