IMPLEMENTATION OF SENSORLESS DRIVE OF BRUSHLESS DC MOTOR WITH POWER FACTOR CORRECTION FOR AIR CONDITIONER APPLICATIONS

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Abstract: Single-phase induction motors have been widely used as fan or compressor motors in air conditioners. However, its efficiency is quite low and speed controllability is impossible when used as ON-OFF operation. During the past few years, the brushless dc (BLDC) motor has been gained more attention to use in air conditioner applications due to higher efficiency and speed controllability. Also, the power quality of BLDC motor driver such as the current harmonics and power factor is concerned. Therefore, this paper presents implementation of sensorless drive of BLDC motor with power factor correction for air conditioner applications. Experimental results show the successfully implementing sensorless drive system with improved power factor (PF) and total harmonic distortion (THD) of input AC current.

Key Words: Air Conditioner/ Brushless DC Motor/ Power Quality/ Power Factor Correction/ Sensorless.

1. INTRODUCTION

Nowadays, the energy saving is essential because of the rising energy price and global warming issues. In air conditioner applications, the conventional single-phase induction motors have been widely used as fan or compressor motors. However, its efficiency is quite low and speed controllability is impossible. The motors are typically turned ON or OFF by the controller. During the past few years, the BLDC motor has been selected to use in air conditioner applications due to higher efficiency and speed controllability. In the BLDC motor drive system, it is necessary to know the rotor position in order to provide the proper commutation sequences. Hall sensor is typically the position sensor used for BLDC motor [1]. To reduce the total cost and increase the system reliability, the sensorless drive of BLDC motor is therefore focused to eliminate Hall sensor.

However, the power quality of BLDC motor driver board such as PF and THD of input AC current is also important. In [2], the poor PF and increased THD are mainly due to uncontrolled charging of the DC capacitor.

The international power quality standards such as IEC 61000-3-2 emphasizes on low harmonic contents and near unity PF current to be drawn from AC mains [3]. Consequently, the power factor correction (PFC) circuit and its algorithm should be implemented in the BLDC driver board [4, 5].

As a result, this paper focuses on implementation of PFC circuit and its algorithm into sensorless drive of BLDC to improve power quality at input AC main in air conditioner applications.

2. PFC BASED SENSORLESS DRIVE OF BLDC MOTOR

Referring to Fig.1, there are three main circuits in this system. In the first circuit, the rectified voltage and Vdc bus are measured and fed to PFC algorithm to compute the duty cycle of PWM for boost PFC converter. Secondly, the output voltage of half-bridge LLC resonant converter is measured and fed into controller for LLC resonant algorithm. Finally, the third circuit is three-phase inverter driving the BLDC motor. The sensorless drive algorithm receives three phase measured terminal voltage for calculating the commutation sequences for driving the BLDC motor before controller would send six PWM signals to the three-phase inverter.

Fig. 1. Overall block diagram of the proposed method.
2.1. Boost PFC Circuit

Fig. 2 shows the boost PFC topology [6].

The continuous conducting mode is selected. As a result, the THD of input AC current can be reduced as well. The maximum boost inductor \( L_{\text{max}} \) can be designed as [7]:

\[
L_{\text{max}} = \frac{(V_o + V_d)D_{\text{max}}(1-D_{\text{max}}-D_w)^2}{2I_o(\text{max})} \quad (1)
\]

where

\[
D_{\text{(max)}} = (1-D_w)\left(\frac{V_o-V_{\text{in(min)}}+V_d}{V_o}\right) \quad (2)
\]

\( V_{\text{in(min)}} \) is minimum input voltage;

\( D_{\text{(max)}} \) is maximum duty ratio;

\( D_w \) is dwell time duty ratio;

\( V_o \) is output voltage;

\( V_d \) is diode voltage;

\( I_o \) is output current;

\( T \) is switching period of boost PFC converter.

The design values of boost PFC converter are aimed for a constant DC link voltage of 380 Vdc, as the input AC voltage \( V_{\text{in}} \) varies between 100 V to 260 V. The switching frequency is configured at 40kHz. Substituting these given parameters in Eqs. (1) and (2), the boost converter’s maximum inductor can be computed as 748 µH. Assuming that the efficiency of boost PFC converter be around 95 percent. The output of the boost PFC converter is connected to the half-bridge LLC resonant converter, reducing the voltage from 380Vdc to 80 Vdc. Finally, the output of the half-bridge LLC resonant circuit is connected to the three-phase inverter, driving the BLDC motor.

2.2. Half-Bridge LLC Resonant Circuit

Fig.3 shows the topology of half-bridge LLC resonant converter. The switching frequency of PWM for half-bridge LLC resonant converter is adjusted according to load. Both switches S1 and S2 are complementarily operated with the constant 50% duty cycle.

The resonant parameters are obtained as follows [8]:

\[
C_r = \frac{1}{2\pi f_o R_{\text{ac}}} \quad (3)
\]

\[
L_r = \frac{1}{(2\pi f_o)^2 C_r} \quad (4)
\]

\[
L_p = mL_r \quad (5)
\]

where

\( C_r \) is series resonant capacitor;

\( f_o \) is resonant frequency;

\( R_{\text{ac}} \) is the equivalent load resistance which transfer to primary side;

\( Q \) is quality factor;

\( L_r \) is leakage inductance;

\( L_p \) is magnetizing inductor;

\( m \) is ratio between \( L_p \) and \( L_r \).

The design values of half-bridge LLC resonant converter are aimed for a constant DC link voltage of 80 Vdc suitable for the voltage rating of BLDC motor. The input DC voltage of the circuit is 380 Vdc. According to Eqs. (3) through (5), the \( C_r \), \( L_p \) and \( L_r \) can be computed 33 nF, 625 µH, and 78 µH, respectively.

The switching frequency is set at 100 kHz.

2.3. Sensorless Drive of BLDC Motor

The rotor position estimation by means of detecting the zero crossing point (ZCP) of back EMFs have been widely used for BLDC motor because of its simplicity. The back EMF of motor has the trapezoidal shape and motor requires the driving current with pulse shape. Fig.4 shows the three-phase inverter driving BLDC motor. Fig 5 shows the commutation sequence in terms of current flow in each commutation stage and switching scheme.
Fig. 5. Commutation sequence (a) Current flow in each commutation stage  (b) Switching scheme.

In Fig 6, the equivalent circuit of phase-a winding excited during commutation stage S1 is shown. The ZCP detection method can be explained as following:

Fig. 6. Equivalent circuit of phase-a winding excited during commutation stage S1.

Referring to Fig.6, the voltage equations during commutation stage S1 are as follows:

\[ V_a = R I_a + L \frac{dI_a}{dt} + E_a + V_n \]  
(6)

\[ V_b = R I_b + L \frac{dI_b}{dt} + E_b + V_n \]  
(7)

\[ V_c = E_c + V_n \]  
(8)

During stage S1, the motor current flows from phase-a winding to phase-b winding, yields

\[ I_a = -I_b \]  
(9)

Summing all three voltage equations (6), (7) and (8), yields.

\[ V_a + V_b + V_c = E_a + E_b + E_c + 3V_n \]  
(10)

At the zero-crossing point, sum of back EMFs are zero (i.e., \( E_a + E_b + E_c = 0 \)), then

\[ V_a + V_b + V_c = 3V_n \]  
(11)

The neutral voltage (\( V_n \)) can be computed when all three terminal voltages (\( V_a, V_b \) and \( V_c \)) are measured as follows.

\[ V_n = \frac{(V_a + V_b + V_c)}{3} \]  
(12)

Finally, the phase-c back EMF (\( E_c \)) can be easily computed as

\[ E_c = V_c - V_n \]  
(13)

The switching scheme, current flows and back EMF detected its zero crossing in different commutation stages are summarized in Table 1.

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>PWM</td>
<td>PWM</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>Q2</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>Q3</td>
<td>OFF</td>
<td>OFF</td>
<td>PWM</td>
<td>PWM</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>Q4</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>Q5</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>PWM</td>
<td>PWM</td>
<td>OFF</td>
</tr>
<tr>
<td>Q6</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
</tr>
<tr>
<td>BEMF</td>
<td>C</td>
<td>B</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Current</td>
<td>A to B</td>
<td>A to C</td>
<td>B to C</td>
<td>B to A</td>
<td>C to A</td>
<td>C to B</td>
</tr>
</tbody>
</table>

3. EXPERIMENTAL RESULTS

In the experiments, the dsPIC33FJ16G504 controller has been used for implementation. The parameters of BLDC motor are summarized in Table 2. Figs.7 and 8 show currents and phase-a voltage terminal with load at 1,500 and 2,100 rpm, respectively. Figs. 9 and 10 show input AC main and BLDC current with load at 1,800 and 2,100 rpm. Input AC main and step speed responses controlled from 1,200 rpm to 3,000 rpm at no load are shown in Fig. 11. The THDI and PF of proposed BLDC drive are reported in Tables 3 and 4, showing the successful implementation of the proposed system.

<table>
<thead>
<tr>
<th>Table 2. Parameters of BLDC motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specifications</td>
</tr>
<tr>
<td>Rated Voltage</td>
</tr>
<tr>
<td>Rated Speed</td>
</tr>
<tr>
<td>Resistance</td>
</tr>
<tr>
<td>Inductance</td>
</tr>
<tr>
<td>Poles</td>
</tr>
</tbody>
</table>
Fig. 7. Three phase currents and phase-a terminal voltage with load at 1,500 rpm. [time: 5 ms/div]

Fig. 8. Three phase currents and phase-a terminal voltage with load at 2,100 rpm. [time: 5 ms/div]

Fig. 9. Input voltage, input current, BLDC current, and phase-a terminal voltage with load at 1,800 rpm. [time: 10 ms/div]

Fig. 10. Input voltage, input current, BLDC current, and phase-a terminal voltage with load at 2,100 rpm. [time: 10 ms/div]

Fig. 11. Input voltage, input current, BLDC current, and speed responses with a step speed command from 1,200 to 3,000 rpm at no load (Lower four traces are zoom ones of above four traces) [time: 0.5 s/div]

Table 3. THD of input AC current and PF at different input AC voltages with constant speed at 2,100 rpm

<table>
<thead>
<tr>
<th>Vac (V)</th>
<th>Iac (A)</th>
<th>P in (W)</th>
<th>THD(%)</th>
<th>PF</th>
<th>I a_rms (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>0.4</td>
<td>77.6</td>
<td>4.7</td>
<td>0.999</td>
<td>1</td>
</tr>
<tr>
<td>190</td>
<td>0.4</td>
<td>77.6</td>
<td>4.2</td>
<td>0.989</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>0.4</td>
<td>77.8</td>
<td>4.2</td>
<td>0.986</td>
<td>1</td>
</tr>
<tr>
<td>210</td>
<td>0.4</td>
<td>77.8</td>
<td>4.3</td>
<td>0.984</td>
<td>1</td>
</tr>
<tr>
<td>220</td>
<td>0.4</td>
<td>77.3</td>
<td>4.3</td>
<td>0.981</td>
<td>1</td>
</tr>
<tr>
<td>230</td>
<td>0.3</td>
<td>77.0</td>
<td>4.2</td>
<td>0.977</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4. THD of input AC current and PF at different speeds with constant input AC voltage at 220 Vac

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Iac (A)</th>
<th>P a (W)</th>
<th>THD(%)</th>
<th>PF</th>
<th>I a_rms (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,500</td>
<td>0.2</td>
<td>37.5</td>
<td>7.2</td>
<td>0.920</td>
<td>0.55</td>
</tr>
<tr>
<td>1,650</td>
<td>0.2</td>
<td>44.6</td>
<td>5.0</td>
<td>0.943</td>
<td>0.65</td>
</tr>
<tr>
<td>1,800</td>
<td>0.2</td>
<td>52.0</td>
<td>5.2</td>
<td>0.955</td>
<td>0.70</td>
</tr>
<tr>
<td>1,950</td>
<td>0.3</td>
<td>63.7</td>
<td>5.3</td>
<td>0.970</td>
<td>0.86</td>
</tr>
<tr>
<td>2,100</td>
<td>0.3</td>
<td>75.2</td>
<td>4.2</td>
<td>0.980</td>
<td>1.00</td>
</tr>
</tbody>
</table>
4. CONCLUSION

This paper has been presented an implementation of sensorless drive of BLDC motor with PFC for air conditioner applications. The power quality of sensorless drive system of BLDC motor has been improved by PFC boost converter operating in discontinuous conducting mode. The THD of input AC main is reduced to 4.3% and PF increased to 0.98 at 220 Vac. Experimental results have shown the feasibility of the proposed system to be commercialized.

5. REFERENCES


