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Self-Sensing Sinusoidal Drive for Spindle Motor Systems

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***Abstract*-Traditionally, spindle motor systems are driven with Brushless DC (BLDC) drive. This drive, however, suffers from torque pulsations which is undesirable from the perspective of motion control and acoustics. In this paper, a self-sensing sinusoidal drive for spindle motor systems is proposed. The drive comprises of (1) an optimal angle sinusoidal drive, (2) an innovative lossless current sensing for self-sensing methodology, (3) a self-sensing sinusoidal drive. The drive introduced was implemented on FPGA and its results are presented.**

I. INTRODUCTION

The introduction of high energy permanent magnet materials coupled with the increasing concerns for power efficiency has opened the gateway for Permanent Magnet Synchronous Motor (PMSM). The benefits of using PMSM are high torque to inertia ratio [1,2], superior power density, high efficiency and low acoustics noise. As such, PMSM has become an attractive option for industrial applications, such as Hard Disk Drives (HDD). The motor deployed HDD are a sub category belonging to PMSM, commonly known as Brushless DC Motor (BDCM). Compared to PMSMs, BDCM has several unique features. The rotor of BDCMs has got surface-mounted permanent magnet constructing a smooth-air-gap machine. As such, reluctance torque contributed by inductance variations can be neglected. In addition, the rotor utilizes fractional-slots which in turn make the cogging torque negligible. These, together with other features, such as sinusoidal/trapezoidal back-emfs and a symmetrical three-phase structure, create an unique PMSM or a BDCM.

BDCMs are typically driven by a three-phase inverter circuit with BLDC drive whereby each gate turns on for 120° and for each phase, there will be two silent periods, each of 60°, where the terminals are floating. Such a methodology aims to inject rectangular currents for torque production. Traditionally, BLDC drive is used to drive BDCMs with trapezoidal back-emf so as to achieve minimal torque ripple. In addition, self sensing is adopted in BDCM instead of hall sensors due to cost and space constraints. However, for BDCMs with sinusoidal back-emfs, sinusoidal drive should be used. Nevertheless, for these BDCMs, BLDC drive is usually employed. The reason being, sinusoidal drive is still yet feasible if self-sensing schemes are to be adopted. Self sensing is adopted in BDCM instead of hall sensors due to cost and space constraints. Owing to this, despite the drawbacks of BLDC drive, BDLC drive is being used.

In this paper, the deployment of self-sensing sinusoidal drive is investigated. Firstly, the derivation of an optimal angle sinusoidal drive for minimal losses will be presented. Secondly, a sinusoidal drive is proposed. Thirdly, based on this, a lossless current sensing method for self-sensing is proposed.

II. OPTIMAL SINUSOIDAL DRIVE

Driving a BDCM with sinusoidal back-emf with sinusoidal drive, will result in a smooth torque as well as generate smaller acoustic noise. In the analysis of these drives, the effects of armature resistance are usually neglected. While its effects might be negligible in certain applications, it might be imperative to conduct an analytical derivation.

Consider the equivalent circuit for an arbitrary phase in a BDCM,

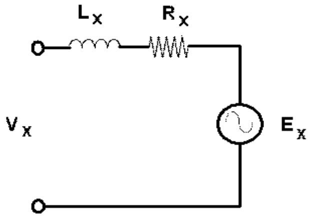

Fig. 1. Electrical Equivalent Circuit

Taking the phase current as reference,

$$I_x = I_m \sin \omega t \tag{1}$$

where I_m is the peak value of the phase current.

The phase voltage V_x and its back-emf E_x can be defined as

$$V_x = V_m \sin(\omega t + \alpha) \tag{2}$$

$$E_x = E_m \sin(\omega t + \varsigma) \qquad (3)$$
$$= K_e \omega \sin(\omega t + \varsigma)$$

where V_x is the peak value of the phase voltage,
α is the power angle,
E_x is the peak value of the phase back-emf,
K_e is the back-emf constant and
ζ is the angular phase difference between Ix and E_x.

To simplify analysis, the impedance per phase is represented as

$$R_x = Z_x \cos\delta \qquad (4)$$
$$\omega L_x = Z_x \sin\delta \qquad (5)$$

where $\delta = \tan^{-1}(\omega L_x / R_x)$,

$$Z_x = \sqrt{R_x^2 + (\omega L_x)^2}$$

From electromagnetic power equation,

$$T_L \omega = 1.5 E_x I_x \cos\varsigma \qquad (6)$$

To run the BDCM at best efficiency,

$$\varsigma = 0$$

that is, the phase currents are in-phase with its respective phase voltages. Hence, the optimal current from (6) would be

$$I_{opt} = T_L \omega / (1.5 E_m) \qquad (7)$$

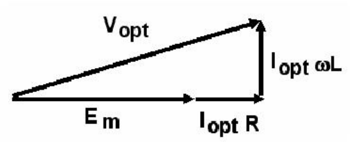

Fig. 2. Phasor Diagram Under Optimality

Thus,

$$V_{opt} = \sqrt{(I_{opt}\omega L)^2 + (E_m + I_{opt}R)^2} \qquad (8)$$

$$\alpha_{opt} = \tan^{-1}\{(I_{opt}\omega L)/(E_m + I_{opt}R)\} \qquad (9)$$

Hence, it can be seen that for a given load and required speed, the optimum voltage and its optimum angle can be found.

III. PROPOSED CONTROL METHODOLOGY

From the derivation in the previous section, it can be seen that for a given load, an optimal current, I_{opt}, as well as an optimal angle, α_{opt}, exists. In other words, in sinusoidal operation and under constant load, for example in HDDs, if the angle is not at

α_{opt}, this means the voltage can be reduced to V_{opt} to achieve , I_{opt} and α_{opt}. Alternatively, it can also be inferred that the rotation frequency, ω, can be increased. Thus, the following control topology is proposed.

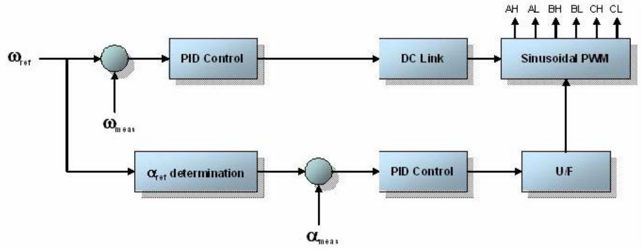

Fig. 3. Proposed Control Topology

The estimated speed, ω*, can be estimated from the injected frequency and the power angle, α*, can be estimated from the current zero crossing points (IZCPs).

IV. LOSSLESS I-SENS

In the adoption of the proposed control methodology, only IZCPs are necessary instead of the full current profile. Traditional method for zero current crossing detection is accomplished via sensing resistors connected in series to the motor windings. The polarity of the resistive voltage will provide the current direction and the zero current crossing is given by the instant of voltage polarity change. The drawbacks of this method are (1) it incurs additional resistive losses and (2) it requires the use of additional resistive elements, thereby increasing the costs. The proposed method avoids the short comings of the resistive elements by making use of the freewheeling diodes for detection.

In avoidance of these shortcomings, the following method is proposed. In a BDCM system, the BDCM is typically driven by a three-phase inverter circuit as shown in Figure 4. It consists of six power semiconductor transistors with a protection diode connected in parallel to each of these transistors.

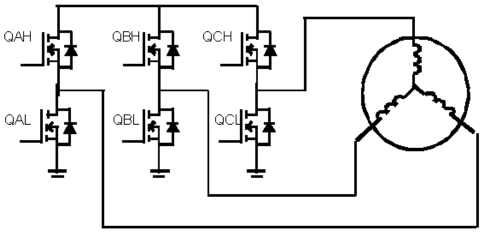

Fig. 4. Bridge Circuit for BLDC Drive

In a PWM drive, the upper and lower switches are gated simultaneously. For example, prior to the gating of the lower switch Q_{AL}, if the output current is negative, it will be freewheeling through the diode D_{AH}. This freewheeling gives rise to a diode voltage across D_{AH}. Conversely, if the output current is positive, prior to turning on the upper switch Q_{AH}, the current will be freewheeling through the diode D_{AL}. This freewheeling similarly gives rise to a diode voltage drop across D_{AL}. The polarity of the current can thus be determined from the occurrence of voltage drop across D_{AH} or D_{AL}. A negative current will give a voltage drop across D_{AH} and a positive current will give a voltage drop across D_{AL}. Consequently, current zero crossing can be given by the polarity change crossing points. The rising edge of voltage drop across D_{AH} will give the zero crossing of positive to negative current and, conversely, the falling edge of voltage drop across D_{AL} will give the zero crossing of negative to positive current. Similarly, the rising edge of the voltage drop across D_{AL} will give the zero crossing of negative to positive current and, conversely, the falling edge of voltage drop across D_{AL} will give the zero crossing of positive to negative current.

Thus, lossless current zero crossing can be detected with the freewheeling diodes without introducing additional elements.

V. HAREWARE IMPLEMENTATION & EXPERIMENTAL RESULTS

In recent years, owing to the progress of VLSI technology, the field programmable gate array (FPGA) has gained world wide acceptance. It has traditionally been perceived as a essential platform for Application Specific Integrated Circuit (ASIC) prototyping. However, in recent years, it has gained significant market share in end-product solutions as fundamentally, FPGA offers fast time to market, low design/manufacturing cost and risk, extremely high processing performance, and programmability [3], [4].

In this paper, the proposed solution is implemented on FPGA for the above reasons and on a Xilinx Virtex-4™ FX12. Connected to the IOs of V4FX12 are comparator outputs providing the sign of the voltage across the diodes.

1. IZCP Sensing

In the initial investigation, due to the narrowing pulse width of the gating signal as the current magnitude increases, the voltage drop across the diode is difficult to detect as the notch goes narrower. The resultant current zero crossing waveform is distorted. Figure 5 shows the distorted IZCP waveform for the upper diode for a particular phase. To rectify this problem, it would be useful to peek into the information that can be available from the waveform generation. Taking a sinusoidal reference, it is reasonable to assume that the current transitions will not occur from 210° - 330° as well as the current would be negative in that interval. Hence, by doing a logic OR, the gap will be set to high. Conversely, in the detection of positive currents, its reasonable to assume that current transistions would not occur 30° - 150°. Figure 6 shows the block diagram of the algorithm and Figure 7 gives the experimental waveform of the modified algorithm.

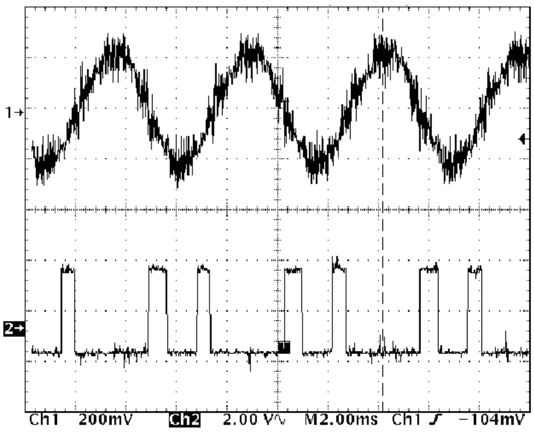

Fig. 5. Current and IZCP Waveforms

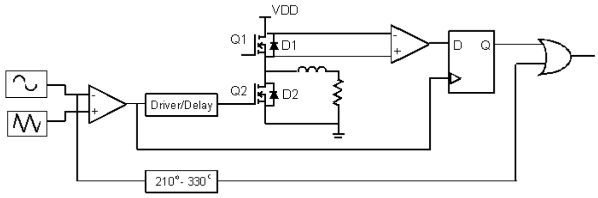

Fig. 6. Modified Algorithm for IZCP Detection

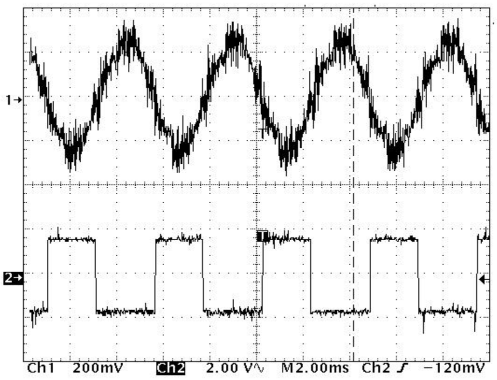

Fig. 7. Current and IZCP Waveforms based on Modified Algorithm

2. *Optimal Angle Control*

In the determination of the power angle, a HDD spindle motor was used and here are its parameters.

TABLE I
MOTOR PARAMETERS FOR EXPERIMENTAL TESTS

MOTOR PARAMETERS	VALUES
Pole Pairs	4
Armature Resistance (Ω)	2.40
Armature Inductance (mH)	0.562
BackEmf Constant (V/krpm)	0.753
Load Torque (mNm)	2.5
Inertia (gcm^2)	33.14
Rated Speed (rpm)	7200

Based on the equation (7)-(9),

$$I_{opt} = 0.23A \quad V_{opt} = 8.39V \quad \alpha_{opt} = 0.47rad$$

Following the proposed control methodology in Figure 3, the α measurement flow chart is provided in the Figure 8 below:

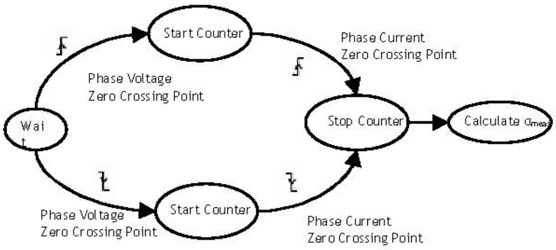

Fig. 8. Flow Chart for α Measurement

The proposed methodology was implemented and the current waveforms are provided below.

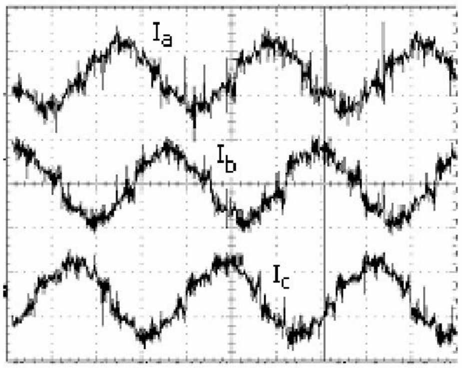

Fig. 9. Current Waveforms For Phase A, B, C

As an indicative comparison, the waterfall acoustic for the drive is compared to a BLDC drive on the BDCM. It can be observed that the acoustics for the sinusoidal drive (solid line) is comparatively lesser to that on a BLDC drive (dotted line).

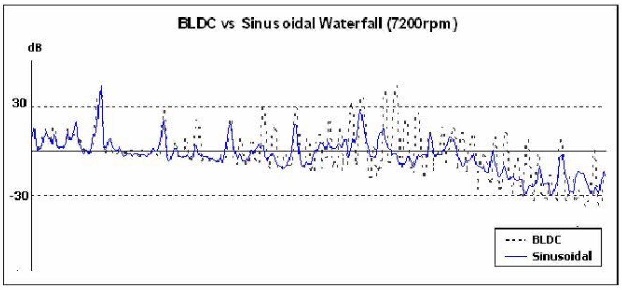

Fig. 9. Acoustics Waveform for BLDC vs Sinusoidal Drive

VI. CONCLUSIONS

In this paper, a self-sensing sinusoidal drive for spindle motor systems is proposed. This drive comprises of (1) derivation of an optimal angle sinusoidal drive (2) an innovative lossless current sensing for self-sensing methodology and (3) a self-sensing sinusoidal drive. The drive introduced was been successfully implemented on FPGA and its results were presented.

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