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Self Compensation Technique for Low Inductance BLDC Motor

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Abstract: *This paper is proposed that the combination of the position sensors and Hall effect sensors will not give the high placement accuracy due to the commutation angle is introduced. As low-resolution position sensors, a high placement accuracy of Hall-effect sensors is hard to achieve. Accordingly, a commutation angle error is generated. so this commutation angle is causes the increase in losses of the low inductance motor and even cause serious consequence, which is the abnormal conduction of a freewheeling diode in the unexcited phase especially at high speed.*

In this paper, the influence of the commutation angle error for the high-speed low inductance brushless dc motor and non ideal back electromotive force in a magnetically suspended control moment gyro (MSCMG) is analyzed. In order to achieve low steady-state loss of an MSCMG for space application the self compensation method for the commutation angle error is introduced in terms of dc link current to reduce the error. The simulation results confirm the feasibility and effectiveness of the proposed method.

Index Terms*—*BLDC motor, commutation angle error, self-compensation, Hall sensors, Low reluctance, steady state loss.

I.INTRODUCTION

BLDC motors are usually driven by a three-phase inverter employing a two-phase conduction method. Ideally, the inverter transistors commutate every 60 electrical degrees. The switching of the inverter transistors is mainly realized through the rotor position detection techniques that can be classified into two categories: sensorless control technique [1]–[5] and the technique based on position sensors [6]–[10], [12]. Unfortunately, a commutation angle error is unavoidable in both techniques [6]–[11]. A sensorless control technique is based on detection of some characteristics of the motor to determine commutation instants, which may introduce additional sensing circuits or complicated estimation algorithms. Many effective sensorless drive solutions that work well especially at medium and high-speed range have been proposed over the past two decades. However, the commutation angle error may be unavoidable in the sensorless control technique too. For example, the research in [6] was focused on the commutation angle error in the back EMF zero-crossing detecting method caused by the phase delay of the low-pass filter and the existence of armature reaction. The technique that places three Hall sensors 120 electrical degrees apart to supply commutation signals is widely used in applications for its simplicity and mature control scheme. Unfortunately, it is very difficult to achieve high placement accuracy of Hall sensors for the ironless and slot less stator, which will result in a commutation angle error. The flat width of the ideal trapezoidal back electromotive force (EMF) waveform is 120 electrical degrees in BLDC motors. However, the undesired shape of a back EMF wave is usually produced for practical reasons [14], [15]. The ideal commutation instants are the zero crossings of the line-to-line back EMF voltages [8] for the motor with a general shape back EMF. When and only when the motor is commutating with the ideal commutation instants, the maximum electromagnetic torque per ampere and the lowest commutation torque ripple will be achieved [6]. Thus, the steady-state power loss of the motor will increase with the current when working with non ideal commutation instant.

In this paper, the problem of commutation angle error and the inefficient performance caused by commutation angle error is analyzed in detail based on a high-speed BLDC motor of the MSCMG with nonideal back EMFs. This paper proposed a new current control method for the BLDC motors with nonideal back EMF. A straightforward method of self-compensation of the commutation angle based on dc-link current is proposed. In view of torque ripples of BLDC motor with nonideal back EMF, there are mainly two kinds of resolvents. This method estimates the commutation time error through the sampled dc-link current without modifications to the current hardware circuit. The motor's phase current, angular position, and speed are measured in real time and the duty cycle is pre calculated in the designed current controller to control the phase current. In addition, commutation time is calculated in the controller. Simulation and experimental results showed that, compared with the conventional current control method, the new control method can reduce the torque ripple effectively. The commutation angle is compensated by the calculated commutation time error and the estimated half-period of one-phase Hall signal that is extrapolated from the previous half-period to eliminate the abnormal diode conduction of the unexcited phase and decrease the steady-state loss of the MSCMG. Simulation and experimental verifications are carried out to validate the method presented.

II.COMMUTATION ANGLE ERROR

As low-resolution position sensors, Hall sensors are popular for its low cost, small volume, and facility in mounting. However, its placement accuracy is hard to achieve in practice for the motor with ironless and slotless stator shown in Fig. 1. Then, the commutation angle error that influences the overall performance of the motor is generated. As shown in Fig. 1, locating teeth is made on the polyimide stator frame to ensure the placement of winding coils. Also, three locating slots are made by removing the corresponding locating teeth to ensure the placement of the three Hall sensors, respectively. Restricted to the thickness of the stator frame, the Hall sensor locating slots are with small depth, which results in low locating accuracy. Since the placing of Hall sensors in a high-speed BLDC motor for the MSCMG is done by hand separately, the placement error of the Hall sensors is hard to be avoided without special precise equipment that will increase the cost. Also, Hall sensors cannot be readily accessible in the testing process since the outer surface of the stator is moulded with epoxy resin sealant during the manufacturing process. Adjusting the position of Hall sensors to ensure the placement accuracy is hard to realize. Thus, the placement error of Hall sensors is non negligible in the motor with ironless and slot less stator. A typical three-phase BLDC motor drive system with three Hall sensors is shown in Fig. 2. H1, H2, and H3 denote the actual positions of Hall sensors and H1', H2', and H3' denote the ideal positions of Hall sensors. The mechanical angle errors of three Hall sensors are represented by φ_{Am}, φ_{Bm}, and φ_{Cm}. The relationship between mechanical angle error φ_{xm} and electrical angle error φ_x is depicted by the equation $\varphi_x = p \cdot \varphi_{xm}$. Here, the subscript x may represent the phases A, B, and C, respectively, and p denotes the number of magnetic pole pairs. In the motor with large number of magnetic pole pairs, a little mechanical angle error may translate into a large electrical angle error, which has adverse effect on the motor.

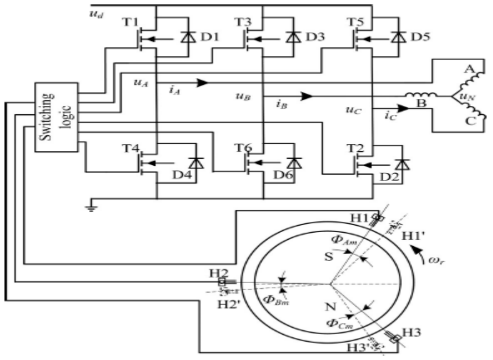


Fig. 1. BLDC motor drive system with Hall sensors.

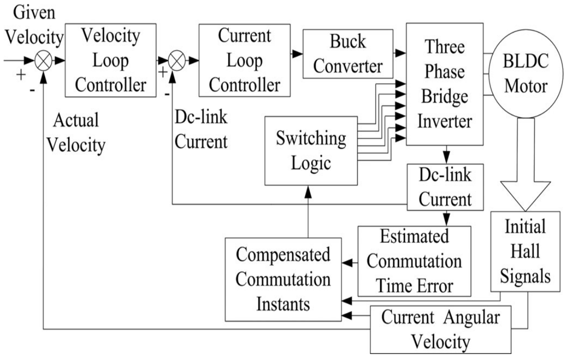


Fig.2: Block Diagram Representing Self Compensation Technique of the Commutation Angle Error of BLDC Motor Controller

Ideal Hall signals, actual Hall signals (denoted as Halla, Hallb, and Hallc), and actual back EMFs (denoted as e_A, e_B and e_C) are shown in Fig. 3. The ideal Hall signal of each phase advances the phase back EMF by 30 electrical egrees. The ideal commutation instants are the zero crossings of the line-to-line back EMF voltages. They also are the intersections of every two-phase back EMFs. Fig. 3 indicates that the ideal Hall signals coincide with the ideal commutation instants. The commutation angle error caused by the placement error of Hall sensors can be expressed as $\varepsilon_x = \varphi_x$. We define that the positive value denotes a delayed angle error and the negative value denotes an advanced angle error.

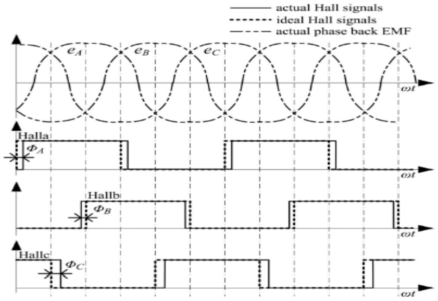


Fig. 3. Hall signals and actual back EMF of three phases.

III. COMMUTATION TECHNIQUES:

In general commutation refers to the process of switching current in the phases in order to generate motion.In the brushless dc motors it refers to the process of maintaining 90^{o}torque angle. The main aim of commutation is to maintain the angle between the stator field and the rotor magnetic field which can be possible by having the knowledge on the position of rotor magnetic field. The brushless dc motors mainly uses two types of commutation techniques. They are sinusoidal commutation and trapezoidal commutation.

A) Trapezoidal Commutation

The trapezoidal commutation will achieved by using hall sensors feedback and by driving the current into the two phases, without entering into the third phase. The Hall sensors mainly used to determine that, to which phase the current is to enter. The following table states that, how the current will flow in the three phases.

In order to maintain the current flow, there will be a switching from one pair to the one phase, so that there will be continuity between them. The following wave form states that the motor torque has the constant phase current and constant speed:

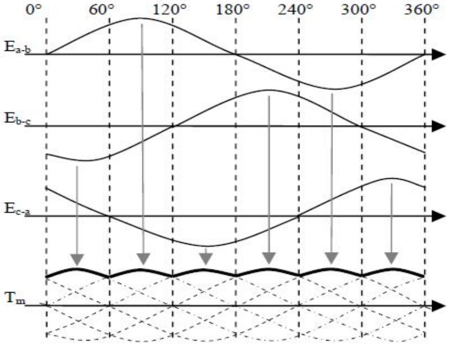


Fig.4: Motor Torque for Different Phase Voltages

The setup and configuration of trapezoidal commutation typically requires permutation for the motor power leads or the Hall sensors. There are six different ways to connect the Hall sensors and with the motor connection, but only one will provide the proper operation.

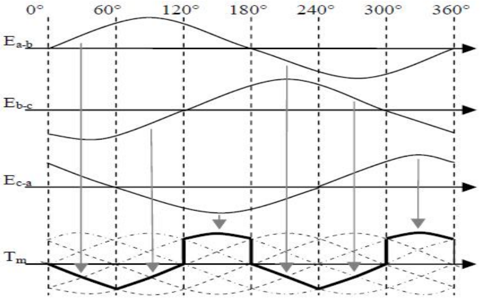


Fig.5: Torque for Different Hall Sensor Positions

When there is a wrong connection , consider the resulting torque as derived above, but this time the two Hall sensor connections are interchanged Thus, the average torque will be zero and also oscillates. In this torque profile there will be a three connections, there is a non-zero net torque with two combinations, but it is sub-optimal.

For example, when interchanging Hall 1 to 2, and 2 to 3 and 3 to 1, the following torque profile results:

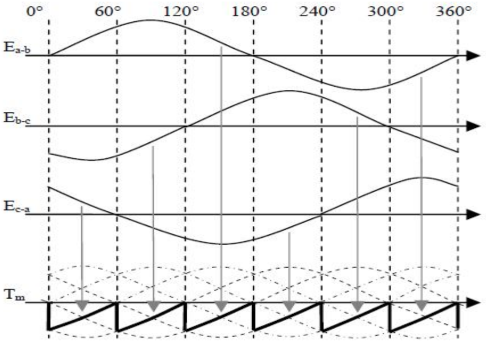


Fig.6: Torque Wave Form for Interchanged Hall Sensors

This combination can sometimes be mistaken as functionally, because the net and non zero torque is present, but it can lead to drive overheating and less efficiency. So, that all six types of possible connections should be performed.

B) SELF COMPENSATION:

The self compensating method is proposed to solve the problem, when the commutation angle error reduces the overall performance and efficiency of the motor. So, a self-compensating method of commutation angle with only a single current sensor is used. To calculate the commutation time error the DC link current is used. The self compensating method is used to estimate the commutation time error and ideal commutation instant and the initial motor controller is composed of a velocity controller to regulate motor speed and current controller. Based on the initial Hall signals the ideal commutation instants can be estimated to compensate the commutation angle error. The initial motor controller is composed of a velocity controller to regulate motor speed and a current controller for the main purpose of restraining the motor current to below the maximum value. The dc-link current is sampled to calculate the commutation time error. Then, the ideal commutation instants can be estimated based on the initial Hall signals to compensate the commutation angle error.

By this method, the initial Hall signal of one phase can be compensated to generate exact commutation signals. A proper time should be set to compensate the commutation angle of one phase, and then the same operation should be done to the next phase. After compensation of three phases, one period of the self-compensation method is done and the commutation angle error will be eliminated. A simplified flowchart of the self-compensating method of the commutation angle is shown in Fig. 7. It should be noted that the analyses presented above are all based on the motor for high speed rotor system of the MSCMG. The motor generally operates in the steady-state condition in which the motor current is stable and the rotor speed changes little between adjacent states of Hall signals. However, for the motor operating in the transient state, the commutation time error Δt_{refx} can be measured using the proposed method in a stable state.

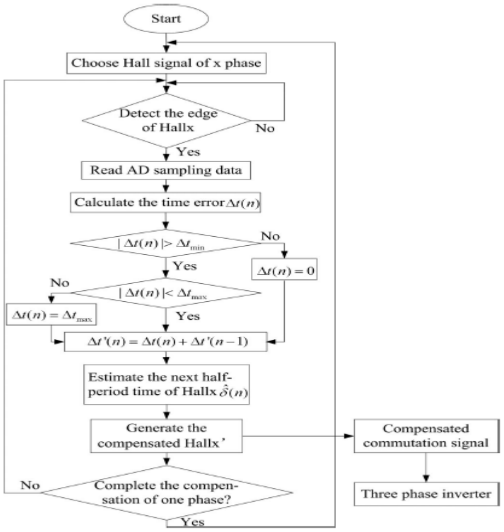


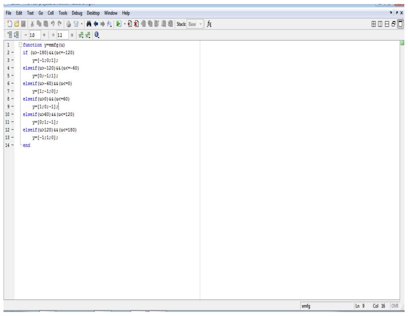
Fig. 7. Flowchart of the self-compensating method of the commutation angle.

The variations of dc-link current with ideal and non ideal commutation instants are as follows:

A. Analysis of DC-link Current due to Correct and Incorrect Commutation Instants
B. Estimation of Commutation Time Error
C. Estimation of Ideal Commutation Signals

IV. SIMULATION RESULTS

A Six-Step Switch-on mode for a trapezoidal PMSM motor rated 1kW, 3000 rpm and speed regulated is simulated in MATLAB environment. A three-phase motor rated 1 kW, 500 V_{dc} , 3000 rpm is fed by a six step voltage inverter. The inverter is a MOSFET bridge of the SimPowerSystems library. A speed regulator is used to control the DC bus voltage. The inverter gates signals are produced by decoding the Hall Effect signals of the motor. The three-phase output of the inverter is applied to the PMSM block's stator windings. The load torque applied to the machine's shaft is first set to 0 and steps to its nominal value (11 Nm) at t = 0.1 s. Two control loops are used. The inner loop synchronizes the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage. The Simulink block diagram of self compensation technique along with the Simulink program is shown below:



```
function y=emfg(u)
if (u>-180)&&(u<=-120)
    y=[-1;0;1];
elseif(u>-120)&&(u<=-60)
    y=[0;-1;1];
elseif(u>-60)&&(u<=0)
    y=[1;-1;0];
elseif(u>0)&&(u<=60)
    y=[1;0;-1];
elseif(u>60)&&(u<=120)
    y=[0;1;-1];
elseif(u>120)&&(u<=180)
    y=[-1;1;0];
end
```

Fig.8: M-File Parameters Setting For Gate Pulses Generation from Emf

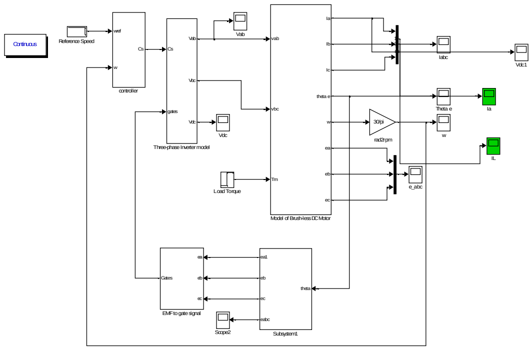


Fig.9: Simulation Model with Hall Effect Sensors and Feedback and by Changing Commutation Angle

The output wave form of the simulink block diagram with delayed commutation angle and with advanced commutation angle is shown below. Simulation results of the comparison between the current waveform of one of the phases and DC link current of the motor with non ideal back emfs is also shown in figures 10, 11.

In the proposed method, the dc-link current should be sampled in real time using a proper frequency of AD sampling. In practice, different sampling frequency is chosen at different motor velocity in order to satisfy the error estimation demand and save controller resources. The frequency of AD sampling is chosen to be f_k = 20 kHz when the motor velocity is below 10 000 r/min and f_k = 40 kHz when the motor velocity is between 10 000 and 20 000 r/min since the commutation frequency is f_c = 4 kHz for the motor with two pole pairs at the rated speed of 20 000 r/min. A FIFO $N \times 13$ data memorizer is designed using VHDL language, where $N = 2m$ and m,N are integral numbers. The 13-bit data DATA (k) consist of a 12-bit AD conversion result of dc-link current and a 1-bit Hall state signal of Hallx. A shift operation and a new data storing operation are accomplished with the AD sampling frequency. In DATA (0) to DATA $(N-1)$, the change of the Hall signal state in DATA $(m-1)$ and

DATA (*m*) will trigger the interruption of DSP. Then, the values of dc-link current will be read in and processed by appropriate filters such as the moving average filter. Also, the commutation current ripple should be rejected from the sampled data according to the commutation interval when the AD sample frequency is quite high.

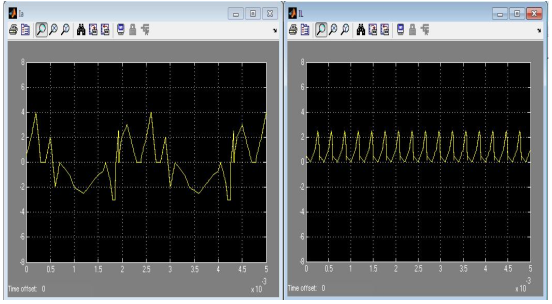


Fig.10.Case (A) With Delayed Commutation Angle

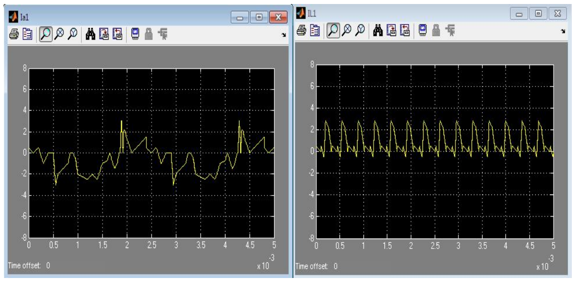


Fig.11 Case (B) With Advanced Commutation Angle

V.CONCLUSION

In this paper, a self-compensating method of the commutation angle with a single current sensor is proposed for the high speed BLDC motor with very low inductance in the MSCMG. Based on the concluded relationship between the amount of commutation time error and the difference value of dc-link currents before and after the commutation instant, the method estimates the commutation time error by sampling the dc-link current in real time. The commutation angle is compensated by the calculated commutation time error and the estimated half period of one-phase Hall signal that is extrapolated from the previous half-period to eliminate the abnormal diode conducting of the unexcited phase. The simulation results are shown to testify the feasibility of the self-compensation method.

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