Comparison Analysis of Two types of Electrical Circuits for Sensorless Brushless DC Motor Control

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In this research, the effects of two types of electrical circuits, which detect back Electromotive Force (EMF) signals and output six step square waveform rotor position signals of 3 phase Brushless DC (BLDC) motors, on sensorless control are analyzed by implementing a coupled analysis of a Finite Elements Method (FEM) model of a BLDC motor and the electrical circuit. The 1st electrical circuit uses a dynamic threshold level which changes automatically according to the back EMF maximum level, and the 2nd electrical circuit uses a static threshold level which is determined at the start of motor control and is fixed regardless of the back EMF maximum level. Also, the results of the coupled analysis are verified by implementing experimental evaluation using an 8 pole 12 slot BLDC motor and embedded motor controller. Through this research, the advantages of the 1st electrical circuit is verified.

Keywords: Brushless DC motor, Coupled analysis, Electrical circuit, Finite Elements Method.
(Received: 7 April 2015, Revised 26 June 2015)

1. Introduction

As the importance of BLDC motors increases in industries such as home entertainment, home appliances and electrical vehicles, the need for high performance BLDC motors, which output high torque, consume low current and maintain low torque ripples with decreased size and manufacturing cost at the same time, have increased, and many companies are trying to develop new BLDC motor structures and control algorithms for obtaining high performance BLDC motors. In particular, efforts to develop new control algorithms that can maintain the stability of the motor in any environment are actively being conducted.

Usually, BLDC motor control is implemented by detecting the signals from a network of three hall Integrated Circuits (IC) to confirm the rotor position. Due to this, we should consider the maximum drive temperature which hall ICs can be operated and design a Printed Circuit Board (PCB) to arrange the hall ICs at regular intervals, and we should operate them according to the position of the Permanent Magnets (PM) in the rotor. These processes increase the manufacturing cost. Furthermore, the PCB needs to be calibrated so that an exact relationship between the hall ICs signals and EMF signals is obtained. If a phase difference exists between these signals, it will affect the performance of the motors.

To overcome the demerits which are caused by sensorless BLDC motor control, many studies have proposed new control methods and applications which do not use hall ICs to detect the rotor position. [1-3] analyzed and compared several starting methods of sensorless BLDC motors, and proposed effective starting methods and simple initial rotor position estimation methods which make it possible to start the motor smoothly and decrease motor control cost. [4, 5] proposed a novel control algorithm and electrically commutated circuit model for sensorless BLDC motor by using back EMF signal detection. Through these research, they could apply their new algorithms to actual experiments and lower the control cost. [6] proposed a new control method by using the 150 degrees conduction mode and [7] designed an optimal current vector trajectory to minimize torque ripple of sensorless BLDC motor control.

[8, 9] proposed a new algorithm and technique for sensorless BLDC motor control. [8] proposed a new predictive algorithm which has a high resolution position and speed identification to reduce position errors, and [9] proposed a new optimized digital PWM technique that uses only one phase line voltage. Also, [10] proposed new methods for sensorless BLDC motor control by using a position and speed observer.

In this research, two types of electrical circuits which detect back EMF signals and output six step square waveform rotor position signals of 3 phase BLDC motors were analyzed to verify the effects of them in sensorless BLDC motor control. The 1st electrical circuit uses a dynamic threshold level whose threshold level changes automatically according to the maximum back EMF level, and the 2nd electrical circuit uses a static threshold level which is determined manually at the start of the motor control and does not change according to the maximum back EMF level. To analyze both electrical circuits and verify the advantages of the 1st electrical circuit, an 8 pole 12 slot FEM BLDC motor model was designed and tested with both electrical circuits. Also, experimental evaluation was implemented by designing an embedded 3 phase BLDC motor controller to verify the results of the coupled analysis.

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Through this research, we expect to apply the 1st electrical circuit to actual actuators to decrease manufacturing cost and obtain more reliable control results.

2. Analysis of two types of electrical circuits

2.1 The 1st electrical circuit

The 1st electrical circuit uses a dynamic threshold level, which changes automatically according to the maximum back EMF level, as shown in Fig. 1. In this electrical circuit, the 1st Low Pass Filter (LPF) filters back EMF signals of each phase. A cut-off frequency of the 1st LPF is set for passing frequencies which can detect back EMF signals and eliminating noise signals which are included in back EMF signals. In this research, the cut-off frequency was set at 33.86 kHz. Although an experimental evaluation was carried out from 195 rpm to 2100 rpm to leave a margin for reliable control, the cut-off frequency was set for general applications. In the case of the lower cut-off frequency than 33.86 kHz using the designed BLDC motor, serious noise signals were included in back EMF signals. However, this value is not the absolute one. According to motor specifications and applications, it should be changed properly.

The 2nd LPF changes the threshold level according to the maximum back EMF level and the threshold levels of each phase are synthesized at point S for using as a reference voltage of the comparator which outputs rotor position signals (see Fig. 1). In this research, the 2nd LPF is comprised of three resistors, which are connected in parallel to the 1st LPF, and one capacitor. The cut-off frequency was set at 2.34 Hz. Since the main purpose of the 2nd LPF is to change the threshold level according to the maximum back EMF level, the cut-off frequency was set at very low value than that of the 1st LPF. If the cut-off frequency of the 2nd LPF is higher than that of the 1st LPF or the same level with it, the synthesized threshold level and rotor position signals are distorted, and this causes motor control failure. However, this value is not the absolute one like that of the 1st LPF. According to motor specifications and applications, it should be changed properly.

Finally, filtered back EMF signals of each phase and the synthesized threshold level are compared at the comparator. If the back EMF signal level is higher than the synthesized threshold level, the comparator outputs a high logic signal. If the back EMF signal level is lower than the synthesized threshold level, the comparator outputs a low logic signal. By using this concept, it is possible to obtain U, V, W six step square waveform rotor position signals which have the same signal duty at any rotation speed after detecting back EMF signals. Fig. 2 shows the flow chart of the 1st electrical circuit.

2.2 The 2nd electrical circuit

Fig. 3 shows the 2nd electrical circuit. The cut-off frequencies were set at the same values with those of the 1st electrical circuit. However, unlike the 1st electrical circuit, there is no point S which can synthesize the threshold levels of each phase (see Fig. 1). Due to this, the threshold level is fixed manually at the start of motor control and is constant throughout motor control, irrespective of the back EMF maximum level.

This causes two serious problems. The first problem is that it is not easy to create about 50 % rotor position signal duty after detecting the initial back EMF signals. The second problem is that this signal duty changes at every rotation speed. Due to these problems, motor control failure can occur since it is not possible to output proper rotor position signals. Fig. 4 shows the flow chart of the 2nd electrical circuit.

Fig. 1. The 1st electrical circuit.

Fig. 2. Flow chart of the 1st electrical circuit.
3. Coupled analysis of 8 pole 12 slot FEM BLDC motor model and electrical circuits

Fig. 5 shows the designed 2D and 3D FEM model of an 8 pole 12 slot BLDC motor, and Fig. 6 shows the EMF analysis results at 60 rpm. The rotor is flower-shaped, and this allows for trapezoidal-shaped EMF signals to be generated as well as decreasing cogging torque. The motor control signals in this research are square waveform. Since the EMF and motor control signals are similar in shape, torque ripples will be decreased. In addition, the magnetization pattern of the PMs in this FEM model of the BLDC motor is parallel since the shape of the PMs is cuboid. The basic motor specification is presented in Table 1.

Fig. 7 shows the schematic diagram of the coupled analysis. As shown in Fig. 7, two types of analysis were implemented. The 1st analysis was carried out at various rotation speeds under no load and the 2nd analysis was carried out by applying various loads.

For deciding the suitable values of the electrical circuit components, the electrical circuits were first simulated using PSpice, and coupled analysis were then implemented.

Fig. 4. Flow chart of the 2nd electrical circuit.
4. Analysis results

4.1 PSpice simulation

First, the electrical circuits were simulated using PSpice. Since it was not possible to make exactly the same EMF signal of the actual motor, general trapezoidal waveforms were used in the simulation.

Fig. 8 shows the simulation results of the 1st electrical circuit. In the simulation, the maximum levels of the trapezoidal waveforms were set at 0.86 V, 1.68 V and 3.62 V, respectively. As shown in the analysis results, the threshold level of the 1st electrical circuit automatically changes according to the maximum level of the trapezoidal waveform, and the ratio of the threshold level to the trapezoid peak remained the same at about 0.39.

Fig. 9 shows the simulation results of the 2nd electrical circuit. In the simulation, the maximum levels of the trapezoidal waveforms were set at 0.86 V, 1.68 V and 3.62 V, respectively. As shown in the analysis results, the ratio of the threshold level to trapezoid peak changes according to the trapezoid peak since the threshold level of the 2nd electrical circuit is fixed. Both of the simulation results are summarized in Tables 2 and 3.
Table 2 Simulation results (The 1st electrical circuit).

<table>
<thead>
<tr>
<th>Trapezoid peak (V)</th>
<th>Threshold level (V)</th>
<th>Threshold level / Trapezoid peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.86</td>
<td>0.34</td>
<td>0.39</td>
</tr>
<tr>
<td>1.68</td>
<td>0.66</td>
<td>0.39</td>
</tr>
<tr>
<td>3.62</td>
<td>1.42</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 3 Simulation results (The 2nd electrical circuit).

<table>
<thead>
<tr>
<th>Trapezoid peak (V)</th>
<th>Threshold level (V)</th>
<th>Threshold level / Trapezoid peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.86</td>
<td>1.42</td>
<td>1.64</td>
</tr>
<tr>
<td>1.68</td>
<td>1.42</td>
<td>0.84</td>
</tr>
<tr>
<td>3.62</td>
<td>1.42</td>
<td>0.39</td>
</tr>
</tbody>
</table>

From Figs. 8 and 9, it can be seen that the trapezoidal waveforms include a DC component unlike the EMF analysis results of the FEM motor model (see Fig. 6). In the EMF analysis of the FEM motor model, the electrical circuit of the inverter and motor was designed by opened-circuit and the assigned rotation speed was input to rotate the motor. This made the EMF signal waveforms symmetrical with respect to the 0 without including the DC component. However, the electrical circuits of the PSXpe simulation were designed by closed-circuit and the DC component was included in the trapezoidal waveforms to make almost the same condition with experimental evaluation. In actuality, the EMF signal waveforms of the actual motor include the DC component and are not vertically symmetrical since the embedded motor controller, which was used in the experimental evaluation, was designed by closed-circuit and driven by the rated input voltage with including noise signals (see Figs. 15-18).

4.2 Coupled analysis

At the previous section, the advantages of the 1st electrical circuit was verified by the PSXpe simulation. However, it was not possible to simulate at various rotation speeds under no load as well as under various loads by the PSXpe simulation. Only the general trapezoidal waveforms were used. For such reasons, coupled analysis of the designed FEM BLDC motor model and the electrical circuit were implemented by applying various conditions.

4.2.1 By changing rotation speed under no load

In this section, coupled analysis were implemented at various rotation speeds under no load.

The analysis results using the 1st electrical circuit are shown in Fig. 10 and are summarized in Table 4. From Fig. 10, the U, V, W phase back EMF signals, threshold level and U phase rotor position signal can be seen. As shown in the analysis results, the threshold level changes automatically according to the rotation speed, and it is proportional to the maximum back EMF level. Also, the ratio of the threshold level to the maximum back EMF level is always about 0.43 and the duty of the rotor position signals are always about 54%. If these values were to change with the rotation speed, malfunction of the motor operation can occur since it would not become possible to detect the exact rotor position.

In this research, the coupled analysis were carried out from 195 rpm to leave a margin for reliable control in the experimental evaluation. However, it is possible to decrease the minimum rotation speed using the designed BLDC motor and the 1st electrical circuit to 100 rpm. For rotation speed under 100 rpm, the time it takes to detect the initial back EMF signals is large and the threshold level is low. In this case, the effect of noise which is included in the threshold level becomes dominant, and this causes motor control failure.

Although the minimum rotation speed was set at 100 rpm by using the designed BLDC motor and the 1st electrical circuit, this value is not the absolute one. According to motor specifications and applications, it should be changed properly for effective control.

![Fig. 10. Coupled analysis under no load (The 1st electrical circuit).](image-url)
Next, coupled analysis using the 2nd electrical circuit was implemented. Fig. 11 shows the U, V, W phase back EMF signals, threshold level and U phase rotor position signal. The analysis results are summarized in Table 5. It can be seen that the ratio of the threshold level to the maximum back EMF level changes with the rotation speed. If the manually fixed threshold level is too close to the maximum or minimum back EMF signal level (see Figs. 11(a) and 12), control failure occurs since it is not possible to detect proper rotor positions.

![Figure 11. Coupled analysis under no load (The 2nd electrical circuit).](image)

![Figure 12. Control failure under no load (The 2nd electrical circuit).](image)

![Figure 13. Coupled analysis under various loads (The 1st electrical circuit).](image)

Table 4 Analysis results under no load (The 1st electrical circuit).

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Back EMF Max. (V)</th>
<th>Threshold level (V)</th>
<th>B / A</th>
</tr>
</thead>
<tbody>
<tr>
<td>195</td>
<td>0.86</td>
<td>0.37</td>
<td>0.43</td>
</tr>
<tr>
<td>900</td>
<td>3.94</td>
<td>1.72</td>
<td>0.43</td>
</tr>
<tr>
<td>1560</td>
<td>6.81</td>
<td>2.96</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 5 Analysis results under no load (The 2nd electrical circuit).

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Back EMF Max. (V)</th>
<th>Threshold level (V)</th>
<th>B / A</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>1.43</td>
<td>1.40</td>
<td>0.98</td>
</tr>
<tr>
<td>420</td>
<td>1.84</td>
<td>1.40</td>
<td>0.76</td>
</tr>
<tr>
<td>750</td>
<td>3.29</td>
<td>1.40</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Table 6 Analysis results under various loads
(The 1st electrical circuit).

<table>
<thead>
<tr>
<th>Load (Nm)</th>
<th>Speed (rpm)</th>
<th>Rotor position signal duty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2833</td>
<td>52</td>
</tr>
<tr>
<td>1.0</td>
<td>2272</td>
<td>52</td>
</tr>
<tr>
<td>1.5</td>
<td>2000</td>
<td>53</td>
</tr>
</tbody>
</table>

4.2.2 By applying load

In this section, coupled analysis of the 1st electrical circuit were implemented under various loads. When loaded, the back EMF signal waveforms are largely distorted. Therefore, it is very important to detect the distortion in the back EMF signals so that an accurate threshold level can be obtained.

The analysis results using the 1st electrical circuit under various loads are shown in Fig. 13 and are summarized in Table 6. From Fig. 13, the U, V, W phase back EMF signals, threshold level and U phase rotor position signal can be seen. As shown in Fig. 13, the threshold level of the 1st electrical circuit reacts automatically to the distortion of the back EMF signals, and the duty of the rotor position signals are always about 52%.

From the PSpice simulation and coupled analysis, it was verified that using the 1st electrical circuit is much more effective for sensorless BLDC motor control.

5. Experimental evaluation

Next, experimental evaluation was implemented under no load to verify the results of the coupled analysis and advantages of the 1st electrical circuit. Fig. 14 shows the experimental evaluation set up.

For implementing sensorless BLDC motor control by using the designed BLDC motor and two types of electrical circuits, the motor was aligned forcibly to the designated point, and then the motor was rotated by opened-loop to detect back EMF signals. After detecting the initial back EMF signals, sensorless control was carried out by closed-loop using the rotor position signals which were output from the electrical circuits.

5.1 The 1st electrical circuit

In this section, the minimum rotation speed using the designed BLDC motor was set at 195 rpm since the minimum PWM duty was set at 12% at the motor control firmware to leave a margin for reliable control.

As decreasing the minimum rotation speed, the time it takes to detect the initial back EMF signals becomes large and the threshold level becomes low. In this case, control failure occurs easily since the effect of noise which is included in the threshold level becomes dominant. With regard for this, it is possible to decrease the minimum rotation speed to 100 rpm by using the designed BLDC motor. However, this value is not the absolute one, and should be changed properly according to motor specifications and applications.

Like in the coupled analysis, various rotation speeds were applied under no load. Fig. 15 shows the U, V, W back EMF signals and threshold level, and Fig. 16 shows the U phase back EMF signal, threshold level and U phase rotor position signal at 195 rpm, 900 rpm and 1560 rpm. The value of each vertical division is indicated in the brackets, in the legend of the graphs. As shown in Figs. 15 and 16, the threshold level of the 1st electrical circuit changes automatically according to the rotation speed, and the duty of the rotor position signals are always about 52%. Table 7 summarizes the experimental evaluation results.
5.2 The 2nd electrical circuit

Next, the experimental evaluation of the 2nd electrical circuit was implemented under no load. Fig. 17 shows the U phase back EMF signal, threshold level and U phase rotor position signal at 195 rpm and 665 rpm. As shown in Fig. 17, the duty of the rotor position signals in the 2nd electrical circuit changes at every rotation speed. Also, Fig. 17(a) shows a distorted rotor position signal due to the threshold level being too close to the maximum back EMF level. Here, motor control failure occurred since the exact rotor position could not be detected. Fig. 18 shows the U phase back EMF signal, threshold level and U phase rotor position signal when motor control failure occurred due to the threshold level being too close to the minimum back EMF level.

Table 7 Experiment results (The 1st electrical circuit).

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Threshold level (V)</th>
<th>Rotor position signal duty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>195</td>
<td>0.47</td>
<td>52</td>
</tr>
<tr>
<td>900</td>
<td>1.74</td>
<td>52</td>
</tr>
<tr>
<td>1560</td>
<td>2.88</td>
<td>52</td>
</tr>
</tbody>
</table>

As shown in the experimental evaluation results, a difference between the coupled analysis and experimental evaluation results can be seen. The first reason for this is that a difference of the input source. In the coupled analysis under no load, the assigned rotation speeds were input for rotating the motor and verifying the advantages of the 1st electrical circuit at various rotation speeds, and this made the EMF signal waveforms symmetrical. However, the rated input voltage was used for driving the embedded motor controller in the experimental evaluation, and this made the EMF signal waveforms filtered and asymmetrical as well as including the DC component.

The second reason for this is that the noise signals of the surroundings and magnetic leakage of the PMs in the actual motor. In the coupled analysis, the output signals did not include the noise signals since it was not possible to consider them. However, the embedded motor controller which was used in the experimental evaluation included the noise signals which were generated from the surroundings. In addition, the magnetic
leakage of the PMs occurred in the actual motor. These made output signals include the noise and distorted with a difference of the voltage levels between the coupled analysis and experimental evaluation.

Although a difference between the coupled analysis and experimental evaluation results can be seen, the advantages of the 1st electrical circuit for sensorless BLDC motor control was verified through the coupled analysis and experimental evaluation.

6. Conclusion

In this research, the analysis of the two types of electrical circuits, which are used to detect back EMF signals and generate rotor position signals of 3 phase BLDC motor for sensorless control, was implemented by coupling the FEM model of an 8 pole 12 slot BLDC motor with the two types of electrical circuits. The results of coupled analysis were then verified through experimental evaluation.

Through the coupled analysis and experimental evaluation, it was verified that the 1st electrical circuit which uses a dynamic threshold level is more effective than the 2nd electrical circuit which uses a static threshold level for sensorless BLDC motor control.

From this research, we expect to apply the 1st electrical circuit to actual actuators to decrease the manufacturing cost of BLDC motors.

References


