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Performance Analysis of BLDC Motor using Virtual Third Harmonic Back Emf Method

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***Abstract*— To improve the performance of the high speed Brushless Direct Current (BLDC) motor, a novel high-precision sensorless drive has to be developed. Owing to the advantages of its compactness, maintenance, high efficiency, and low cost, the BLDC motors are getting more and more attention in many areas. Precise detection of the rotor position for the sensorless drive scheme is essential to ensure the high efficiency and low loss of the overall system, especially in the high speed range. The third harmonic-based method provides a better solution, in which the commutation points can be extracted from the third harmonic of the back-EMF. Hence the performance analysis of BLDC motor using virtual third harmonic method is to be evaluated and experimental analysis of the BLDC motor have to be conducted.**

Keywords— High-speed brushless direct current (BLDC), Phase locked loop (PLL), synchronic frequency filter (SFF), second order generalized integrator (SOGI), sensorless drive, virtual third harmonic back electromotive force (back-EMF).

I INTRODUCTION

The use BLDC motors are increasing day by day due to the high speed operation, low maintenance, low cost and high efficiency. BLDC motors are most commonly uses in blowers, compressors, as computer peripherals (disk drives, printers), Hand-held power tools, Vehicles ranging from model aircraft to automobiles, Electric vehicles / hybrid vehicles, Electrically powered RC models, Pump, fan etc. The speed of BLDC motor can reach up to tens of thousands revolutions per minute; hence they can be used for high speed applications. In conventional BLDC motor, it uses mechanical position sensors i.e. Hall sensors for finding the rotor position. But in case of sensorless BLDC motor rotor position can be perfectly detected using the back EMF based method. Back EMF based method is more cost effective and applicable because there is no need of sensors (hall sensors).

There are different sensorless methods for finding the rotor position. The most popular methods are back electro motive force (back EMF) based method [5], third harmonic based method, integration based method [6], flux linkage estimation based method [7], pulse locked loop (PLL) based methods and other sensorless methods [1]. From these methods, the third harmonic based method is better because it precisely detects the rotor position and also the commutation points.

Commutation error is one of the major problems of BLDC motor drive system which are produced due to the inaccurate hardware parameters of the motor, variable operating temperature, different load condition especially in high speed application. Hence an error compensation method is needed to reduce the commutation error. The compensation method should eliminate the commutation error even without the neutral wire. Most of the sensorless methods avoid the use neutral wire because it is costlier. Hence virtual neutral point is considered in most of the sensorless methods.

The main benefit of this paper is that a new high precision sensorless drive method with commutation error compensation techniques is proposed which can operate in a wide speed range. This method does not need a neutral wire. For detecting the actual commutation points, a new technique is used which is known as Synchronic Frequency Filter incorporating the Second Order Generalized Integrator based Phase Locked Loop (SFF-SOGI-PLL) incorporating the virtual third harmonic back EMF[2].

II. SENSORLESS DRIVE METHOD FOR BLDC MOTORS

A. Control Scheme of BLDC motors

The BLDC motors are mainly used for high speed applications. One of the advantages of the applications is that the motor load increases with rotating speed of the motor. The speed of high speed BLDC motor is always greater than tens of thousands revolutions per minute (kr/min) [3]. On the same time; winding resistance and inductance of the high speed motor is very much lower the traditional low speed motors. So here we have to use a new hybrid scheme which combines he pulse width modulation (PWM) and pulse amplitude modulation (PAM) technique [4]. During the start stage and the low speed motors PWM technique is employed which helps to overcome large phase current. Speed and back EMF are directly proportional. When the back EMF increases which counteract with the dc link voltage and then PAM technique is employed. The control scheme which combines the PAM and PWM techniques improves the efficient operation of the BLDC motor in wide speed range.

B. Virtual Third Harmonic Back EMF Method

In mechanical position sensor based control method, the three control signals are obtained by the Hall sensors (Hall A, Hall B, Hall C). In sensorless methods, these three signals are obtaining through sensorless detecting methods which are indirect method for detecting rotor position signals. Here in this drive scheme, the sensorless method used is virtual third harmonic back EMF based position sensing.

Fig.1. represents the diagram of a conventional motor drive circuit where the three phase inverter is switching with the help of commutation logic which are obtained from the hall sensors. In sensorless method, these hall sensors are absent.

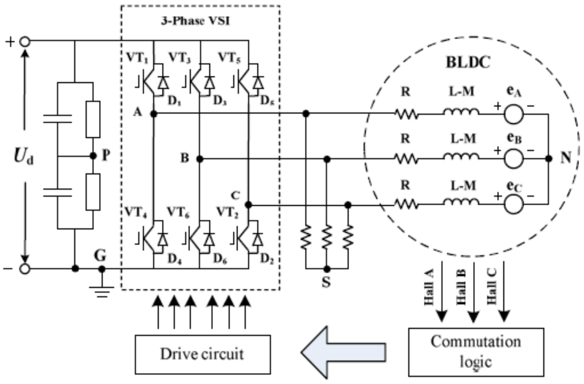

Fig.1. Diagram of motor drive circuit.

From Fig.1.the y-connected resistors are used to detect the rotor position signals [1]. In pre-researches, the rotor position is obtained from the voltage between the neutral point “N” and the virtual neutral point “S” (u_{SN}). But neutral wire is not provided for many applications because neutral wire is expensive. Here the rotor position signals are obtained from the voltage between the virtual neutral point “S” and the midpoint of the dc link “P” (u_{SP})

According to Fig.1. the phase EMF can be written as

$$eA = \sqrt{2}E\cos(\omega t) \tag{1}$$
$$eB = \sqrt{2}E\cos(\omega t - 2\pi/3) \tag{2}$$
$$ec = \sqrt{2}E\cos(\omega t + 2\pi/3) \tag{3}$$

where E is the back EMF virtual value.

Based on Kirchhoff’s voltage law, u_{SP} can be expressed as

$$u_{sp} = (u_{AG} + uBG + u_{CG})/3 - u_d/2 \tag{4}$$

where u_d is the dc link voltage.

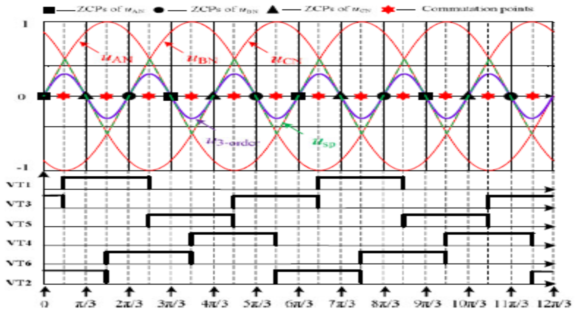

Fig.2. Relationships between the phase back-EMFs, the third harmonic back- EMF, u_{sp}, and the commutation points.

The frequency of u_{sp} and the third harmonic back EMF are related each other as the frequency of u_{sp} is three times as that of the third harmonic back EMF. Fig.2. shows the relationship between the phase back EMF, third harmonic back EMF, and the commutation points [1]. From figure it is clear that the frequency and zero crossing points of u_{sp} and third harmonic back EMF are same. This method cannot be strictly called as third harmonic method because there is no third harmonic back EMF term in the derivation. Hence this method can be called as virtual third harmonic back EMF method.

III HIGH PRECISION COMMUTATION DETECTION

As explained above, the virtual voltage difference (u_{sp}) has the same zero crossing points (ZCP) [8] and frequency as the third harmonic back EMF. For precise detection of the commutation points precise detection of rotor position signals is needed. For this purpose, i.e for the precise detection of commutation points a new algorithm is used which is called as SFF-SOGI-PLL technique. By using this method the detection of commutation points is possible. For extra degree commutation error compensation is possible by detecting the commutation points precisely.

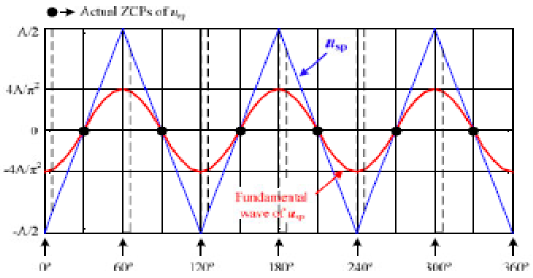

Fig.3. u_{sp} and the fundamental wave of u_{sp}.

Fig.3. shows the virtual voltage u_{sp} and the fundamental wave of u_{sp}. From figure it is clear that both the u_{sp} and the fundamental wave of u_{sp} (u_{sp-1}) have the same frequency and ZCPs.

A. High Precision Commutation Points Detecting Method

If the fundamental wave of u_{sp} (u_{sp-1}) is precisely extracted then we can obtain the precise ZCPs of the u_{sp} waveform. In order to achieve the precise ZCPs [8] and also the commutation points a hybrid sensorless method is used.

1) Phase Locked Loop (PLL) processing: PLL technique has a wide range of speed performance in motor drive system. Low speed to extreme high speed applications can be done with this method. So this method is widely applicable in industrial field. Due to the advantages like simple digital implementation, desired performance, low commutation burden etc PLL is incorporating with SOGI for more efficient operation. PLL with SOGI technique can be used to synchronize the output signal with the input signal for acquiring the rotor position.

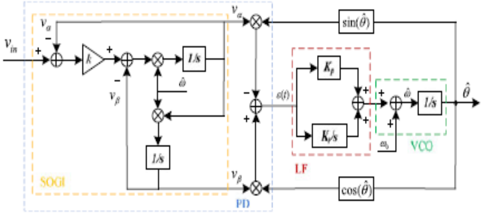

Fig. 4. Block diagram of the single-phase PLL based on SOGI.

Fig.4. shows the single phase PLL based on SOGI which can be easily written as SOGI-PLL. Phase Detector (PD), Loop Filter (LF) and Voltage Controlled Oscillator (VCO) are the main parts of SOGI-PLL.

The characteristic transfer function of SOGI can be expressed as

$$G_\alpha(s) = v\alpha(s)/vin(s) = (k\omega s)/(s^2 + k\omega s + \omega^2) \tag{5}$$
$$G_\beta(s) = v\beta(s)/vin(s) = (k\omega^2)/(s^2 + k\omega s + \omega^2) \tag{6}$$

Where the damping factor (a constant) and ω is is the estimated frequency.

From the above equations, $G_\alpha(s)$ acts as a band-pass filter with a center frequency of ω and the constant value k determines the band pass range of $G_\alpha(s)$. If the value of k is les, then the band width is also narrower and it offers better filtering capacity. $G_\beta(s)$ acts as a low-pass filter.

2) SFF processing: Synchronic Frequency Filter is used as a pre-filter of SOGI-PLL.

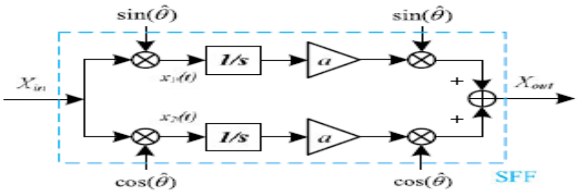

Fig.5. Block diagram of SFF.

The input and output signals are indicated by X_{in} and X_{out} and "a" is the gain constant. The reference signals are sin (θ) and cos (θ) which are having a phase difference of 90°. One of the advantages of SFF is it can precisely extract the fundamental wave from the input signal (X_{in}). Stability margin of SFF is comparatively very small in low speed so it can be considered as it is stable at whole speed range.

3) Incorporating SOGI-PLL with SFF: The proposed system here is based on the sensorless method which is based on the SOGI-PLL with SFF method. The whole block diagram is described in Fig.6.

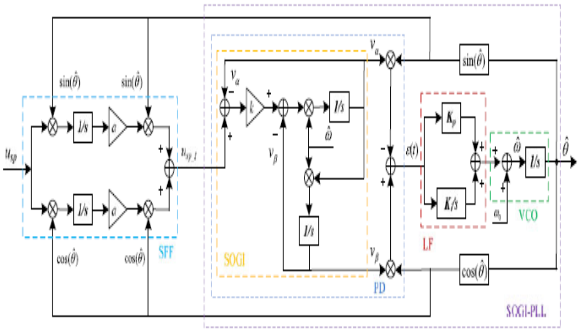

Fig.6.Active compensation block diagram based on SFF-SOGI-PLL

SFF is located at the starting point to filter out the harmonic components in the virtual voltage difference (u_{sp}) and the output of SFF is the fundamental wave of u_{sp} (u_{sp1}). The signals sin (θ) and cos (θ) are estimated using the rotor position signals which are obtained from the SOGI-PLL output signals. The reference frequency (ω_0) is obtained from the commutation signals detection unit.

B. Commutation Error Compensation

There is a chance of inaccurate rotor position detection error due to the wide range of speed operation of the motor. Hence an extra method of rotor position degree compensation is needed. For adjusting the rotor position signals and for compensating the link consists of PI adjusting module. A difference integrator is also provided which is obtained from integration of the first commutation point to the ZCP of the fundamental wave of u_{sp}, and the integration from the fundamental wave of u_{sp} to the second commutation point. The difference between two integrations is controlled by the PI regular and also it helps to adjust the difference between the two integrations equal to zero. The fundamental wave of u_{sp} doesn't contain any voltage pulses hence commutation error can be effectively compensate with this method.

IV EXPERIMENTAL SETUP

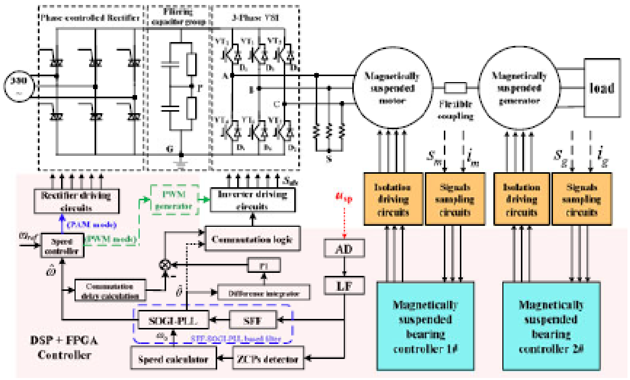

Fig.7. Overall high-speed magnetically suspended BLDC experimental setup control block based on the proposed sensorless drive scheme.

Experimental setup for the BLDC drive line is shown in Fig.7.[1] This is used for testing the performance of high speed BLDC motor. The PWM is taken below the switching speed and PAM is adopted when the switching speed is reached.

PARAMETER	VALUE
No. of pole pairs	8
Rated dc voltage	500V
Rated power	1kW
Rated speed	3500rpm
Stator phase resistance, R	2.875Ω
Stator phase inductance, L	8.5 mH
Rotational inertia	0.0008Kgm^2
Torque constant	1.4

Table.1. machine parameters

The phase controlled rectifier helps to obtain an adjustable dc link voltage when Pulse Width Modulation (PWM) is working. VSI helps to obtain the commutation control. PI module and the difference integrator are used to obtain the commutation control of the BLDC motor. By this the compensation can be obtained and hence efficient operation of the BLDC motor is possible.

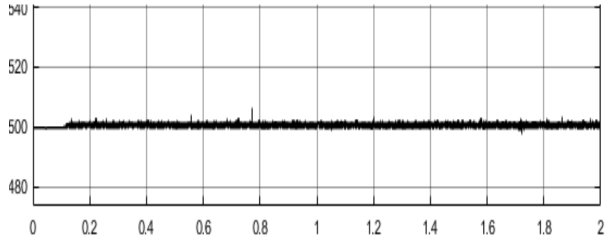

Fig.8. Filtered output voltage after the filtercapacitor section.

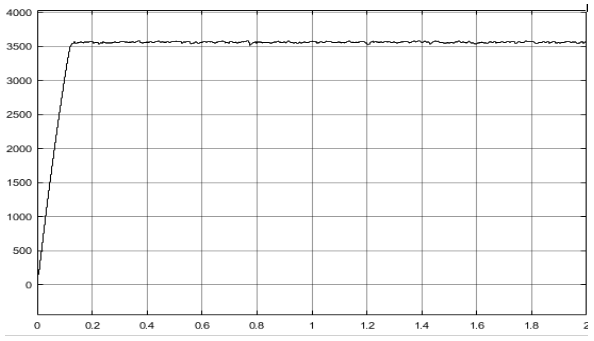

Fig.9. speed response of BLDC motor

A supply voltage of 500V is applied across the filter capacitor section. Filter capacitor heps to produce a filterd output and acts as a voltage devider. Two capacitors and two resistors are connected to form the filter capacitor group. The rotating speed of BLDC motor is 3500 rpm.

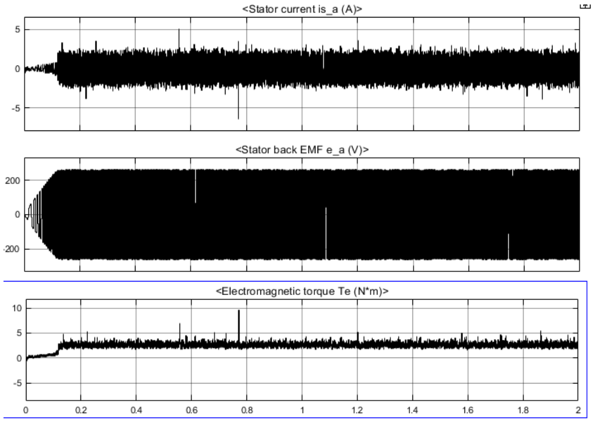

Fig.10. MATLAB/SIMULINK results of the BLDC motor wbased on virtual third harmonic back EMF method. (a)stator current in Ampere, (b) Stator back EMF IN Voltage, (c)Electromagnetic torque in Nm

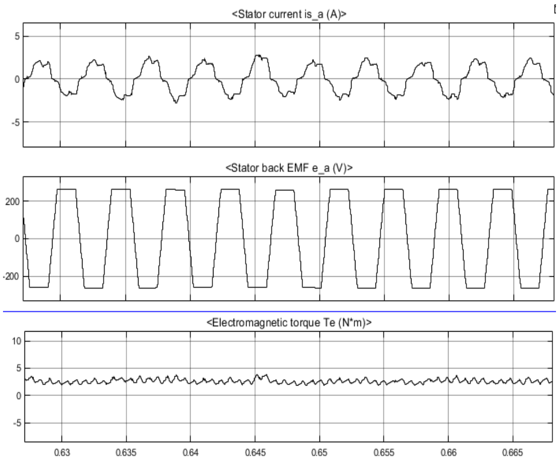

Fig. 11. Expanded view of the results (a)stator current, (b)stator back EMF, (c)electromagnetic torque

The MATLAB/SIMULINK simulation results are given above. Stator current of 2A and back EMF of 220V are obtained when a torque of 3Nm is given to the motor. The reference speed of the motor is 3500 rpm. Supply voltage is 500V dc.

V CONCLUSION

High speed operation of BLDC motor is possible with a number of methods. The most effective method which is sensorless back EMF based methods. It can precisely detect the commutation points. sensorless virtual third harmonic back EMF sensing method is the most advanced method for rotor position detection. This method also helps to compensate the commutation error. Hence a perfect operation is offered by this method. There is no neutral point in this method and also there are no hall sensors. Hence cost effective and accurate operation is possible. High speed range operation is possible by this method.

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