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Research paper on BLDC Motor's Detection Methods in Sensorless Speed and Position Control Applications

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Abstract: Brushless DC (BLDC) motors are widely used for many industrial applications because of their high efficiency, high torque and low volume. Sensorless means fewer parts, i.e. the omission of the position sensors and auxiliary decoding circuitries. High reliability, cost reduction and compactness are main advantages of sensor less strategies. The only reliable way to utilize the BLDC machine drives in harsh environments is sensor less techniques. For sensorless control Direct back-EMF detection and Indirect back-EMF detection methods are used, in this research paper we will discuss Direct and Indirect back-EMF detection methods like back-EMF Zero Crossing Detection/Terminal Voltage Sensing Method, PWM Strategies and back-EMF Integration, Third Harmonic Voltage Integration, Free-Wheeling Diode-Conduction/Terminal Current Sensing methods respectively for detecting rotor position signal accurately and reliably, so that BLDC motor can commute and runcorrectly.

Keywords: BLDC motor, sensorless, Terminal Current Sensing, back-EMF, Terminal Current Sensing, Third Harmonic, Integration, speed and position control.

I. INTRODUCTION

Brushless DC Motor uses electronic commutation to replace the electro-brush in DC motor. It not only keeps the advantages of DC motor, but also avoids the disadvantages of DC motor caused by electro-brush. Because of its advantages such as good mechanical characteristic linearity, wide speed range, long service life, easy to maintain, high reliability, low-noise, no commutation spark, etc. it was widely used in electrical and household appliances, industrial equipment, automotive and military equipment is widely applied in the field. In DC commutator motor, current polarity is altered by commutator and brushes. In the BLDC motor polarity reversal is performed by power transistors switching in synchronization with the rotor position. To accomplish this, BLDC motor is inverter fed. Inverter is designed in such a way that, its output frequency is function of instantaneous rotor speed and its phase control will correspond to actual rotor position.

Third Harmonic Voltage Integration method uses the third harmonic of the back-EMF to determine the commutation instants of the BLDC motor. The main benefits of this technique are simplicity of implementation, low susceptibility to electrical noise, and robustness. Signal (back-EMF) 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) [1].

Free-wheeling Diodes Conduction Detection (Terminal Current Sensing) is indirect back-EMF sensing method in which the position information can be detected based on the conducting state of free-wheeling diodes connected in antiparallel with power transistors because a current flow 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.This method makes it possible to detect the rotor position over a wide speed range, especially at a lower speed, and to simplify the starting procedure [2]. In back-EMF Integration Method, the commutation instant is determined by integration of the silent (unexcited) phase's back-EMF. The concept is that the integrated area of the back-EMFs is approximately the same at all speeds. 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[3].

II. MATHEMATICALMODEL

In the figure 1 [3], three inverter phases are shown in a different colour: red phase A, green phase B, blue phase C, and pink neutral point N. The initial position of the rotor is determined by non-linear magnetic saturation characteristic of stator iron. The inductance of stator winding is a function of the rotor position because when the stator winding is excited, applying a DC voltage for a certain time, a magnetic field with a fixed direction will be established. Then, the current responses are different due to the inductance difference, and this variation of the current responses contains the information of the rotor position. The study of the circuit shown in Figure 1 is based on the BLDC motor model for phase A, shown in Figure 2 and the following assumptions are considered [4]:

1. The motor is notsaturated
2. Iron losses arenegligible
3. Stator resistances of all the windings are equal(Rs)
4. Self-inductances are constant(Ls)
5. Mutual inductances (M) are zero
6.

Now, voltage function of the conducting phase winding might be expressed as indicated in Equation (1):

$$V_{DC} = I.R_s + L_s.dI/dt + e \qquad (1)$$

Where, VDC = DCvoltage.
Rs& Ls = equivalent resistance and inductance of stator phase winding respectively.
e = trapezoidal shaped back-EMF.

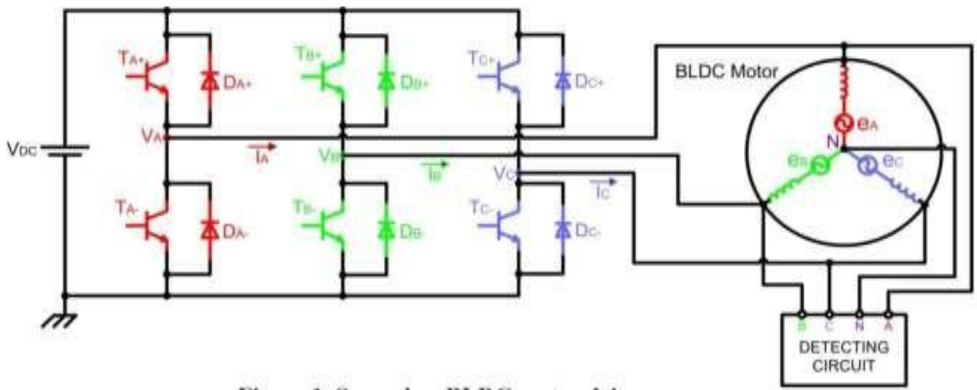

Figure 1. Sensorless BLDC motor drive

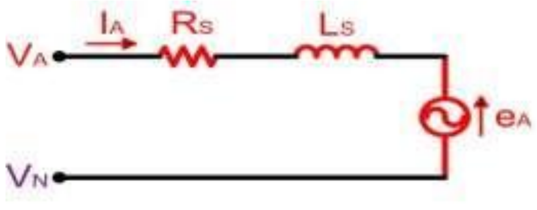

Figure 2. BLDC motor model for phase A

III. THIRD HARMNIC VOLTAGE INTEGRATIONMETHOD

The method of Indirect sensing the rotor fluxposition is applicable to trapezoidal back-EMF typeofBLDCmotors. The open circuit stator phase voltages, also called back-EMF, have a trapezoidal shape that contains a fundamental and higher order frequency harmonics This method 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 an elimination of all poly-phase components (fundamental and all the characteristics harmonics components like 5th, 7th, etc.); only the zero sequence components are left from the summation [5].The resulting sum 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 appropriate processing of the third harmonic signal allows the estimation of the rotor flux position and a proper inverter current control. In contrast with indirect sensing methods based on the back-EMF signal, the resulting thirdharmonicsignalispracticallyfreeofnoisethatcanbeintroducedbytheinverterswitching;onlyasmallamount of filtering is necessary to eliminate the switching frequency and its side bands. 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 bedetected at low speeds.

Figure 3 shows the idealized air gap flux density distribution for a BLDC motor with surface mounted magnets [6]. The resultant trapezoidal air gap flux density has a dominant third harmonic component that links the stator phase windings inducing a third harmonic voltage component in each one of the phases. The summation of the three stator phasevoltages results only in the third harmonic plus other high frequency components. This summation, however, requires access to the neutral point connection of the stator. This extra wire connection to the neutral carries only signal currents. Two possible implementations for acquisition of the third harmonic voltage signal, one using the neutral connection (4-wire method) and another without neutral connection (3-wire method).

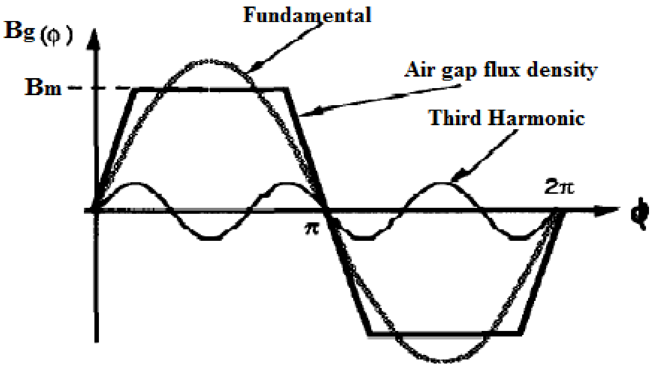

Figure 3. Air gap flux distribution and its fundamental and third harmonic components

The stator voltage equation for phase A, for instance, is written in Equation 1. Similar expressions canbe written for the other two stator phases. Where VDC=VA, I=IA, and e=eA

The harmonic content of the motor air gap or internal voltages eA, eB and eC is a function of the rotor magnets and stator winding configurations [7].For a full pitch magnet and full pitch stator phase winding, the internal voltages can be represented using the Fourier transform, obtaining many voltage harmonic components. From the summation of three-terminal to neutral voltages, the third harmonic of the back-EMF can be measured by Equation (2)[3]:

$$\begin{aligned} V_{sum} = V_3 &= V_{AN}+V_{BN}+V_{CN} \\ &= (e_A+e_B+e_C) \\ &= 3*E_3*\sin(3*W_e*t) \qquad (2) \end{aligned}$$

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 (3):

$$\lambda_{r3} = \int v_3 \, dt \quad . \qquad (3)$$

Figure 4 gives the motor internal voltage corresponding to phase A, eA, the third harmonic signal, VSUM, obtained from the summation of the stator phase voltages, the rotor flux third harmonic component λr3, the rotor flux λr, and the stator phase currents [7]. In order to obtain 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, exactly at every desired current commutationinstant.

This sensing method requires access to the neutral connection of the stator phases. It also requires a stator winding pole pitch and rotor pole pitch different of 2/3, otherwise the third harmonic rotor flux component does not link the stator winding and no third harmonic voltage is induced in the stator phases. The important advantage of this technique, besides its simplicity, is its low susceptibility to noise.

Signal detection at low speeds is possible because the third harmonic signal has a frequency three times higher than thefundamental back-EMF,allowing operation in awider speed range.

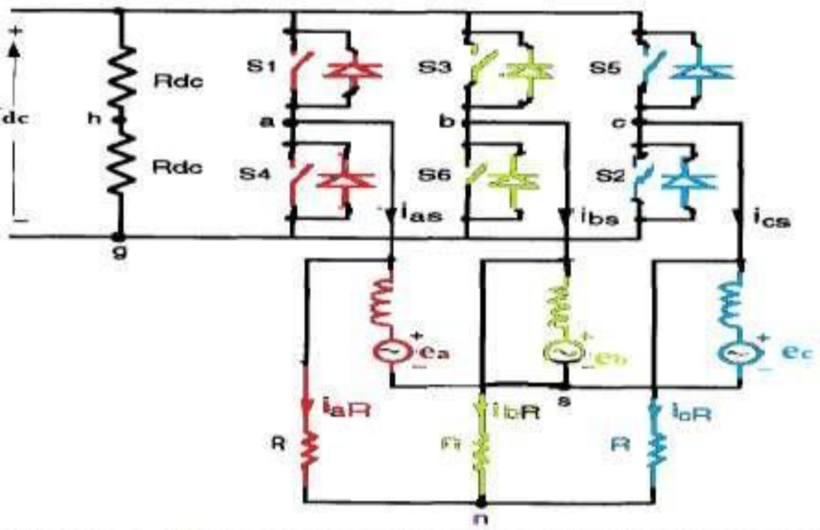

Figure 4. Third Harmonic sensing registor interface connected to an inverter bridge

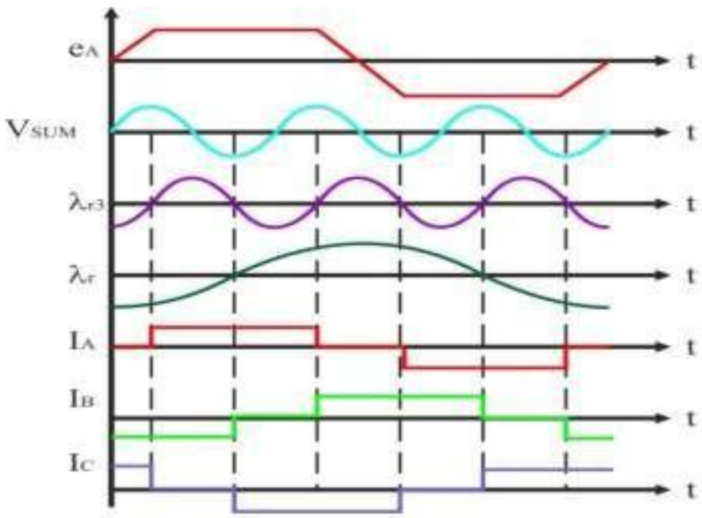

Figure 5. Back-EMF, third harmonic voltage, rotor flux and rotor flux fundamental components, and motor phase

Figure **4** shows a generic three phase inverter used to drive, a three phase BLDC motor. A star network of resistors of same value R is connected across the motor terminals and its common point labelled, n.Two other resistors, Rdc,are connected across the dc-link bus, forming a reference point labelled **h.** Note that the stator neutral point is labelled **s** and each one of the stator terminals labelled **a, b**, and **c**. Since the stator is star connected, so the summation of the stator currents reduces to zero.

It is interesting to note that the third harmonic voltage is obtained directly from the voltage across the two neutral points and no electronic summation means is necessary to add the three phase voltages [8]. In summary, the third harmonic stator voltage component can be obtained either from the voltage between the resistor network neutral and the motor statorneutral, VNNorfrom the resistor network neutral and the mid-point reference at the dc bus, VHN,in spite of the switching method used for the inverter bridge. A filter is necessary to eliminate the high switching frequency components. It is clear, then, that 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 ifdesired.

IV. BACK-EMF INTEGRATIONMETHOD

In this indirect back-EMF sensing technique, the commutation instant is determined by integration of the silent (unexcited) phase's back-EMF. The main characteristic is that the integrated area of the back-EMFs shown in Figure 5 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 [3]. 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.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 ensure that the integrator does not start until the residual current in the open phase has passed azero-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.

Finally, the back-EMF integration approach provides significantly improved performance compared to the zero-crossing algorithm. 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.

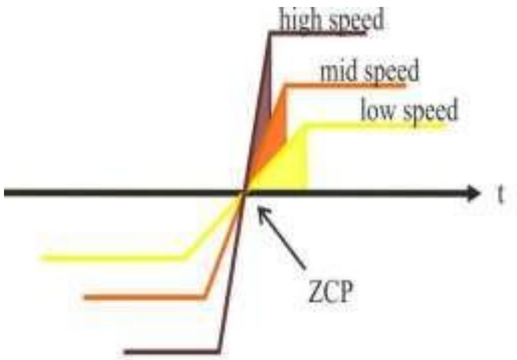

Figure 6. Integrated areas of back-EMF signals at various speeds

V. FREE-WHEELING DIODES CONDUCTION DETECTION METHOD (TERMINALCURRENT SENSING)

In this technique the position information is detected based on the conducting state of the free-wheeling diodes connected in antiparallel with power transistors, because a current flowing in a phase, in which no active drive signal is given to the positive or negative side transistor, results from the back-EMF's produced in the motor windings. The three-phase permanent magnet synchronous motor has the trapezoidal back-EMFs shown in Figure 7. The inverter used here is shown in Figure 1, but the conducting interval is 120" by electrical angle as shown in Figure 7.

Therefore, only two transistors, i.e. a positive side transistor in one phase and a negative side transistor in another phase, are ON-state at a time. The other phase, in which no active drive signal is given to the positive or negative transistor, is called the "open phase". To produce the maximum torque, the inverter commutation should be performed every 60º 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[2].

Therefore, the conducting condition of DC- is given by Equation (4), taking into account that VCE and VF are much smaller than the back-EMFs. Then, when the back-EMF of phase C (eC) becomes negative, the open-phase current flows through the negative-side diode DC:

$$V_{CE}, V_F << e_A, e_B, e_C \Rightarrow e_C < -\frac{V_{CE}+V_F}{2} \approx 0 \Rightarrow e_C < 0 \quad (4)$$

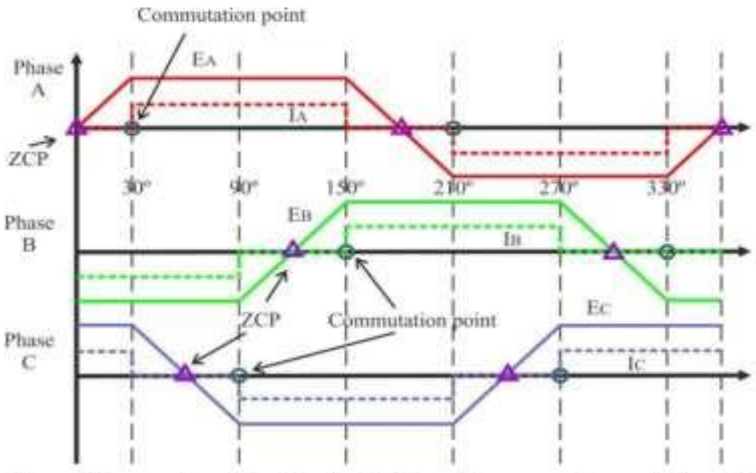

Figure 7 Zero crossing points of the back-EMF and phase current commutation points

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 pre-set time. The rotor turns to the direction corresponding to the excited phases. At the end of the pre-set time, the open-loop commutation advancing 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 [2]. 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 atlow-speeds.

VI. PWM STRATEGIES

Various type of PWM techniques used for direct back-EMF detection for sensorless speed and position control of BLDC motors. In this section, we will discuss Conventional 120º PWM strategy, Virtual Neutral Point Elimination Technique and Direct Current Controlled technique, Improved PWM technique for small power applications, Complementary PWM method.

A. CONVENTIONAL 120° PWM TECHNIQUE

Circuit in Figure 1 controlled by the PWM technique to give proper sequence of commutations so that two phases are with ON states and the third one phase is with floating state. Now, the inverter performs the functions of brush and commutator in a conventional DC motor, to generate a rotational stator flux [2,6]. PWM waveforms for 120° Conventional techniques are shown in Figure 4. In the conventional approach, 120° PWM method is used where the conducting interval of each phase is 120° electrical angle as shown in Figure 4. In order to produce maximum torque, inverter should be commutated every 60°, so that the current is in phase with the back-EMF. This method has merit of low switching losses in the inverter side but posse's high harmonic content which results in increase in loss on the motorside.

B. VIRTUAL NEUTRAL POINT ELIMINATIONTECHNIQUE

The zero crossing of the back-EMF can be obtained by comparing the terminal voltage of floating phase to the neutral point as shown in Figure 5.In 120° conventional PWM technique the virtual neutral point fluctuates at the PWM frequency which results in very high common-mode voltage and high-frequency noise. To eliminate these problems voltage dividers and low-pass filters are used, as shown in Figure 5.

Now, Virtual Neutral Point elimination technique means when measuring back-EMF, no filtering is required and zero crossing points of the back-EMF voltage of the floating phase can be obtained directly from the motor terminal voltage referred to ground.In this method the PWM signal is applied on high side switches only, and the back-EMF signal is synchronously detected during the PWM off time [7], as shown in Figure 6.The low side switches are only switched to commutate the phases of the motor. Then, the true back-EMF can be detected during PWM off time because the terminal voltage of the motor is directly proportional to the phase back EMF during this interval. Terminal voltage is referenced to the ground instead of the floating neutral point, so the neutral point voltage information is not needed to detect the back-EMF zero crossing [8]. The resulting signal is not attenuated or filtered and it has a good signal/noise ratio, including a much wider speedrange.

C. DIRECT CURRENT CONTROLLED PWM TECHNIQUE (HYSTERESIS CURRENTCONTROL)

The direct current PWM control technique is based on the current controlled PWM method, instead of the voltage controlled PWM, which generates robust speed and torque responses and is simple to be implemented from the hardware and software points of view. One switch leg of BLDC motor drive as shown in Figure 1 is replaced with a split capacitor pair as shown in Figure 7. In this technique, two phases are connected to the switch legs and the other phase to the midpoint of DC-Link capacitors. But, the limited voltages make very difficult to obtain 120° conducting profiles. This is the well-known problem asymmetric voltage PWM [4], which results in the 60° phase-shifted PWM strategy to generate three-phase balanced current profiles. In a PWM control strategy for the four-switch three-phase BLDC motor drive, the three-phase currents always meet the condition of Equation (3):

$$I_c = -(I_a + I_b) \quad (3)$$

Hence, control of the two-phase currents can guarantee the generation of the 120º conducting three-phase currents profiles. The two-phase currents are directly controlled using the hysteresis current control method by four switches.

D. IMPROVED PWM TECHNIQUE FOR SMALL POWER APPLICATIONS

For small power applications of BLDC drives power consumption reduction is the main objective because of the use of battery and limited space for heat dissipation. In the PWM technique presented by Yen-Shin Lai et al. [7] the high side power device is chopped in 1/6 fundamental period, duty ratio is derived from the speed reference or error of speed. For the next 1/6 fundamental period, it is clamped to positive dc link for both intervals of high side device, the associated low side device is off as shown in Figure 8. Similar control signals are given to low side devices with 180° shift.

However as the low side device is on, output terminal is connected to the negative dc link. For other two phases the control signals are applied with 120°shift.As the high-side device is with chop control, the associated low-side power device is triggered by the inverse signal of chop control. To highlight the feature of this PWM technique, the voltage drop caused by the turn-on resistance of power device and load current is significantly reduced as compared to the forward voltage drop of diode. Therefore, the power consumption and the heat losses can be significantly reduced.

E. COMPLEMENTARY PWMMETHOD

Technique for low speed or low voltage applications, the voltage drop across the BJT's or MOSFET's will affect the performance. When the motor speed goes low, zero crossing is not evenly distributed. Besides, if the speed goes further low, the back-EMF amplitude becomes too low to detect [7].There are basically two methods to correct the offset voltage of back-EMF signal. One of them is to use complementary PWM as shown in Figure 9, which also reduces the conduction loss. Another method is to eliminate the effect of diode voltage drop in order to add a constant voltage to compensate the effect of diode, and threshold voltage for avoiding the asymmetry in the distribution of zero crossing [5]. Then, in order to eliminate the non-zero voltage drop effect, a complementary PWM can be used, which will also reduce the power dissipation in the devices [5].However, at low speed especially during the start-up, the back-EMF itself is very small so an amplifier can be used as a pre-conditioning circuit.Finally, the motor speed can be greatly expanded with the improvements explained before.

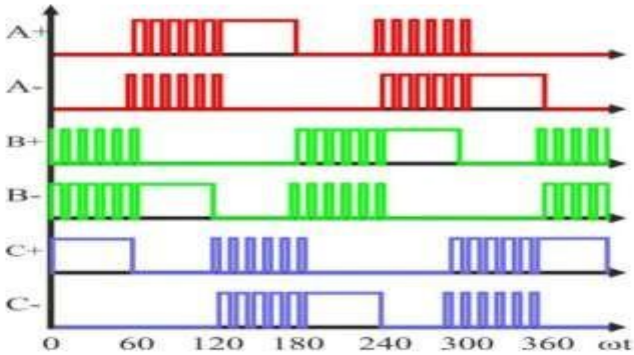

Figure 8. PWM scheme with reduces power loss

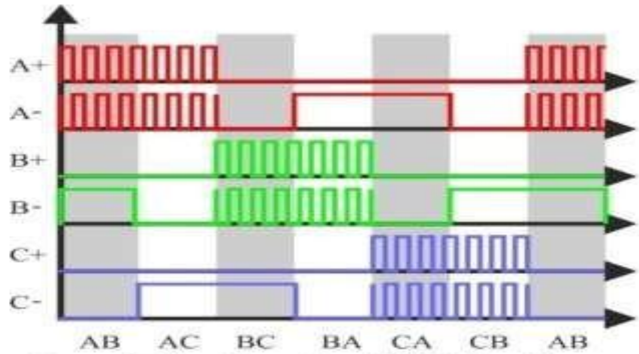

Figure 9. Complementary PWM algorithm

CONCLUSIONS

A completestudy of direct back-EMF detection for sensorless control of BLDC motors is presented. 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 reason why in all back-EMF-based sensorless methods the low-speed performance is limited, and an open-loop starting strategy is required [8].

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