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CLOSED LOOP SPEED CONTROL OF A WORKSHOP FABRICATED BRUSH-LESS DC MOTOR DRIVE PROTOTYPE

ODIGWE FIDELIS OBI
Department of Electrical/Electronics Engineering, Federal Polytechnic Oko

ABSTRACT
This paper presents steps and procedures of designing a closed loop speed controller for a surface mounted permanent magnet(SM-PM) brush-less DC machine(BLDC). The closed- loop speed control technique has been implemented using Hall-effect position sensor. The BLDC motor control algorithm has been modelled and simulated first. The same has been thereafter practically implemented on a 0.75 hp, 1500 r.p.m BLDC motor that was designed and developed as a lab prototype. Both the simulation and the experimental results are in excellent in agreements.

Index Terms—*Permanent magnet, Brush-less DC motor, Closed loop speed control, position sensor, Hysteresis current control, Simulation results, Experiments on BLDC motor.*

INTRODUCTION
Brush-less DC Motor(BLDC)[1] is emerging as an attractive alternative to induction motors(IM) in different variable speed drive applications for reasons which are well known - the most important ones being high energy density and absence of brushed contacts. The use of permanent magnets (PMs) in electrical machines in place of electromagnetic excitation results in many advantages such as elimination of excitation losses, improved efficiency, fast dynamic performance, lower maintenance, higher speed ranges and high torque or power density([1], [2], [4]).
Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically in an appropriate sequence[1]. The rotor position may be

also sensed by using Hall-effect sensors mounted on the stator[2], resolvers, inductive modular absolute system(IMAS), shaft-mounted incremental encoders [3] etc.

BLDC motors are used for position , speed and torque control[2], [3] for variable speed drive in motion control applications. For speed control applications, an outer position control loop is not required and the set speed serves as the command signal. Torque control is incorporated in high performance motion control through closed -loop regulation of phase currents in synchronization with rotor rotation through shaft position feedback. In majority of the BLDC motors, torque is linearly related to currents and torque command maps onto current commands through a simple proportionality constant. Current regulation in the phase windings of BLDC motors (rectangular waveforms)[3] is carried out using current controlled voltage source inverter(VSI). Pulse Width modulation(PWM), hysteresis and predictive current controllers ([2],[8]-[11]) are used to generate the switching signals to the devices of the inverter to keep winding currents close to the set reference/command currents. Speed control is generally achieved by using a speed feedback and generating speed command through speed controller which outputs a command signal for torque controller. Position control is implemented through position feedback and position command using position controller. The output of the position controller[2] provides the speed command for the inner speed loop.

In this paper, a speed control technique of BLDC motor has been designed, analysed and finally implemented on a laboratory developed 0.75hp BLDC motor prototype. The speed control technique presented here is valid for 4-quadrant VSD applications ([2], [3]), though implementation has been done here for 2-quadrants (i.e. forward motoring and forward braking) only.

BASICS OF BLDC MOTOR SPEED CONTROL

A. Modelling of a BLDC motor

The BLDC motor can be viewed as a permanent magnet AC (PMAC) motor with trapezoidal back emf. The motor is operated with 1200 rectangular current pulses(2 phase conducting at a time), such that its operating characteristics (torque-speed characteristics) are similar to that of a DC shunt motor. To turn-on and turn-off the switches of the inverter/converter (shown in Fig.1) in synchronism with the rotor position and at the rotational frequency of the rotor, a position sensor is required to feedback the rotor position signal. The stator (3- phase) windings are placed in slots within 60oe phase belts.

Fig.2 shows the ideal phase back-emf pattern and the corresponding the phase current wave-shape. It also shows the converter switching sequences required to achieve the desired current and hence mmf wave-shape for each phase of a BLDC motor

The dynamic machine model ([2], [5]) of BLDC motor can be described by (1), (2), (3) and (4).

where, p = d dt operator, v =applied phase voltage, e =phase back emf, Lm = mutual inductance between phases, L=self inductance of each phase,and Rs= resistance of each stator phases. 'a', 'b', 'c' , 'n' are the three phase terminals and neutral terminal respectively. In a 3-phase 3 wire system, since ia + ib + ic = 0. where, B= co-efficient of damping, J=moment of inertia of rotor with dead load, Ml=load torque, ωm= rotor mechanical speed in rad/s. At any instant, the inverter output voltage,vis=±Vdc, is applied to the combination of two phases(let phase 'a' & 'c') in series, having a net impedance of Z = 2{Rs +p(L−Lm)} = Ra + pLa and ia= -ic in case of star connected stator. The voltage equation for the stator is given by (5)

where, ea = ec =λpωm and the emf constant for both the phases is combined into one constant as kb = 2λp , V/rad/s. (5) can be written in Laplace domain as, (6).

where, Id= average dc-link current. The load torque is assumed proportional to the speed: Ml=Bl ωm and Ba= co-efficient for air damping. So, the net damping coefficientB=Bl + Ba.

B. BLDC motor control

A two loop control technique[2] is used here. Fig.3 shows the schematic diagram for the closed loop speed control of a BLDC motor. The outer speed control loop generates equivalent torque reference(i^*_p) for the inner current loop that is used to generate current references for each phases respectively i.e. i^*_a,i^*_b and i^*_b . The current control loop uses a hysteresis control technique. The line current is sensed using a Hall sensor. This leads to a sensor reduction, since 2 phases are on at a time without much effect on the transient performance. The error signal ($e_i = i^*_a - i_a$) is passed through the hysteresis controller and controller output control the switching instants device turned on or off to keep error current in a specific band(Δi). Three inner current control loop are required for each phase current. The design of control algorithm is done based on a 0.75 hp BLDC motor drive ([6],[7]). The parameters of the 0.75 hp BLDC motor is given in Table-I.

1) Logic pulse generation: H1, H2 and H3 are three position sensor pulses which are synchronized with the line to line induced emf eAB, eBC and eCA accordingly (shown in Fig.7 and Fig.9(b)). These position sensor output pulses are used to generate the control logics for running the BLDC motor in open loop condition. The logic pulses for each switching device of the BLDC converter (shown in Fig.1) are as following: Q1=H1H3, Q2=H2H3, Q3=H1H2, Q4= H1H3, Q5= H2H3 and Q6= H1H2. In case of closed-loop control, these logic pulses are used to generate the current references for respective phases accordingly like Q1 & Q4 for generating i^*_A (shown in Fig 3). The hysteresis controller output pulses of each phases are logically 'AND' -ed with respective main logic pulses (i.e. open loop switching logic pulses) appropriately to achieve 120^o quasi-square current waveform. 2) Closed loop controller design: Fig. 4 and 5 show the current and speed control loops. T1, T2 shown in Fig.5 mostly depend on the electrical and mechanical time constant. The width of hysteresis band for the current control loop is kept as 5% of the rated load current.

For the speed control loop , current loop appears ideal due to high mechanical time constant(i.e.$T_m = J/B$) of the BLDC motor. The band-width of speed control loop is kept within 3 Hz. Fig.6 shows a simplified model of speed control loop. A tacho-generator is used to provide the speed feedback of the rotor shaft. The gain of the techo-generator is 2.33×10^{-3}

The closed loop speed control technique of BLDC motor presented here is valid only in the constant torque region. As the speed increases, the back emf increases proportional to speed, and eventually, the current control is lost when the PWM controller saturates at the edge of the constant torque region. The constant torque ([3], [13]) region is limited by the rated voltage of BLDC motor. It is difficult for a SMPMBLDC motor to perform at constant power operation (above base/rated speed) because field wreaking operation is very difficult to be implemented over a wide range [14], [15]. The SMPM-BLDC motor has constant flux characteristics, low magnetizing inductance Lm, and negligible salient pole effect(Lad=Laq=Lm). A very high demagnetizing component of stator current is required to perform field weakening operation, because the magnetizing inductance Lm is very low in BLDC motor.

RESULTS AND DISCUSSIONS

Closed loop speed control of BLDC motor has been implemented on a 400 V DC, 0.75hp, 1500 rpm star connected BLDC motor ([6],[7]) which was also designed and fabricated by the present authors. An important point may be made here. The design of the motor was done earlier([6],[7]) so as to reduce the torque ripple/ cogging torque etc. Additionally, the control strategy implemented here reduces the torque ripple further. Table II enlists the effect of design and control on the torque ripple.

The closed loop control scheme of BLDC motor has been tested at 560W load at 1500 rpm. A 0.5 hp, 1500 rpm separately exited DC generator has been mechanically coupled with the BLDC motor for loading . The closed loop control algorithm has been simulated first and then implemented on the the above mentioned system. Fig.9(a)shows waveforms motor of the line to line induced emf eAB and corresponding phase emf eA in the generating mode at 850 rpm while Fig.9(b) shows line to line induced emf eAB and position hall sensor pulses H1 of corresponding line voltage. Hall sensor pulse H1 and line to line voltage vAB has been set such that are in phase. It can be easily proved that this ensures the maximum utilization of motor and converter KVA.

Fig.10 shows the simulated waveforms of speed and line current IA for a steady state speed of 1000 rpm. Fig. 11 shows the corresponding experimental waveforms. The line current IA is trapezoidal in nature and has a value of 1.6A at 34 Hz with 0.5 hp load. Fig.12(a) shows the simulated waveforms line current of two phases iA & iB and while Fig12(b) shows corresponding experimental waveforms. Line currents are 120oe phase displaced. Fig.13 shows experimental waveforms of position sensor pulse H1 and line current iA of 1.2 A at 40Hz i.e at 1200 r.p.m shaft speed. Fig.14 shows the experimental waveforms of speed and the phase current during sudden decrease of speed reference reference. It clearly shows the transient nature of motor speed and line current under motor generator loading.

CONCLUSIONS

In this paper the design of a closed loop speed controller for BLDC motor has been presented. Torque rippler eduction has been achieved both through motor design (earlier [6],[7]) and then through closed loop control strategy. The BLDC machine has been modelled first and then simulated with closed loop speed control algorithm. An appropriate speed control strategy has also been implemented on a 0.75hp, 1500 r.p.m, 400V (DC-link) surface mounted BLDC motor in FPGA platform. A 0.5 DC shunt generator coupled with the BLDC motor has been used as loading purpose. The simulated and experimental results are presented and the they are found to be in excellent mutual agreement.

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