Brushless dc motors inverters sensorless commutation engineering essay

Engineering

Laboratory of Electromechanical Energy Conversion, Department of Electrical Engineering and Computer Science, University of Patras, Rio – Patras 26504, GreeceA Novel Method for Zero Crossing Detection of Back Electromagnetic Force for Position Sensorless Commutation in a Brushless DC Motor Drive SystemAbstract -- In this paper a novel method for position sensorless commutation of a brushless dc motor without using any filters or integrators is proposed. The back electromagnetic force of the non conductive phase is derived from the corresponding terminal voltage in respect to the half of the DC inverter input voltage. Zero crossings are detected by appropriate sampling of the terminal voltage, the motor speed is calculated, a phase shift of 30o from the zero crossing is achieved and commutation signals are obtained which are similar to those created by the use of Hall sensors. Simulation and experimental investigation verify the effectiveness of this method. Index Terms— EMF detection, Drives, Brushless DC motors, Inverters, sensorless commutation.

Introduction

Permanent magnet brushless DC (BLDC) motors have been widely used in various areas such as industry and automotive applications due to their excellent serviceability and durability, their high power density, high efficiency and ease of control. The BLDC motors have a trapezoidal back electromagnetic force (EMF) waveform and are usually supplied by a three phase inverter, where the commutation control is achieved in respect to the variation of the motor flux. Six instants per electrical cycle of the permanent magnet rotor position must be specified for the inverter operation. For this reason, position sensors are required such as encoders, resolvers or magnetic Hall sensors. The most commonly used are the Hall – effect switches because of their relatively low cost. The sensors have to be mounted in specific positions inside the motor and extra wiring is needed. Also these sensors are subject to the stresses of operating conditions and so the reliability of the system is decreased. In order to overcome the disadvantages that the rotor position sensors cause a lot of research has been conducted about sensorless techniques of brushless DC motors. The basic structure of a BLDC motor drive system and the ideal waveforms of current and back EMF voltages are shown in Fig. 1. According to the paper [1], there are several sensorless methods to achieve proper inverter commutation in a brushless DC motor drive system: a) detection of back EMF, b) inductance variation and c) flux linkage variation. In the first category of methods, zero crossing of the induced back EMF is detected in the non conducting phase of the motor. In the second category, rotor position can be known by measuring the rate of change of the three phase stator currents. In the third group, an estimate of flux linkage can be produced by integration of the result coming from the subtraction of the resistive voltage drop from the phase voltage [2]. In the present work a method is proposed based on deriving back EMF from the corresponding terminal voltage which is related to the rotor position and so the commutation instances can be computed. fig_1. emf(a)fig_1_b. emf(b)Fig. 1. (a) Circuit diagram of a brushless DC motor driven by a three phase inverter, (b) Ideal waveforms of stator currents and back EMFs. In general, this approach has attracted wide attention and many researchers have reported different techniques such as determination of zero crossing point of back

EMF from phase voltages or line to line voltages [3 - 7], detection of freewheeling diode conduction [8] where complicated sensing circuits are required, and sensing third harmonic of the back EMF [9, 10]. The back EMF zero crossing techniques are sensed with respect to a virtual neutral point [11] or to the negative DC bus voltage [12]. As it is known, filters are usually required to remove high switching frequency signals caused by the pulse width modulation (PWM) inverter operation [11 - 13]. These filters result in a time delay which is depended from the rotor speed and thus from the frequency of the rotating field. Therefore, the use of the filters has influence on the dynamic performance of the drive system. It must be mentioned that a small phase error in commutation instant can produce significant pulsating torques in these drive systems [14]. Moreover, phase shift delay circuits are required to improve performance with a fixed phase delay of 30o or 90o electrical degrees, which is impossible over a wide speed range for most analog filter designs [8]. In the present work the use of any king of filters is avoided and so the phase delay depends only of the rotor speed. Another method to extract rotor position is by utilizing the third harmonic of back EMF. In this method, voltage between the star connection point of the machine and a virtual neutral point is measured and integrated in order to be shifted. The zero crossings of the resulting waveform are the commutation instants [15, 16]. This technique suffers also from integration error. Another way to define the commutation instances is by determining the zero crossings of back EMF through the intervals that freewheeling diodes conduct. This scheme operates over a wide speed range but requires complicated sensing circuits and additional power supplies [17 -20]. The contribution of the proposed method in the present paper is a sensorless commutation method based on zero detection of back electromagnetic force without using filters or integrators. The zero crossing points of the back EMF in each phase are independent of the motor speed and occur at rotor positions where the stator phase winding is not conducting, so this technique is obviously advantageous. These points of the back EMF are estimated from the terminal voltages in respect to the half of the DC voltage, as it can be shown in Fig. 1. The half of DC voltage is obtained by using a broadband voltage divider. This signal is sampled using a zero order hold unit with the inverter switching frequency. The sampling is accomplished in the middle of the pulse’s duration, thus the proposed technique is independent from duty cycle. Another reason for this sampling is to avoid the spikes that appear in the non conductive terminal voltage because of the switching on – off action. A frequency independent phase shift delay of 30o electrical degrees by counting the rising and the falling zero crossings is achieved.

The drive system – structure and mathematical model

In this study, a three phase BLDC motor with star connection windings and trapezoidal back EMF is considered. The motor is supplied by a six step inverter. The equivalent circuit topology of the motor is shown in Fig. 1, where M1 – M6 are MOSFETs. The high side power switches are controlled by a PWM signal with 20 kHz switching frequency, every 120o in a fundamental period. The low side power switches are controlled by a continuous pulse with duration of one third of the fundamental frequency. This technique is advantageous when bootstrap driver circuit is adopted. Also the switching losses are reduced. The ideal trapezoidal back EMF waveforms ea, eb, ec and the armature currents ia, ib, ic are presented respectively in Fig. 1(b). The six power MOSFETs operate in a defined conducting sequence so that the current has ideally a rectangular waveform and is in phase with the flat part of the corresponding back EMF. In practice, the current waveform is far from rectangular due to the motor and parasitic inductances and because of the PWM modulation. As it can be observed in Fig. 1(b), during operation current flows in only two phases at any instant. This leaves the third phase available for computing the next commutation instant by sensing the back EMF. The magnetic field of this motor is uniformly distributed in the air gap. With motor running at constant speed, this results in a back EMF which has a trapezoidal shape in time and its instantaneous magnitude is proportional of the rotor speed. Therefore, the switching technique has to ensure that the switching action is synchronized with the rotation of the flux in the air gap, and so a sensor is necessary to be included inside the motor for detecting the position of the flux wave relative to that of the stator windings [21 - 25]. This fact results in a constant power delivered to the rotor and the torque can be considered as constant. According our proposed method, the use of sensors is avoided and the commutation is achieved by measuring the terminal voltages of the motor in respect to the half of the DC voltage VxO (x = A, B, C), as shown in Fig. 1(a). In order to extract precisely the half of the DC voltage a broadband voltage divider has been implemented on the input of the inverter. The use of this divider is due to the voltage variation which is caused by the inverters operation. In the non supplied motor phase the back EMF appears. During these time intervals the polarity of back EMF changes and thus zero crossings occur, which must be detected. Each phase terminal voltage with respect to star point S, VxS, is given below, where x = A, B, C:, (1), (2), (3)where R is the stator resistance, L is the phase inductance, exn is the back EMF of the x phase and ix is the corresponding current. In order to define the terminal voltage of the motor in respect to the half of the DC voltage VxO, is necessary to introduce two branch functions f1 and f2 according to inverter operation:(4)(5)For example, consider the interval that phase A and B are conducting and phase C is open. It should be iA = -iB and iC = 0. For the back EMFs applies that eaS = - ebS, while the voltage ecS varies linear and changes its polarity. Now the terminal voltages could be rewritten:(6)(7)(8)The terminal voltage of the non conducting phase C in respect to the half of the DC voltage VCO could be calculated by the two loops that are formed and are presenting in the following:(9)(10)Adding equations (9) and (10) leads to the equation (11):(11)Substituting equations (6) - (9) in equation (11) results to equation (12):(12)So during this interval zero crossing of the back EMF can be detected. Finally, the motion equations of the BLDC motor are [12]:(13)(14)where Kt is the torque coefficient, im is the stator current, TL is the load torque, ω is the rotor speed of the motor, em is the induced back EMF and Ke is the back EMF coefficient of the armature winding. Equations (13) and (14) reveal that the induced back EMF is directly proportional to the motor speed and the torque is directly proportional to the phase current, which should be considered in designing the control system.

The proposed method for sensorless commutation

The features of the proposed back EMF detection technique include measurement of the terminal voltages of the motor in respect to the half of the DC voltage (point O Fig. 2), wide speed range operation and suitability for microprocessor/ DSP implementation. It is assumed that rotor speed does not change over one sixth of the electrical period, due to the rotor inertia and taking into account that this time interval is very short. Fig. 2 shows the implementation of the proposed commutation technique in the BLDC motor drive system. fig_2. emfFig. 2. Basic structure of the implementation of the proposed commutation technique in the BLDC motor drive system. An illustration of this method is presented in Fig. 3 through a block diagram, which can be considered as the basis of the algorithm for the signals creation, which are similar to those arising from the use of Hall sensors that determine the commutation process. Fig. 3. Block diagram for proposed back EMF detection strategy for phase A. In order to clarify this process, a motor terminal voltage waveform in respect to the half of the DC voltage (VAO) is presented in Fig. 4. This waveform has been obtained via simulation of the system using MATLAB/SIMULINK software and consists of high switching frequency pulse train caused by the pulse width modulation (PWM) control. Also, during the time interval that the motor phase VAO is not supplied, spikes are superimposed to the induced back EMF due to the pulse voltage waveform applied to the other two phases. In order to reject this high switching frequency signal and to overcome the zero crossing points that don’t belong to the back EMF, a sample and hold logic is implemented. The sampling occurs at every middle point of the pulse duration of the switches. As a result the obtained waveform (V*AO) is independent from the duty cycle as pulses do not exist in these waveform (Fig. 5). Fig. 4. Terminal voltage of the motor in respect to the half of the DC voltage (VAO), (simulation results).

Fig. 5. Terminal voltage of the motor in respect to the half of the DC voltage after the sample and holder (V*AO), (simulation results). As it can be observed in Fig. 5, six zero crossings occur during the fundamental period from which four are caused by the freewheeling diode conduction and have to be eliminated. When a zero crossing occur due to freewheeling diode’s conduction, the voltage V*AO is changing incrementally in steps greater than VDC/2 (≈ 25 V). This variation appearing in the terminal voltage is independent from machine’s operating point. This means that the proposed algorithm is fully independent from the torque load and so from the conduction time of the diodes. The rate of change of the terminal voltage is the criterion for back EMF’s rising and falling edges. Particularly, the algorithm for defining the actual zero crossing point of the back EMF and neglecting the edges caused by the diodes conduction is developed only by storing two consecutive values of the voltage V*AO. To determine the zero crossing of back EMF rising edge the following three conditions must be fulfilled simultaneously:(15)(16)(17)To determine zero crossing of back EMF falling edge the following three conditions must be also fulfilled simultaneously:(18)(19)(20)The aforementioned process is implemented on the three phases respectively. As the sequence of the supplied phase voltages and the zero crossing points of the three back EMFs are known now, the rotor speed can be calculated. In specific, when a zero crossing (rising or falling edge) of one phase of back EMF occurs, a timer starts to count until a second zero crossing of the next phase will happen. This time interval τ lasts 60o electrical degrees. The value of the timer is stored and then the timer resets and starts counting until the next zero crossing. The rotor speed ns is

calculated by using the stored value τ and the motor pole pairs p from equation (21):. (21)In this way the rotor speed is known at every one sixth of the fundamental electrical period. A phase shift of 30o electrical degrees from the correspondent back EMF zero crossing point in each stator phase is achieved by using the former stored timer value, which represents the 60o electrical degrees. This timer value is divided by two in order to obtain the 30o interval. When the timer starts to count again and reaches the half of the previous stored value, then a pulse is generated similar to a Hall sensor output. Therefore commutation signals are created without the use of any shaft sensor.

Simulation of the drive system using the proposed method

In this work, the brushless DC motor drive system of Fig. 2. is simulated by MATLAB/SIMULINK software. The system includes a three phase inverter where MOSFETs are used as power switches and the switching frequency is 20 kHz. Also a BLDC motor with trapezoidal back EMF is used. The motor parameters are presented in Table I. TABLE IThe BLDC motor parametersRated Power660 WNumber of poles8Rated speed3000 rpmRated torque2. 1 NmTorque constant0. 11 Nm/ABack EMF11. 5 V/krpmRotor inertia2400 g/cm2The proposed commutation strategy described in the previous section has been implemented in this drive system for position sensorless control. Firstly, a step variation of Load torque reference, as a test function, is imposed to the system without the implementation of PI controllers. This scenario is carried out in order to investigate the open loop response of the drive system, under constant DC input voltage, and also to test the effectiveness of the proposed commutation method. It is assumed that the motor speed is 3000 rpm and the load requires 25% of the nominal torque. At t = 1. 6 s a rapid variation of the load torque occurs at the rate of 75% of the nominal torque. Some characteristic results are presented in Fig. 7. As it is expected, the rotor speed is decreased, approximately 14. 6%, and the system reaches the new steady state within only 50 ms. Also, the amplitude of the trapezoidal back EMF is slightly reduced due to the speed variation. Phase currents are far from the ideal quasisquare waveform, shown in Fig. 1.(b), due to the inductance of stator windings and to high frequencies introduced by the PWM technique. Afterwards, the complete system with the proposed commutation technique is simulated, which includes two PI controllers for the stator current and the rotor speed as shown in Fig. 6. As it was mentioned above, in a brushless DC motor the induced back EMF is directly proportional to the motor speed and the torque is proportional to the phase current. The inner current (torque) controller has to be faster than the outer and therefore speed loop merely adapt the conventional controller. OPENLOOP_FIGS. emfFig. 7. Open loop response of the BLDC motor drive system. (a) motor phase current, (b) line to line motor voltage, (c) terminal voltage in respect to half DC voltage, (d) motor speed, (e) back EMF phase voltage, (f) electromagnetic torque, (g) torque load reference signal, (simulation results). In this scenario, the motor operates by 3000. rpm. and at. t = 1. 6 s a rapid variation of the torque load reference occurs from 25% to 75% of the nominal motor torque. This test function is the same with the first scenario for comparison of the open and closed loop response of the drive system. Some characteristic results are presented in Fig. 8. In this case the system reaches the new steady state in 250ms and the variation of the speed is at the rate of 2. 6% during transient. Fig. 6. Basic structure of the controlled brushless DC motor drive system. CLOSED_FIGS_PRIN_ISOROPIA. emfFig. 8. Closed loop response of the BLDC motor drive system when motor speed reference remains constant at 3000 rpm. (a) motor phase current, (b) line to line motor voltage, (c) terminal voltage in respect to half DC voltage, (d) motor speed, (e) back EMF phase voltage, (f) electromagnetic torque, (g) torque load reference signal, (simulation results). An very small oscillation around the speed reference value is observed of about 0. 06% at steady state. Additionally, current sinking observed when the corresponding motor phase is supplied due to the commutation that occurs in the other two phases. The rate of current sinking depends on the load demand. In these time intervals an electromagnetic torque ripple occurs. Fig. 9. presents the motor speed for a larger time interval in order to clarify that the speed returns to the value of 3000 rpm within 250 ms. MONO_STROFES. emfFig. 9. Motor speed for the closed loop drive system. Third scenario simulates the BLDC motor drive system while a rapid variation of the rotor speed reference occurs from 100 rpm to 3000 rpm at t = 0. 6s. The torque load remains constant at 10% of the nominal motor torque. Fig. 10. shows some of the basic electrical and mechanical characteristics of the system. BHMA_STROFES_FIGS. emfFig. 10. Closed loop response of the BLDC motor drive system when torque load reference remains constant at 3000 rpm. (a) motor phase current, (b) line to line motor voltage, (c) terminal voltage in respect to half DC voltage, (d) motor speed, (e) back EMF phase voltage, (f) electromagnetic torque, (g) torque load reference signal, (simulation results). In this case the system reaches the new steady state within 58ms. At t = 0. 6 s an overshoot in current occurs where its value reaches four times the nominal current. A corresponding overshoot in electromagnetic torque occurs at the same instant. These overshoots are expected to happen due to the great difference between the two reference rotor speed values (100 rpm and 3000 rpm). From Fig. 10 (a) (b) (c) and (e) the rapid change of frequency can be observed. Particularly, in Fig. 10 (e) the intensive dependence of back EMF magnitude and frequency from the rotor speed are shown.

Experimental investigation

For the experimental investigation of the examined BLDC motor drive system a set-up has been made in the laboratory, which consists of a BLDC motor with trapezoidal back EMF (data are included in table I), a DC generator as mechanical load coupled to the motor, a resistor device connected to the generator, a three phase MOSFET inverter, a DC power supply and instrumentation for data acquisition. This set-up is shown in Fig. 11. fig_11_TELIKI. emfFig. 11. Experimental set-up. The DC power supply output voltage has been set to the constant value of 48 V. Through the variation of the duty cycle, the appropriate terminal voltage has been supplied to the BLDC motor according to the load or the speed demand. The designed and constructed inverter consists of six MOSFETs with their fixed antiparallel diodes and operates at 20 kHz. The value of the switching frequency has been chosen in order to achieve better normalization of the armature current without increased switching losses. For the switching pulse generation of the MOSFETs, a dsPIC microcontroller has been programmed. In an open loop operation, where the load torque demand is 25% of the nominal value, some characteristic waveforms are obtained and shown in Fig. 12. at steady state. The motor was operated by using the Hall sensors. The most importantFig. 12. BLDC motor waveforms at a load of 25% of the nominal value. (a) phase current, (b) line to line voltage, (c) motor speed, (experimental results). Fig. 13. BLDC motor waveforms at almost full load. (a) phase current, (b) line to line voltage, (c) motor speed, (d) generator current, (e) generator voltage, (f) mechanical torque of the BLDC motor (experimental results). system variables under almost full load as time functions are depicted in Fig. 13. To test the system dynamical behavior a load step variation from 25% to 75% of the nominal load value has been imposed. The experimental results are presented in Fig. 14. Comparing the simulation results, showing in Fig. 7., toFig. 14. System dynamical behavior at a load step variation. (a) phase current, (b) line to line voltage, (c) motor speed, (d) generator current, (e) generator voltage, (f) mechanical torque of the BLDC motor (experimental results). the experimental results of Fig. 14. it can been seen that they are similar. The simulation results have been obtained under implementation of the proposed commutation strategy. The experimental system operation using the proposed commutation technique is under investigation.

Conclusion

In this paper, a novel commutation method for a BLDC drive system without position sensors, based on zero detection of back EMF, is presented. The three terminal motor voltages in respect to the half of the DC voltage are used to derive the back EMF. A simple mathematical analysis is introduced, in order to detect the time intervals within which the zero crossing points of the back EMF appear. An algorithm for neglecting zero crossings of the derived signals due to freewheeling diodes conduction is implemented. A phase shift of 30o electrical degrees related to the zero crossing point is achieved by calculation of the rotor speed. The simulation results reveal that the method allows sufficient operation of the system in a wide speed range independent of the duty cycle of PWM applied to the inverter. This method is easily implemented in microprocessor/ DSP applications. The experimental results of a BLDC drive system operation during transient and steady state are closed to those obtained by simulation.