Asynchronous motor drive system using an improved APFC converter

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Abstract Due to the high input current harmonics created from the power diodes as well as the switching of the inverter, the power factor cannot achieve a unity power factor. This paper presents an improved active power factor correction (APFC) converter for three-phase asynchronous motor drive system. This improved APFC operating in a discontinuous inductor current mode based on bridgeless canonical switching cell is designed and corrects the power factor in grid. In order to obtain high performance of the motor drive system, the dual-mode control strategy and the fuzzy PID is used in this system. Finally, the whole system is verified by software simulation and hardware experiment.

Keywords: APFC, asynchronous motor, dual-mode control, fuzzy PID

Classification: Power devices and circuits

1. Introduction

Asynchronous motor has the advantages of simple structure, convenient maintenance, low quality, low cost and high operating efficiency. The AC-DC converter of electric power is an indispensable part in the asynchronous motor drive system [1, 2]. However, it produces a large amount of current harmonics, resulting in the poor power factor at the input ac mains [3, 4]. In order to improve the power quality as well as the efficiency and performance of motor drive system, some methods are studied and proposed.

The traditional passive power factor correction (PPFC) in asynchronous motor drive system uses some passive devices after the rectifier bridge to prolong the conduction time of the diode [5, 6, 7]. The current harmonics are reduced to make the current waveform sinusoidal for improving the power factor of grid [8]. However, with large inductance and large capacitance, the volume of the whole circuit is larger. Moreover, the power factor will be affected by the change of working environment and conditions [9, 10].

Among the traditional active power factor correction (APFC) in asynchronous motor drive system, for example, the bridge Boost-PFC [11, 12], the bridgeless Boost-PFC [13, 14] and the CSC converter have mandatory control of input current through DC-DC converter [15, 16]. Therefore, the current in grid side is sinusoidal and as far as possible keeps the same phase with the input voltage which indicates the power factor is almost one. Compared to the PPFC, APFC can reduce harmonic pollution in grid and achieve the requirement of unit power factor [17]. Nevertheless, considered some relevant factors such as high power loss, voltage conversion ratio, switching loss and the number of components, its application is also limited in asynchronous motor drive system.

The asynchronous motor of electric forklift is taken as the research object in this paper, and a method of asynchronous motor drive system based on improved APFC is proposed, which operates in a discontinuous inductor current mode (DCM) and overcomes the shortcomings of traditional PPFC and APFC converter. The simulation model is built in Matlab/Simulink. Finally, a real hardware system is implemented to verify the improved motor drive system. The results show that the power factor of the grid is nearly the unit power factor, the harmonics are decreased and the power quality is increased.

2. The fundamentals of improved APFC converter

This paper presents an improved APFC converter shown in Fig. 1(a). The improved APFC circuit consists of switching device, the energy stored inductor, power diode and an output capacitor. It combines the advantages of CSC converter with the bridgeless structure. Also, it has low loss of bridgeless structure and less devices [18, 19]. The structure of improved APFC converter is shown in Fig. 1(a).

The design of the improved APFC converter makes the switches ($S_{w_1}$ and $S_{w_2}$) work in the positive-half period and the negative-half period of the supply voltage $V_S$ respectively. As shown in Fig. 1(b), (c) and Fig. 2, the input current $i_L$ flows through the switch $S_{w_1}$, inductor $L_1$ and the current recovery diode $D_1$, during the positive half period of the supply voltage $V_S$. Similarly, as shown in Fig. 4, the switch $S_{w_2}$, inductor $L_2$ and diode $D_2$ are working during the negative half period of the supply voltage $V_S$. Fig. 3(a) shows waveforms of supply voltage ($V_S$), inductor currents ($i_{L1}$ and $i_{L2}$) and intermediate capacitor voltages ($V_{C1}$ and $V_{C2}$). Fig. 3(b) shows the relevant waveforms during the three modes of operations.

Fig. 1–Fig. 4 lists all the modes of operation of the improved APFC converter used in this paper, which are divided into six modes. The first three modes are similar to the last three. However, the first three work in the positive half cycles. The latter works in the negative half cycle. Therefore, only the first three working modes are described.
in this paper, the latter three working modes can be referred to the first three.

Mode I-A: As shown in Fig. 1(b), when the switch $S_{w1}$ is on, the current $i_s$ emitted from the power supply sequentially flows through $S_{w1}$, the input side inductor $L_{i1}$ and the diode $D_{p}$. Therefore, a closed circuit is formed to charge the inductor $L_{i1}$. However, intermediate capacitor $C_1$ starts discharging, which charges the capacitor $C_d$. Fig. 3(b) shows that during this mode, the inductance current $i_{Li1}$ increases continuously, the voltage $V_{c1}$ decreases as a result of the discharge, and the $V_{dc}$ increases due to the charge from $C_1$.

Mode I-B: In this mode of operation, as shown in Fig. 1(c), when the switch $S_{w1}$ is disconnected, the current $i_s$ flows through the capacitor $C_1$, leading that the $C_1$ is charged by power supply and the $V_{c1}$ is increased. The inductor $L_{i1}$ begins discharging, which charges the capacitor $C_d$ through a closed circuit with the load and the diode $D_1$, and the waveform is as shown in Fig. 3(b). Fig. 3(b) shows that during this mode, the voltage $V_{dc}$ increases with the increase of current $i_{Li1}$, meanwhile, the voltage $V_{c1}$ increases because the capacitor $C_1$ starts charging.

Mode I-C: this mode is discontinuous inductor current mode (DCM) in which the current $i_{Li1}$ flowing through the inductor $L_{i1}$ becomes zero, as shown in Fig. 2. At this point, the inductance $L_{i1}$ is fully discharged, meaning that the current is reduced to zero to form the DCM mode. The current $i_s$ still flows into the intermediate capacitor $C_1$ to form a charging state, maintaining the energy of $C_1$. The capacitor $C_d$ provide energy to the load. As shown in Fig. 3(b), the voltage $V_{dc}$ decreases because the capacitor $C_d$ is discharged, and the voltage $V_{c1}$ still increases.

3. Asynchronous motor control system based on improved APFC

Fig. 5 is the whole structure of three-phase asynchronous motor system based on improved APFC converter. The system includes the rectifier module, APFC module, voltage source inverter (VSI) module, motor module, the speed controller and the voltage controller [20, 21, 22].

3.1 Speed controller using dual-mode speed control strategy

The traditional PWM scheme produces more harmonics in the high speed state, the PWM mode is not suitable for high speed application. The dual-mode control method proposed in this paper is able to achieve a better performance both at low speed and high speed. Fig. 5 shows the application of dual-mode control in this paper [11]. When working in low-speed situation, the PWM mode is adjusted by changing the duty cycle while keeping the input voltage $V_{dc}$ of the VSI constant. When working in high-speed situation, the system works in PAM mode. The control of the switch of the APFC is the same with the low speed mode, but the control of the switch of the VSI adopts PAM mode, in which the pulse amplitude is modulated by changing bus voltage $V_{dc}$ rather than duty cycle.
3.2 Control of the voltage controller

Fig. 5 shows the structure diagram of the control of DC bus voltage controller [23, 24]. The reference voltage \( V_{dc}^{\text{ref}} \) is given by Eq. (1).

\[
\begin{align*}
V_{dc}^{\text{ref}} &= k_v \omega, \quad \text{(PWM)} \\
V_{dc}^{\text{ref}} &= \text{cons} \tan t, \quad \text{(PAM)}
\end{align*}
\]

The error signal \( V_e \) is represented by

\[
V_e = V_c^{\text{ref}} - V_c
\]

This error voltage \( V_e \) is given to the fuzzy PID controller to generate a controlled output voltage \( V_{cc} \) [25, 26, 27], which is expressed as

\[
V_{cc} = k_p V_e + k_i \int V_e dt + k_d \frac{dV_e}{dt}
\]

where \( k_p \), \( k_i \) and \( k_d \) are the proportional, integral and derivative gains of the fuzzy PID controller, respectively [28, 29].

Finally, the PWM signals are generated by comparing the output \( V_{cc} \) of the fuzzy PID controller with the high-frequency sawtooth signal \( m_d(t) \), which are given as

\[
\begin{align*}
\text{if} \ m_d < V_{cc} \ \text{then Switch1} &= 1, \ V_s > 0 \\
\text{if} \ m_d \geq V_{cc} \ \text{then Switch1} &= 0, \ V_s > 0 \\
\text{if} \ m_d < V_{cc} \ \text{then Switch2} &= 1, \ V_s < 0 \\
\text{if} \ m_d \geq V_{cc} \ \text{then Switch2} &= 0, \ V_s < 0
\end{align*}
\]

Where 1 and 0 represent on and off of APFC switches, respectively [30].

4. Simulation scheme and results of the proposed system

The above presented system shown in Fig. 5 has been simulated using MATLAB/SIMULINK software. The machine parameters are described in Appendix. The AC power \( V_s \) 220 V is assumed for all the simulation tests. As is shown in Fig. 6(a), the waveform of grid current \( i_s \) is sinusoidal shapes, and the phase of \( i_s \) is nearly same with the phase of \( V_s \). The power factor in this system is 0.9976 from Fig. 6(a).

Fig. 6(b) and Fig. 6(c) show that the waveforms of the capacitance voltage (\( V_c^1 \) and \( V_c^2 \)) and the inductance current (\( i_L^1 \) and \( i_L^2 \)). The obtained waveforms are almost consistent with the theoretical waveforms above described. It can be concluded that the improved APFC controller can work normally in this system.

In Fig. 7(a) and (b), the power factor of grid and the DC bus voltage \( V_{dc} \) by conventional and proposed APFC are demonstrated, where the benefit of the proposed method is clearly shown. It can be seen that 0.01 s after operation starting, the power factor begins to increase. At \( t = 0.021 \) s, it achieves unit power factor first time, and it maintains stable after \( t = 0.03 \) s. In Fig. 7(c) and Fig. 7(d), the range amplitude of the voltage \( V_{dc} \) in improved APFC converter is about 6 V, the range amplitude of the voltage \( V_{dc} \) in conventional converter is about 13 V. Compared with the conventional Boost-APFC converter, the improved converter gives fast and stable power factor value at \( t = 0.03 \) s, and the voltage \( V_{dc} \) in improved APFC converter is more stable with smaller ripple.
Fig. 8(a) shows the waveforms of motor in steady state and Fig. 8(b) shows the bus voltage $V_{dc}$, rotor speed $n$, electromagnetic torque $T_e$ and line voltage for a step change on the speed reference ($n^* = 450$ rpm) at $t = 0$ s. The waveforms of the motor parameters during the low speed mode change to high speed mode are as shown in Fig. 8(b) (at $t = 1$ s.) From the dynamic waveform of motor shown in Fig. 8(b), it can be seen that the bus voltage also can maintain stability on motor start-up operation or step change operation of speed reference. When the motor is running at high speed, the motor speed can be adjusted effectively by changing the bus voltage using a dual-mode control. In terms of function and performance, the simulation results show that the structure is reasonable and effective in the application of the system.

5. System hardware implementation

An experimental system based on microcontroller has been constructed in order to verify proper operation of the proposed technique. The real system consists of a microcontroller-DSPF28335, the drive circuit, an asynchronous motor, the VSI and the improved APFC circuit. A photograph of the experimental system is shown in Fig. 9.

Fig. 10(a) shows that the phase of the voltage (the green curve in Fig. 10(a)) and current (the yellow curve in Fig. 10(a)) in grid side is almost the same, and the smaller amplitude of the curves is the voltage waveform. Therefore, it can be concluded that the structure of improved APFC converter has improved the power factor. Fig. 10(b) and Fig. 10(c) show that capacitor voltage and inductor current in improved APFC converter are consistent with the theoretical analysis in Section II. From the phase current and line voltage shown in Fig. 11, it can be concluded that the motor is running normally and motor speed can be regulated by changing the output duty cycle under the high-speed mode and adjusting the bus voltage under low-speed mode. The waveform indicates that the proposed dual-mode control strategy can achieve more precise control of motor speed.
In the presented paper, an improved APFC converter for using in induction motor drive is discussed and presented. In order to achieve a high performance of the motor drive system, the dual-mode control strategy and fuzzy PID are considered in the controller. After designing the speed controller and the voltage controller with the proposed improved APFC converter, an improved asynchronous motor drive system is built and simulated in MATLAB/SIMULINK. A detailed simulation analysis is presented. In addition, the real system is implemented using a digital microcontroller. Simulation as well as experimental results show that proposed method highlights the effectiveness of the improved APFC modules. Therefore, the power factor in grid and overall efficiency of the motor drive system can be increased considerably.

7. Appendix

Parameters of induction motor. Rated power 1.5 kW, rated voltage 220 V, rated speed 1600 rpm, 2 poles, stator resistance 0.0229Ω, rotor resistance 0.015Ω, stator leakage inductance 0.000102 H, rotor leakage inductance 0.000054, magnetizing inductance 0.000741 H. Parameters of improved APFC circuit. \( V_S(t) = V_m \sin(2\pi f_1 t) = 220\sqrt{2} \sin(314t) V \), \( L_{1r} = L_{2r} = 300 \mu H \), \( C_1 = C_2 = 0.078 \mu F \), \( C_f \approx 49.8 \mu F \), \( L_f = 54 \text{ mH} \).

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