Position and Speed Control of Brushless DC Motors using Sensorless Techniques: A Review

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***Abstract*- In this paper,different methods define the position and speed control fundamentals of BLDC motors using sensors and the control improvements applying sensorless techniques including limitations and suggestions. The proposed Position and Speed Control method improve the performance and reliability of BLDC motor drivers because the conventional control and sensing techniques have been improved through sensorless technology. For realization of Sensorless operation, zero crossing of back emf is detected. In order to generate the proper firing pulses for commutation of inverter circuit and to remove the noise from the back emf signals, low pass filters are used.**

Keywords*:- *BLDC, back-EMF, sensorless, position, speed, estimator, Hall-effect sensors

I. INTRODUCTION

Permanent Magnet Brushless DC (PMBLDC) Motors are the latest choice of researchers due to their high efficiency,silent operation, compact size, high reliability and low maintenance requirements. These motors are preferred fornumerous applications; however, most of them require sensorless control of these motors. The operation of P.M.B.L.D.C.motors requires rotor-position sensing for controlling the winding currents. The sensorless control would need estimationof rotor position from the voltage and current signals, which are easily sensed.

The use of permanent magnets (PMs) in electrical machines in place of electromagnetic excitation results in many advantages such as no excitation losses, simplified construction, improved efficiency, fast dynamic, and high torque or power per unit volume. The PM excitation in electrical machines was used for the first time in the early 19th century, but was not adopted due to the poor quality of P.M materials. In 1932,the invention of Alnico revived the use of PM excitation systems, however it has been limited to small and fractional horse powered commutator machines.[1] In the 20th century, squirrel cage induction motors have been the most popular electric motors, due to its rugged construction. Advancements in power electronics and digital signal processors have added more features to these motor drives to make them more prevalent in industrial applications. However squirrel cage induction motors suffer from poor power factor and efficiency as compared to synchronous motors. On the other hand, synchronous motors and dc commutator motors have limitations such as speed, noise problems, wear and EMI due to the use of commutator and brushes. These problems have led to the development of permanent magnet brushless or commutatorless synchronous motors which have P.M excitation on the rotor.

Therefore, permanent magnet brushless (PMBL) motors can be considered a kind of three phase synchronous motor, having permanent magnets on the rotor, replacing the mechanical commutator and brushes. Commutation is accomplished by electronic switches, which supply current to the motor windings in synchronization with the rotor position.

The popularity of PMBL motors are increasing day by day due to the availability of high energy density and cost effective rare earth PM materials like Samarium Cobalt (Sm-Co) and Neodymium-Iron-Boron (Nd-Fe-B) which enhance the performance of P.M.B.L.D.C.M. drives and reduce the size and losses in these motors. The advancements in geometries and design innovations have made possible the use of PMBL motors in many of domestic, commercial and industrial applications. PMBL machines are best suited for position control and medium sized industrial drives due to their excellent dynamic capability, reduced losses and high torque/weight ratio.[1]

PMBL motors find applications in different fields such as domestic appliances, automobiles, transportation, aerospace equipment, power tools, toys, vision and sound equipment and healthcare equipment ranging from microwatt to megawatts. Advanced control algorithms and ultra-fast processors have made P.M.B.L.D.C. motors suitable for position control in machine tools, robotics and high precision servos, speed control and torque control in various industrial drives and process control applications. With the advancement in power electronics it is possible to design PMBL generators for power generation on board ships, aircraft, hybrid electric cars, while providing reduced generator weight, size and a high payload capacity for the complete vehicle.[25]

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1.1 Modelling of BLDC motor

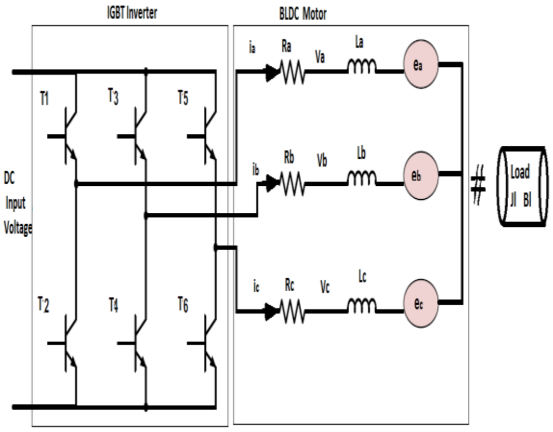

Figure 1.1: Equivalent circuit of BLDC motor drive system

The mathematical model of PMBLDC Motor is similar to that of a conventional DC Motor. The differentials equation of PMBLDC Drive describing the response of electrical quantities can be derived as:

$$V = iR + L\frac{di}{dt} + E \qquad (1)$$

Where,
V= DC voltage in Volts
L= Inductance of windings in Henry
R= Resistance of the windings in Ohms
E=Kb*w= Back emf of the motor
w=Speed in red/sec
Above equation can be written as

$$\frac{di}{dt} = (-E - iR + V)\frac{1}{2} \qquad (2)$$

Where,
i= current in Ampere
The relation between speed, electromagnetic torque and load torque can be expressed by the following equation as,

$$T = J\frac{dw}{dt} + Bw + Tl \qquad (3)$$

T = Electromagnetic Torque in Newton-meter
J = Moment of inertia in Kg.m2
TI = Load torque.
B = Coefficient of friction in Kg / ms.
The above equation (3) can also rearrange as:

$$\frac{dw}{dt} = (Bw + T - Tl)\frac{1}{J} \qquad (4)$$

The voltage equations for the armature winding of the motor are as follows:-

$$Va = Ria + L\frac{di_a}{dt} + e_a \qquad (5)$$

$$Vb = Rib + L\frac{di_b}{dt} + e_b \qquad (6)$$

$$Vc = Ric + L\frac{di_c}{dt} + e_c \qquad (7)$$

Where L-armature self-induction in [H]
R-armature resistance in [ohm]
Va, V band Vc-phase voltage in [V]
ia,ib and ic-motor input current in [A]
ea, eb and ec-motor back-Emf in [V]
Back-Electromotive Force of each phase has a phase difference of 120 (electrical) degrees and back-Emf and rotor position can be related via some function. Equation of back- Emf for each phase is as follows:

$$e_a = Kwf(\theta_e, w) \qquad (8)$$

$$e_b = Kwf\left(\theta_e - \frac{2\pi}{3}, w\right) \qquad (9)$$

$$e_c = Kwf\left(\theta_e + \frac{2\pi}{3}, w\right) \qquad (10)$$

Where,
Kw-back-Emf constant of one phase [V/rads-I]
Be is the rotor angle in electrical degree and w-rotors peed [rad. S-1]
Rotor angle electrical Be and Rotor angle mechanical Bm are related as:

$$\theta_e = \frac{P}{2}\theta_m \qquad (11)$$

Where,
P is the no of poles on rotor.
The total electromagnetic torque Te in N-M can be expressed as follows:

$$T_e = \frac{P}{w} = \frac{(e_a i_a + e_b i_b + e_c i_c)}{w} \qquad (12)$$

II. DIFFERENT POSITION AND SPEED CONTROL METHODS OF BLDC MOTOR USING SENSORLESS TECHNIQUES:

Position sensors can be completely eliminated, thus reducing further cost and size of motor assembly, in those applications in which only variable speed control is required and system dynamics is not particularly demanding. In fact,

some management ways, such as back-EMF and current sensing, provide, in most cases, enough information to estimate with sufficient precision the rotor position and, therefore, to operatethe motor with synchronous phase currents. A PM brushless drive that does not require position sensors but only electrical measurements is called a sensorless drive.

The BLDC motor provides fair candidate for sensorless operation as a result of the character of its excitation inherently offers a cheap way to extract rotor

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position info from motor-terminal voltages. In the excitation of a three-phase BLDC motor, except for the phase-commutation periods, only two of the three phase windings are conducting at a time and the no conducting phase carries the back-EMF. There are many categories of sensorless control strategies; however, the most popular category is based on back electromotive forces or back-EMFs [4].
Sensing back-EMF of unused section is that the most value economical methodology to get the commutation sequence in star wound motors. Since back-EMF is zero at standstill and proportional to speed, the measured terminal voltage that has large signal-to-noise ratio cannot detect zero crossing at low speeds.

That is the rationale why altogether back-EMF-based sensorless ways the low-speed performance is restricted, and an open-loop starting strategy is required.

In this paper, conventional and recent advancement of back-EMF sensing methods for The Back-EMF detection methods' Back-EMF Zero Crossing Detection (ZCD) or Terminal Voltage Sensing.
1. Third Harmonic Voltage Integration.
2. Free-wheeling Diode Conduction or Terminal Current Sensing.
3. Back-EMF Integration Method
1) Back-EMF Zero Crossing Detection method (Terminal Voltage Sensing)

The zero-crossing approach is one in all the best strategies of back-EMF sensing technique, and is predicated on detection the moment at that the back EMF within the unexcited section crosses zero.

This zero crossing triggers a timer, which can be as easy as associate RC time constant, so sub sequent serial electrical converter commutation happens at the tip to the present timing interval [10].
For typical operation of a BLDC motor, the phase current and back-EMF should be aligned to generate constant torque. The current commutation point shown in Figure 9 can be estimated by the zero crossing point (ZCP) of back-EMFs and a 30° phase shift [3], using a six-step commutationscheme through a three-phase electrical converter for driving the BLDC motor.

The conducting interval for every section is 120 electrical degrees. Therefore, only 2 phases conduct current at any time, leaving the third phase floating.In order to produce maximum torque, the inverter should be commutated every 60° by detecting zero crossing of back-EMF on the floating coil of the motor [8], so that current is in phase with the back-EMF.

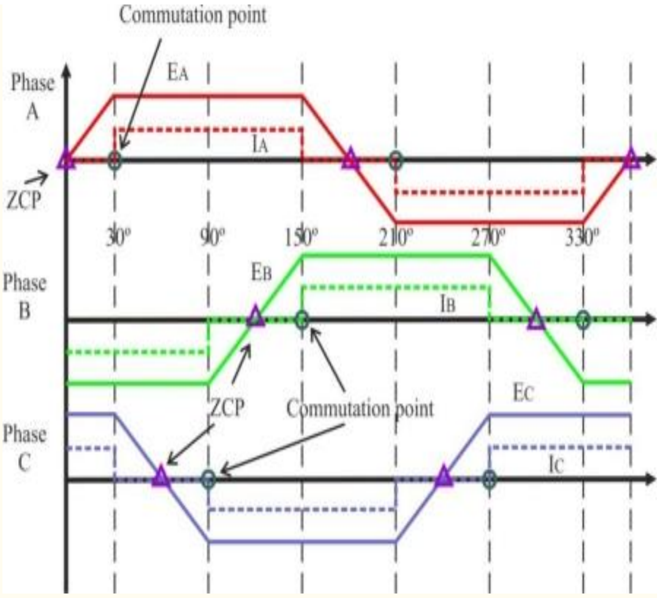

Figure 2.Zero crossing points of the back-EMF and phase current commutation points [9].

This technique of delaying 30° (electrical degrees) from zero crossing instant of the back-EMF is not affected much by speed changes [4]. To detect the ZCPs, the phase back-EMF should be monitored during the silent phase (when the particular phase current is zero) and the terminal voltages should be low-pass filtered first.

Three low-pass filters (LPFs) are utilized to eliminate higher harmonics within the section terminal voltages caused by the inverter shift. The time delay of LPFs will limit the high speed operation capability of the BLDC machine [8,10]. It's necessary to entails the importance of filters once a BLDC motor drive is intended, that are commonly eliminate high frequency parts of the terminal voltages and to extract back-EMF of the motor.

The terminal voltage of the opened or floating phase is given by Equation (13):

$$V_C = e_C + V_N = e_C + V_{CE} - V_{F2} - e_A + e_{B2} \quad (13)$$

Where eC is the back-EMF of the opened phase (C), VN is the potential of the motor neutral point, and VCE and VF are the forward voltage drop of the transistors and diodes, respectively, which implement the motor inverter of Figure 2, respectively.

As the back-EMF of the two conducting phases (A and B) have the same amplitude but opposite sign [19] the terminal voltage of the floating phase results in Equation (14):

$$e_A = -e_B = V_c = e_C + V_{CE} - V_{F2} = e_C + V_B + V_{A2} \quad (14)$$

where $V_A = -V_F$ (forward current of diode D_{A-}) and $V_B = V_{CE}$ (collector-emitter voltage of transistor T_{B-})

Since the zero-crossing point detection is finished at the tip of the PWM on-state and only the high-side of the inverter is chopped and VCE is similarto T_{A+} and T_{B-} transistors, the final detection formula can be represented by Equation (15):

$$\begin{aligned} V_A + CE &\approx V_B - CE = V_C \\ &= e_C + V_B - CE + V_{DC} - V_A + CE \\ &\approx e_C + V_{DC2} \qquad (15) \end{aligned}$$

Therefore, the zero-crossing happens once the voltage of the floating section reaches one half of the DC rail voltage. The reason why the end of the PWM on-state is selected as the zero-crossing detection point is that it is noise free to sample at that moment [6].

On the other hand, instead of using analogue LPFs, a unipolar pulse width modulation (PWM) scheme can be used to measure terminal voltages [11]. The difference of the ZCD method between on and off state of the PWM signal can also be taken into account [12,13]. Also, the true phase back-EMF signal could be directly obtained from the motor terminal voltage by properly choosing the PWM and sensing strategy (without the motor neutral point voltage information) This could givebenefits like no sensitivity to switching noise, no filtering needed, and good motor performance a wide speed range [8,14].

The price for the simplicity of the zero-crossing technique tends to be noise sensitivity in detection the zero crossing, and degraded performance over wide speed ranges unless the timing interval is programmed as a function of rotor speed [7]. Another disadvantage is that it is not possible to use the noisy terminal voltage to get a switch pattern at low speeds since back-EMF is zero at standstill and proportional to rotor speed. Also, the calculate commutation points have position error throughout the transient period when the speed is accelerated or decelerated quickly, particularly for a system that has low inertia. With this method, rotor position can be detected typically from 20% of the rated speed, then a reduced speed operating range is normally used, typically around 1,000–6,000 rpm.

1.1 Optimizations

As the rotor position information is extracted by indirectly sensing the back-EMF from only one of the three motor-terminal voltages for a three-phase motor, it's obvious that sensing each terminal voltage can provide two commutation instants. Measuring the time between these two instants, it's possible to interpolate the further four commutation instants (Figure 9 shows that six commutation points are needed), assuming motor speed does not change significantly over consecutive electrical cycles. Depending on the terminal voltage sensing locations, either a low-pass filter or a band-pass filter is employed for position information retrieval. The circuit for sensing the other two terminal voltages will thus be eliminated, resulting in a major reduction within the component count of the sensing circuit. Also, the ZCD technique can be improved if a digital filtering procedure is employed to spot truth and false ZCPs of phase back-EMF, which are caused by the terminal voltage spikes due to phase commutations [15].

An indirect way of detecting the ZCP of the back-EMF from the three terminal voltages without using the neutral potential is using the difference of the line voltages [16]. Another modification of the technique is to realize the sensorless commutation by suggest that of a Phase Locked Loop (PLL) and sensing of the phase winding back-EMF voltages. This PLL has a narrow speed range due to the capabilities of the phase detector, and is sensitive to switching noise. In order to simplify the BLDC driver design, it can be built around a sensorless controller chip ML4425 from Fairchild Semiconductor [16].

A sensorless Field Oriented Control (FOC) of brushless motors, that is thought to be additional economical in terms of torque generation compared to back-EMF zero crossing detection strategies, is currently under development, and it could be successfully applied to the design of motor pump units for automotive applications.

At low speeds or at standstill, the back-EMF detection method cannot be applied well because the back-EMF is proportional to the motor speed. In spite of this problem, a starting procedure can be used to start the motor from standstill [6]. In critical applications, such as the intelligent Electro-Mechanical (EMA) and Electro-Hydraulic (EHA) actuators of aviation systems, it is necessary to ensure correct start-up of the DC motor. Electrical commutation in the first running stage is normally realized by classical PWM signal that drives a transistor power stage (see Figure 2), which is open-loop control without any position feedback [3].

At high speeds, the long settling time of a parasitic resonant between the motor inductance and therefore the parasitic capacitance of power devices will cause false zero crossing detection of back-EMF. The solution to this problem is to detect the back-EMF during on time at high duty cycle [15], so there is enough time for the resonant transient to settle down. Then, during motor start-up and low speed, it is preferred to use the original scheme since there is no signal attenuation; while at high speed, the system can be switched to the improved back-EMF sensing scheme. With the combination of two detection schemes in one system, the motor can run very well over a wide speed range [8,12].

1.2 Applications

The terminal voltage sensing technique is widely used for low price industrial applications like fans, pumps and compressor drives where frequent speed variation isn't required. Nevertheless, BLDC motors want a rotor position detector, and this reduces the system ruggedness, complicates the motor configuration and its production. This sensor may be has been eliminated through this sensing technique. In spite of the back-EMF being zero at standstill, this system permits the beginning of a separately controlled synchronous motor without a sensor, as a result of the PWM signal generated in the control computer chops the motor voltage by the commutation transistors to control the motor speed. An example could be a motor pump unit, developed

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for commercial vehicle applications, in which control strategy can be based on the back-EMF zero-crossing method, and speed control loop is closed by means that of the virtual feedback provided by the commutation purpose prediction.

Another vital field is that the super high speed motors, which are receiving increasing attentions in numerous applications like machine tools, owing to the benefit of their small size and light weight at the same power level.

2) Third Harmonic Voltage Integration method

This method utilizes the third harmonic of the back-EMF to determine the commutation instants of the BLDC motor. It is based on the fact that in a symmetrical three phase Y-connected motor with trapezoidal air gap flux distribution, the summation of the three stator phase voltages results in the elimination of all polyphase, that is fundamental and all the harmonics components like 5th, 7th, etc. . The ensuring total is dominated by the third harmonic component that keeps a constant phase displacement with the fundamental air gap voltage for any load and speed.

An applicable process of the third harmonic signal allows the estimation of the rotor flux position and a correct inverter current control. In distinction with indirect sensing strategies supported on the back-EMF signal, the third harmonic requires only a small amount of filtering. As a result, this method is not sensitive to filtering delays, achieving a high performance for a wide speed range. A superior motor starting performance is also achieved because the third harmonic can be detected at low speeds [19].

Referring to 3, the stator voltage of the BLDC motor for phase A can be written similarly to Equation (3), where $V_{DC}=V_A$, $I=I_A$, and $e=e_A$. Equivalent expressions are often obtained for the other two stator phases. The harmonic content of the motor air gap or internal voltages e_A, e_B and e_C is a function of the rotor magnets and stator winding configurations [17]. For a full pitch magnet and full pitch stator phase winding, the inner voltages can be represented using the Fourier transform, getting several voltage harmonic components. If each phase inductance is constant at any rotor position, from the summation of three-terminal to neutral voltages, the third harmonic of the back-EMF can be measured by Equation (16)[9]:

$$V_{SUM} = V_{AN} + V_{BN} + V_{CN} \approx (eA + eB + eC) \approx 3 * E_3 * \sin(3 * we * t) \qquad (16)$$

The summed terminal voltages contain only the third and the multiples of the third harmonic due to the fact that only zero sequence current components can flow through the motor neutral. To obtain switching instants, the filtered voltage signal which provides the third harmonic voltage component is integrated to estimate the rotor flux linkage, as it is shown in Equation (8):

$$\lambda_{r3} = \int V_{SUM} \cdot dt \qquad (17)$$

Figure 10 depicts the motor internal voltage similar to phase A, e_A, the third harmonic signal, V_{SUM}, obtained from the summation of the stator phase voltages, the rotor flux third harmonic component λ_{r3}, the rotor flux λ_r, and the stator phase currents [13]. In order to get maximum torque per ampere, the stator current is kept at 90 electrical degrees with respect to the rotor flux. In addition, the zero crossings of the rotor flux third harmonic component occur at 60 electrical degrees, specially at each desired current commutation instant.

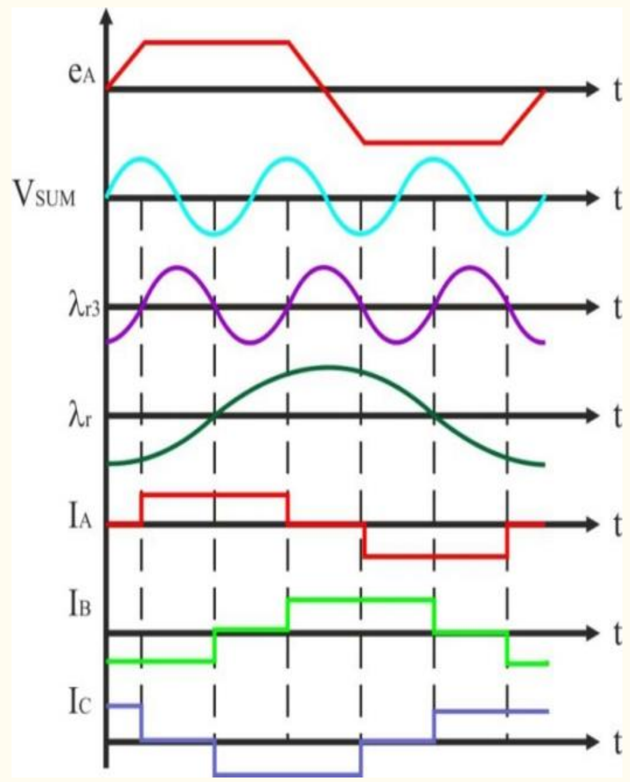

Figure 3.Back-EMF, third harmonic voltage, rotor flux and rotor flux fundamental components, and motor phase currents

Basically, there are three methods to extract the third harmonic component of the back-EMF, using as reference a permanent-magnet brushless drive with Y-connected resistors to enable the third harmonic component of the back-EMF to be sensed [5]. These methods are the following:

- From the voltage V_{SN} between the star point S of the resistor network and the neutral point N of the stator windings [20,21].
- From the voltage V_{SH} between S and the midpoint H of the DC bus.
- Fromthevoltage V_{NH} between N and H[22]

From the foregoing, only the voltage V_{SH} is suitable for the third harmonic back-EMF sensorless operation of BLDC motors, but as with all back-EMF based sensorless methods, an open-loop starting procedure has to be employed [5].

2.1Optimizations

The improved version of this method has been developed by using a PLL [6], in which the freewheeling diode conduction period takes place right after the commutation. The inverted terminal voltage measured during the diode conduction period causes position error because of the unbalanced integration, and the commutation angle error was decreased by inverting the measured terminal voltage during the diode conduction period. The method can be integrated into the ML4425 application-specific integrated circuit (ASIC) [9,17].

The implementation of this improvement in an experimental system, such as an air compressor, requires low starting torque and the commutation of the BLDC drive is significantly retarded during high-speed operation [4]. To overcome the problem, the ASIC should integrate the third harmonic back-EMF instead of the terminal voltage, such that the commutation retarding is largely reduced and the motor performance is improved [23].

2.2 Applications

The key advantages of this technique are simplicity of implementation, low susceptibility to electrical noise, and robustness, what makes it a good option for applications requiring a wide motor speed range. Signal detection at low speeds is possible because the third harmonic signal has a frequency three times higher than the fundamental back-EMF, allowing operation in a wider speed range (100–6,000 rpm) than techniques based on sensing the motor back-EMF. However, at low speed the integration process can cause a serious position error, as noise and offset error from sensing can be accumulated for a relatively long period of time [19].

3) Free-wheeling Diodes Conduction Detection method (Terminal Current Sensing)

Up to now, the indirect sensing algorithms explained can be applicable only to the SMPM motors whose winding inductances are almost the same and do not vary with the rotor position. These algorithms, except terminal current sensing method, utilize low pass filters or integration circuits to eliminate PWM frequency noise and to provide a phase delay for correct commutation of the stator current. But, in case of IPM motors, the inductance of stator winding varies with the rotor position. This characteristic introduces unbalance of phase impedances and variation of the potential of the neutral point, and it is impossible to apply the terminal current sensing algorithm. IPM motors are more practical than SMPM motors because of the ruggedness of rotor structure and low inertia.

In this technique, the position information can be detected on the basis of the conducting state of free-wheeling diodes connected in antiparallel with power transistors because a current flows in a phase. In this phase any active drive signal is given to the positive and negative side transistors and the current results from the back-EMFs produced in the motor windings. The three-phase permanent magnet synchronous motor has the trapezoidal back-EMFs shown in Figure 2. To produce the maximum torque, the inverter commutation should be performed every 60° so that the rectangular-shaped motor line current is in phase with the back-EMF signal. A starting circuit is needed to give a commutation signal for starting. This approach makes it possible to detect the rotor position over a wide speed range, especially at a lower speed, and to simplify the starting procedure .

Therefore, the conducting condition of D_{C-} is given by Equation (9), taking into account that V_{CE} and $V_F$are much smaller than the back-EMFs. Then, when the back-EMF of phase C (e_C) becomes negative, the open-phase current flows through the negative-side diode D_C:

$$V_{CE}\ , V_F \ll eA, eB, eC = eC < -V_{CE} + V_F 2 \approx 0 = eC < 0 \qquad (18)$$

Since the open-phase current results from the back-EMFs, it is impossible to detect the rotor position at a standstill. Therefore, a suitable starting procedure is necessary to the position sensorless BLDC motor drive. The procedure starts by exciting two arbitrary phases for a preset time. The rotor turns to the direction corresponding to the excited phases. At the end of the preset time, the open-loop commutationadvancing the switching pattern by 120° is done, and the polarity of the motor line current is altered. After the starting procedure, the motor line current indicates that satisfactory sensorless commutations are performed by the free-wheeling diode conduction method .

3.1 Applications

This method has a position error of commutation points in the transient state as other back-EMF based methods. But, the most serious drawback of this method is the use of six isolated power supplies for the comparator circuitry to detect current flowing in each freewheeling diode, which prohibits this method from practical applications. However, this technique outperforms the previous back-EMF methods at low-speeds.

4) Back-EMF Integration Method

In this technique, the commutation instant is determined by integration of the silent phase's back-EMF (that is the unexcited phase's back-EMF). The main characteristic is that the integrated area of the back-EMFs shown in Figure 4 is approximately the same at all speeds. The integration starts when the silent phase's back-EMF crosses zero. When the integrated value reaches a pre-defined threshold value, which corresponds to a commutation point, the phase current is commutated. If flux weakening operation is required, current advance can be achieved by changing the threshold voltage. The integration approach is less sensitive to switching noise and automatically adjusts for speed changes, but low speed operation is poor due to the error accumulation and offset voltage problems from the integration. As the back-EMF is assumed to vary linearly from positive to negative (trapezoidal back-EMF assumed), and this linear slope is assumed speed-insensitive, the threshold voltage is kept constant throughout the speed range.

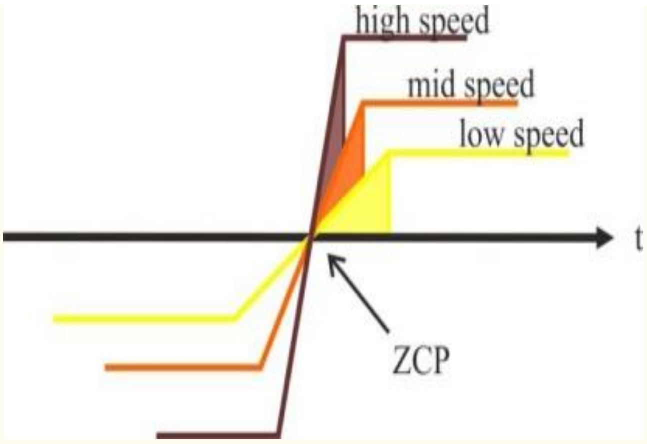

Figure 4. Integrated areas of the back-EMF

Once the integrated value reaches the threshold voltage, a reset signal is asserted to zero the integrator output. To prevent the integrator from starting to integrate again, the reset signal is kept on long enough to insure that the integrator does not start until the residual current in the open phase has passed a zero-crossing.

The use of discrete current sensors for each motor phase will provide complete current feedback, but the cost associated with individual current sensors (e.g., current transformers or Hall-effect sensors) is often prohibitive. An appealing alternative is the use of current sensors which are integrated into the power switches, such as power MOSFET'S and IGBT's, which are available from several device manufacturers with ratings up to several hundreds of volts and several tens of amps. However, embedded current sensors impose their own constraints; for example, the current sensing terminal is not electrically isolated from the associated power device. Also, the availability of new power integrated circuits makes it possible to take more complete advantage of these sensors for the combined purposes of current regulation and overcurrent protection [30].

Finally, the back-EMF integration approach provides significantly improved performance compared to the zero-crossing algorithm explained before. Instead of using the zero-crossing point of the back-EMF waveform to trigger a timer, the rectified back-EMF waveform is fed to an integrator, whose output is compared to pre-set threshold. The adoption of an integrator provides dual advantages of reduced switching noise sensitivity and automatic adjustment of the inverter switching instants according to changes in rotor speed [10].

CONCLUSION

This paper represents review on sensorless control schemes of BLDC Motor.In all the four schemes control is achieved by without the use of sensor.In back EMF sensing technique the information regarding the back EMF is referred.This scheme reduces switching noise and suitable for high voltage, low voltage and high speed, low speed drives. In second method the stator third harmonic signal can be obtained without a direct access to stator neutral, eliminating the need of a fourth wire connection to the motor if desired. The third scheme is based on the conduction interval of freewheeling diode which are connected in antiparallel with power transistor, this approach make the detection possible for wide range of speed. In fourth method back emf integration provides improved performance compared to zero crossing method.

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