Docupling Control of High Power Factor Inverter without Electrolytic Capacitor SRM Driver Simulation

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**Abstract.** DC bus electrolytic capacitors influential on the life of Switched reluctance motor (SRM) due to their chemical properties. For the drive system without electrolytic capacitor SRM, the power decoupling type without electrolytic capacitor scheme is studied. The parallel bidirectional Buck/Boost compensation circuit is a power decoupling circuit, a feed-forward control strategy for output voltage fluctuations of the electrolytic capacitor PFC circuit. The inverter side uses the voltage hysteresis control to stabilize the DC bus voltage. During the two-phase adjacent commutation period, the measured DC bus voltage is compared with two predetermined high and low voltages, make the DC bus voltage fluctuate within a certain range. The effectiveness of the control strategy is verified by electrical tools. The grid-side power factor is 0.958, and the grid current harmonics meet the EN61000-3-2 standard.

**Keywords:** DC-link voltage fluctuation; Feed-forward control; High power factor; SRM; PFC circuit without electrolytic capacitors.

1. Introduction
In recent years, SRM [1-3] is a new type of motor with simple structure and rapid development. It is application in various industries such as industrial manufacturing, automotive and household appliances. Switched reluctance driver (SRD) DC bus side parallel large electrolytic capacitors will to store, buffer energy, stabilize the DC bus voltage and power the three-phase unbalanced bridge inverter. Meanwhile, the power factor correction (PFC) circuit is of great significance for improving grid-side power quality and reducing SRD current total harmonic distortion (THD). However, large-electrolytic capacitors will lead to increased SRD volume and shorten life span [4-6]. For solving the above question, the driving technology without electrolytic capacitor motor has been developed [7-9]. Compared with electrolytic capacitor motors, the drive system without electrolytic capacitors is smaller. In the SRD of a single-phase diode rectifier, the electrolytic capacitor in parallel to the DC-link is generally several hundred to several thousands, while the non-electrolytic capacitor (film capacitor) is only 3.7%-5% of the electrolytic capacitor. Due to insufficient energy stored in the DC bus capacitor, the DC bus voltage fluctuates following the grid voltage. In the traditional SRD, the electrolytic capacitor PFC circuit can adjust the grid power factor with stabilize the bus voltage. However, removing the electrolytic capacitor in the PFC circuit will cause power ripple and voltage ripple during inverter commutation, causing the bus voltage fluctuation too drastically and reduce the grid-side power factor.
Decoupling circuit, the principle is to convert the ripple power to the auxiliary energy storage capacitor or inductor by adding an auxiliary circuit. Since the energy storage element is not immediately linked to the DC-link side, it can allow more largely voltage fluctuations to reduce the capacitance value. Use power decoupling scheme as auxiliary circuit scheme. The power decoupling type without electrolytic capacitor solution is to achieve a decoupling of reactive and active power by paralleling (or electromagnetic coupling) a decoupling circuit on the DC side to absorb the ripple component flowing in the circuit to get rid of the converter’s reliance on electrolytic capacitor. The auxiliary circuit of the power decoupling scheme only deals with excess unbalanced power, so the system efficiency can be improved, and the current loop bandwidth is large, and the system dynamic response speed becomes faster, so it is widely used.

2. Analysis of High Power Factor of PFC Circuit without Electrolytic Capacitor

**METHODS**

2.1. Ripple Power Analysis

In AC/DC, it is assumed that the voltage and current at the network side are sinusoidal waves with the same phase, as follows:

\[ u_g = \sqrt{2} U_g \sin(\omega t) \]  
\[ i_g = \sqrt{2} I_g \sin(\omega t) \]

In (1) and (2), \( i_g \) and \( u_g \) are the instantaneous values of grid-side current and voltage; \( I_g \), \( U_g \) are the effective values of grid-side current and voltage; \( \omega = 2\pi f \), \( \omega \) are the grid side angular frequency, and \( f \) is the grid side frequency. The instantaneous power on the grid side is:

\[ p_g(t) = i_g(t)u_g(t) = 2I_gU_g \sin^2(\omega t) = I_g U_g - I_g U_g \cos(2\omega t) \]

Through (3), the network side input power is two parts: constant output power and ripple output power, as follows:

\[ p_g(t) = p_o - p_o \cos(2\omega t) \]

Supposing that the power loss of the three-phase inverter and SRM is negligible, the motor power is approximately the input power of the inverter after rectification. When the torque and speed of the motor are stable, the power of the motor is constant, as follows:

\[ p_M = p_o = V_g I_g \]

It from (4) and (5) that the motor power is constant, so a ripple power of double the AC frequency in the circuit. This ripple power decided by the nature of the SRM power conversion circuit, the difference in control strategy, and topology not make it disappear. The expression is as follows:

\[ p_c = -p_o \cos(2\omega t) \]

The materials and methods section should contain sufficient details so that all procedures can be repeated. It may be divided into headed subsections if several methods are described.

3. Feed-Forward Control of Power Decoupling Non-electrolytic Capacitor

Known by the traditional power decoupling circuit control method, regardless of the voltage or current control, the current detection phase lag makes the system compensation accuracy not high and the dynamic response speed slow. If there is a compensation control method that does not require current detection, these deficiencies will disappear. DC-link side parallel boost bidirectional Buck/Boost
circuit charge and discharge can play the role of power decoupling, and the control strategy is simple, according to the direction of energy flow to control the closing and conduction of the switch tube in the bidirectional Buck/Boost circuit. A strategy for eliminating ripples can be realized. Through the above analysis, the use of open-loop structure to control the bidirectional Buck/Boost circuit (decoupling circuit) can achieve a better power compensation effect. The basic principle and implementation method of feed-forward control of boost power decoupling circuit.

4. The Basic Principle and Implementation Method of Feed-forward Control of Boost Power Decoupling Circuit

The proposed feed-forward parallel connect compensation control structure is shown in Figure 3. There is no current detection link in this scheme, only the voltage signal needs to be sampled, the sampled voltage directly generates the driving signal with the PWM comparator, and the dynamic response speed is fast.

In Figure 1, $V_r$ and $V_{ref}$ are the sampling value and reference value of the DC-link voltage. The bias voltage $V_b$ exists, so the duty cycle of the switch is always greater than zero. Suppose the duty ratio of the switch $s_1$ is $d$, the output voltage of the PFC converter is $V_o$, $s_1$ and $s_2$ are complementarily conduction, when $V_o$ increases, the duty ratio of the boost bidirectional Buck/Boost circuit also enlarges, the voltage of the decoupling capacitor on output side increase, and the power converted from the PFC system to the decoupling capacitor $C_s$ becomes larger (or the duty cycle of $s_2$ decreases, and the power converted from the decoupling capacitor $C_s$ to the PFC system decreases) make reduction. It is similar when $V_o$ decrease. As can be seen, feed-forward control of fluctuation can enable the boost bidirectional Buck/Boost circuit to compensating output voltage ripple in the PFC converter due to the decrease of the capacitance value, realize power decoupling, improve power factor, and realize without electrolytic capacitors.

4.1. Mathematical Analysis of Feed-forward Control of Boost Power Decoupling Circuit

Analyse the compensation effect of the feed-forward control method of the boost decoupling circuit, as shown below:

![Figure 1. Decoupling circuit feed-forward control strategy block diagram.](image-url)

Figure 1 are a block diagram of the control strategy of the boost-type bidirectional Buck/Boost circuit. Assuming that the main circuit and the compensation circuit of the SRM power conversion circuit are in stable operation, the AC component is considered. The DC-link voltage is $V_o$: $V_o = V_0 + \bar{V}_o$, $V_0$ is the average voltage, $\bar{V}_o$ is the ripple component, the duty cycle of the switch $s_1$ is:
\[ d = D + \frac{\alpha K \bar{v}}{v_a} \]  

In (7), \( \alpha, v_a \) with \( K \) are the DC bus voltage sampling coefficient, carrier amplitude, and proportional magnification. According to the input and output relationship of the motor power conversion circuit voltage, the energy storage capacitor voltage is:

\[ v_{cs} = \frac{v_o + \bar{v}_o}{1 - d} \]  

It is known from (8) that when the decoupling circuit uses a feed-forward control method based on \( v_o \) fluctuation, the duty cycle \( d \) of the switch tube \( s1 \) and the change of the DC-link voltage jointly determine the voltage waveform of the energy storage capacitor. When \( \bar{v}_o = \bar{v} \), only this size of the duty cycle \( d \) determines the voltage waveform of the storage capacitor. Through the conservation of input and output energy, the current flowing into the inductor \( i_{LS} \) is:

\[ i_{LS} = \frac{i_o}{1 - d} = \frac{C_s}{1 - d} \frac{dv_{cs}}{dt} \]  

From (8), the input current of the decoupling circuit is:

\[ i_{LS} = \frac{C_s}{(1 - d)^2} \left[ 1 - D + \frac{\partial K}{v_a} V_o \right] \frac{dv_o}{dt} \]  

According to the duty ratio control method [26], the decoupling circuit is equivalent to the same energy storage device as the capacitor, and the capacitance value is:

\[ C_s = \frac{C_{s1}}{(1 - d)^3} \left[ 1 - D + \frac{\alpha K}{v_a} V_o \right] \]  

Assuming that the DC-link voltage ripple component are: \( \bar{v}_o = \gamma V_o \sin(\omega t) \), let \( \beta = \frac{\alpha K \gamma V_o}{v_a} \). When the circuit works in a stable state and the system parameters are determined \( \beta \), is the determined value. From equation (7), the duty cycle of the switch \( s1 \) is:

\[ d = D + \beta \sin(2\omega t) \]  

Therefore, the ratio of the equivalent capacitance \( C_m \) of the decoupling circuit to the film capacitance \( C_a \) is:

\[ \lambda = \frac{1 - d + \beta}{\left[ 1 - D - \beta \sin(2\omega t) \right]^2} \]  

It is know from (13) that when \( \sin(2\omega t) = -1 \), \( \lambda \) takes the minimum value. \( \sin(2\omega t) = -1 \), \( \gamma = 1\% \); since \( 0 < D < 1 \), \( 0 < d < 1 \), and \( 0 < \beta < 1 \). Considering \( D \) and as variables, are a binary function, and Fig.2 is a three-dimensional graph of equation (13):
Figure 2. The relationship between the average value of the duty cycle $D$ and the coefficient $\beta$ and $\lambda$.

The figure 2 above is a three-dimensional diagram of a binary function. It can be seen that changes with the different values of $D$ and $\beta$. The minimum value is $\lambda_{\text{min}} = 1$ at the origin of the coordinate, as known from (13), the size of $\beta$ is only determined by the system parameters, and the system is in a stable state with $\beta$ unchanged. $\lambda$ are proportional to the duty cycle $D$. As $D$ increases, it becomes larger, the larger the decoupling circuit equivalent capacitance amplification factor, the stronger the corresponding power compensation capability. When $D$ is unchanged, $\lambda$ only increases with the increase of $\beta$, and the decoupling circuit's ability to compensate reactive power also increases.

For a single-phase AC/DC converted SRM, the power is generally 100W to 1000W. When there is no parallel power decoupling circuit, the DC bus capacitance is 100µF to 1000µF. After paralleling this decoupling circuit, the bus capacitance decrease and the bus voltage is stable.

Take a point in Figure 5, $\beta = 0.22$, $D = 0.27$ and $\lambda = 27.34$, use the large electrolytic capacitor filter directly, assuming that the power of the SRM is 27KW, and the electrolytic capacitor is $2000\mu F$. After using feed-forward parallel decoupling compensation, theoretically only a $73\mu F$ is needed. Thin film capacitors are sufficient.

5. Results and Discussion

Confirm the effectiveness of the suggested control method, the DC bus non-electrolytic capacitor driver electric tool platform is studied. The experimental platform is show in Figure 6. All control algorithms are realized by matlab/simulink simulation. When fluctuating feed-forward control, the bus voltage of filter capacitor is $56\mu F$. In the power decoupling circuit, the filter inductance is $L_S = 1mH$, the decoupling capacitor $C_s = 56\mu F$, and the circuit switching frequency is 50kHz. Take the average value of the duty cycle of the decoupling circuit $D = 0.26$, the proportional amplifier amplification factor $K_e = 15$. Figure 6 is the waveform of the grid voltage, current and THD when the power tool is running at 1000 and 1500 r/min. Figure 6(a) is a harmonic analysis diagram of the grid-side current waveform at 1000 r/min. The grid current is approximately sinusoidal, and THD satisfy the EN61000-3-2 standard. The experimental results in Figure 6(b) when the speed rises to 1500 r/min can preserve a high power factor with low THD. Film capacitor drive system can satisfy the requirements of electrical tools.

Figure 3 illustrates the waveforms of and using the control strategy proposed by us when the load torque is used as a pulsation signal. The grid-side input power factor is 95.28%. The grid-side input current waveform and THD are within the standard range. Knowable when the load fluctuation is large, the DC-link single-phase input speed regulation system without electrolytic capacitor (film capacitor) that we propose can operate stably.
6. Conclusion
This paper proposes a feed-forward control strategy for the output voltage fluctuation of the non-electrolytic capacitor PFC circuit for the power decoupling type non-electrolytic capacitor scheme. Using this control method to control the boost bidirectional Buck/Boost power decoupling circuit, the power decoupling circuit absorb ripple power to stabilize DC bus voltage, improve power factor, and control grid current harmonics in compliance with EN61000-3-2 standards. This method has verified on electric tools.

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