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DIRECT TORQUE & INDIRECT FLUX CONTROL OF BLDC MOTOR

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ABSTRACT

The reduction of torque ripples is achieved by suppressing error between command and estimated torque. The conduction and commutation controller controls the torque instantaneously. The instantaneous control achieved with torque controller and torque estimator. The PI controller and back EMF feed forward controller controls the high torque in conduction region and by controlling out going phase the torque ripples are reduced in commutation region. To regulate BUCK BOOST Converter during commutation output of commutation ripple controller used. The sensorless control applied to detect position of the rotor through optimizing current and reducing torque pulsation. This is the advanced method of Field Oriented Control (FOC) of BLDC motor for non sinusoidal back EMF rotor speed achieved by Kalman filter. Finally the proposed torque control method is verified through simulation results. The simulation results using Matlab/Simulink are shows the torque ripples are eliminated effectively.

Index Terms — BLDC, FOC, Back EMF, BUCK BOOST Converter, PI controller, sensorless control, instantaneous torque control, Torque Ripple reduction

INTRODUCTION

Brushless DC motor (BLDC) is extensively used in several high-performance applications, which have distinct advantages such as high power density, high efficiency, large torque to inertia ratio, and simplicity in their control. Torque smoothness is essential for high-performance motion control applications and obtaining an accurate and ripple-free instantaneous torque is of great importance for BLDC motor.

The torque mainly includes cogging torque, reluctance torque, and mutual torque, among which the cogging torque is induced by the stator slots interacting with the rotor magnetic field and is independent of stator current excitation. And, reluctance torque is caused by the variation in phase inductance with respect to position, while mutual torque is created by the mutual coupling between the stator winding current and rotor magnetic field. From the machine design perspective, it is of great interest to find the fundamental components of the total flux linkages. For a coreless stator permanent magnet machine, the flux linkage harmonics due to iron stator slots and magnetic saturation are absent.

Ideally, a BLDC motor, with a trapezoidal back-electromotive-force (EMF) waveform will produce ripple-free torque when supplied with rectangular 120◦ electrical phase current waveform. However, in a practical BLDC drive, significant torque pulsations may arise due to the back-EMF waveform departing from the ideal, as well as phase current ripple resulting from commutation events, pulse width modulation (PWM), and cogging. A sensor-less FOC scheme has been applied to BLDC motor with non-sinusoidal Back EMF [1].

Torque ripple due to phase current commutation is usually considered to be one of the main drawbacks of BLDC drives, compared to brushless ac (BLAC) drives with sinusoidal Back EMF, it could be eliminated at low speed by employing current

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control based on direct current sensing [2]. The control of BLDC motors can be done in sensor or sensorless mode, but to reduce overall cost of actuating devices, sensor-less control techniques are normally used [3]. The advantage of sensor-less BLDC motor control is that the sensing part can be omitted, and thus overall costs can be considerably reduced.

Other authors [4] made use of injected high-frequency signals, obtaining the rotor position in a manner similar to a resolver and a resolver-to-digital converter sensing system. The technique utilizes the dependence of inductance on rotor position in interior permanent magnet machines to produce position and velocity estimates both for field orientation and for all motion control of the drives. The sensed currents are then processed with a heterodyning technique that produces a signal that is approximately proportional to the difference between the actual rotor position and an estimated rotor position.

Recently, some approaches to compensate the misalignment effect of Hall sensors have been introduced in [5]. This method has presented an automated process that can obtain the actual Hall state transition points in whic4 an iterative routine determines the offset between ideal and actual points, and the resultant actual state transition values are stored in a lookup table during only initial commissioning. Since it is main algorithm is based on the average speed, the performance may degrade at a variable-speed operation the repetitive control technique is applied to the torque-ripple reduction in high-performance PMSM drives, where the -axis current reference has been modified so as to impose a constant torque in spite of back-EMF distortion. More specifically, the repetitive controller is merged with a conventional PI controller, where the PI control dominates during transients and large-signal dynamics, while the repetitive control ensures the compensation of the remaining errors so as to achieve a near perfect tracking of a periodic current reference signal [7].

Some studies use current sensors to feedback current signals for commutation control [6], [8]. This method detected the dc link current to determine the commutation instants during the start-up process. As the current magnitude is greater than the specified value, commutation occurs. However, current spikes caused by commutation and how to determine this specified current value are some of the practical concerns. The slope of phase-current ripple is detected to achieve commutation control, as shown in [8]. However, in order to calculate the slope of current ripple, the phase current should be detected more than twice for each chop on or chop off period. Therefore, high-speed A/D converter is required for current sampling.

Several approaches to zero-crossing detection of back EMF have been proposed. These methods include using position sensors, e.g., Hall sensors [9], current sensor [10], center-tap voltage, and current feedback via the resistor connected in series with dc-link voltage. A novel Fault Tolerance (FT) ripple-free torque controller for BLDC motors operating under a single-phase failure. Multiple failures can be also recovered for motors with four or more phases [12]. The FT controller tends to increase the power loss and decrease the maximum attainable motor torque under a fault condition. The phase current and torque ripples are severe for BLDCM when three phase inverter is modulated. Here the torque ripple reduction method has been proposed by adding buck converter in the front of three phase inverter. Also the torque ripple in non commutation region is eliminated effectively. Torque ripples due to phase current commutation is reduced in proposed system. Torque ripples reduced by optimizing duty ratio of the active voltage vectors.

System configuration High precision instantaneous torque estimator is performed with the help of line-to-line back EMF acquirement, and hall sensor position calibration & compensation. Instantaneous Torque controller accurately controls the torque through conduction and commutation region controller. High torque in the conduction region is achieved by means of PI controller, asymmetry compensation function, and Back EMF feed forward control. The torque ripple in commutation is reduced by controlling the outgoing phase which is enabled by state judgment. The o/p of commutation ripple controller is used to regulate the three phase inverter during commutation its control frequency is high to avoid ripples.

TORQUE CONTROL

The speed to torque relation of BLDC Motors, there are two torque parameters used to define a BLDC motor, peak torque (TP) and rated torque (TR). During continuous operations, the motor can be loaded up to the rated torque. In a BLDC motor, the torque remains constant for a speed range up to the rated speed. The motor can be run up to the maximum speed, which can be up to 150% of the rated speed, but the torque starts dropping off.

Direct Torque Control

The basic principle of DTC is to directly select stator voltage vectors according to the torque and flux errors which are the differences between the references of torque and stator flux and their estimated values.

The governing equation for torque for this scheme is due to the interaction of stator and rotor fields. Torque and stator flux linkage are computed from measured motor terminal quantities i.e. stator voltages and current.

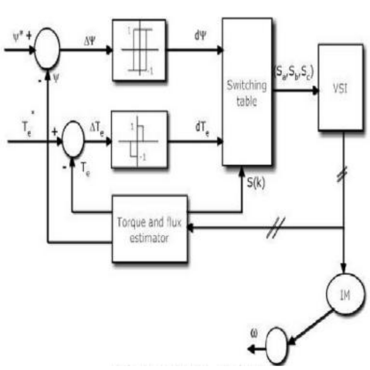

Fig.1 Direct Toque Control

An optimal voltage vector for the switching of VSI is selected from the six nonzero voltage vectors and two zero voltage vectors by the hysteresis control of stator flux and torque.

Flux Control

Field Oriented Control is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. This control does not need co-ordinate transform, voltage modulator block, as well as other controllers such as PI for flux and torque. Even this method is better than the vector method because its torque response time minimum.

The way to impose the required stator flux is by means of choosing the most suitable Voltage Source Inverter state. The reference values for the flux stator modulus and the torque are compared with the actual values, and the resulting error values are fed into the two-level and three-level hysteresis blocks respectively. The outputs of the stator flux error and torque error hysteresis blocks, together with the position of the stator flux are used as inputs of the look up table. The position of the stator flux is divided into six different sectors.

The stator flux modulus and torque errors tend to be restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band affects basically to the stator-current distortion in terms of low order harmonics and the torque hysteresis band affects the switching frequency. Once the speed is high, then the angle of the stator flux increases fast. Under these circumstances, states that are supposed to increase the torque do it in a very small quantity.

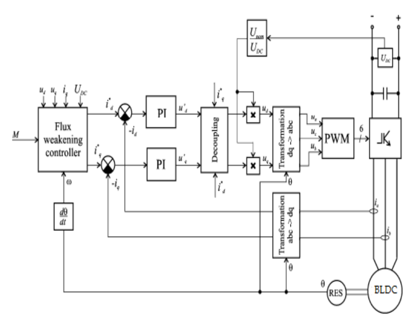

Fig.2 Flux Control

IMPLEMENTATION OF INSTANTANEOUS CONTROL

Instantaneous torque control would in principle permit the fastest possible response and the elimination of torque ripple, along with many other advantages not possible with conventional control algorithms, most of which are set up to control a time-averaged torque.

Torque Controller

In the instantaneous torque control, torque is regulated by controlling the instantaneous phase currents. The reference torque is converted to equivalent reference phase currents so that they can be tracked in the inner current control loops. By using the phase current profiling technique, optimal phase torques corresponding to torque sharing functions can be generated and, ultimately, torque ripples can be minimized. Various methods of torque ripple-minimization using instantaneous torque control have been successively proposed in the last three decade. However, torque-to-current conversion in BLDC is complex and becomes non-trivial due to their nonlinear relationship. Analytical expression of such conversion is complicated and leads to intensive on-line computation. On the other hand, the current profiles can be pre-calculated and pre-stored in the controller memory.

The main of instantaneous torque control characteristics are: the instantaneous torque (which can be estimated from motor terminal quantities) is considered directly as a control variable, torque-to-current conversion and closed-loop control of phase currents are no longer required. As the instantaneous torque is considered directly as a control variable, instantaneous torque control encounters the torque error instantaneously with fast dynamic response and effectively minimizes the inherent torque ripple. The Instantaneous torque control scheme also eliminates the use of current controllers.

PID Controller:

A proportional integral derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable. So, that the system can adjust the process accordingly. The general structure of PID controller is given below.

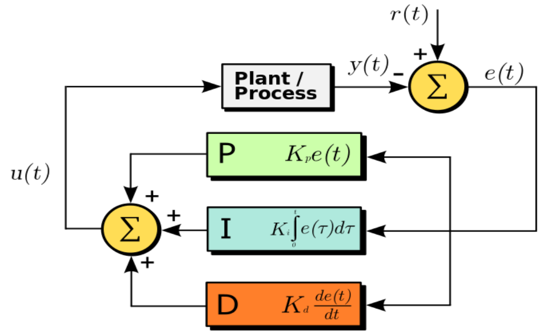

Fig. 3 structure of PID Controller

For PID control the actuating signal consists of proportional error signal added with derivative and integral of the error signal. The transfer function for the above block diagram i.e. for PID controller is given as,

$$G_{PID} = k_p \left(1 + s k_d + \frac{k_i}{s} \right)$$

Where, 'K_p' can be represented as proportionality gain, and 'K_i' as the integral gain constant. The 'n' proportional control the actuating signal for the control action in control system is proportional to the error signal. The error signal is being the difference between the reference input signal and the feedback signal obtained from the output.

For integral control action the actuating signal consists of proportional-error signal added with integral of the error signal. By the help of an integrator, it reduces the steady state errors through low frequency compensation. By the help of this integral term the actual variable will track the reference variable more quickly. As the integral of the error is used in actuating signal and as such if the error varies with time, then in that case the integral control reduces the error.

Back EMF Feed forward control:

The sensor-less speed and position estimation gets divided into two basic which is Sensing or measurement of back-emf from armature terminals and Back-emf observer based on mathematical equations describing motor behavior. A classical example of back-emf sensing based algorithm is 120 degree commutation or trapezoidal control of BLDC motor in which back-emf of non-energized phase is measured for rotor position. This helps to efficiently commutate the motor. The back-emf voltage is calculated indirectly by passing the error between actual measured current and estimated current through PI controller. As true with most sensorless schemes, the presented back-emf observer scheme is also sensitive to motor parameter variation especially to armature resistance. The unbalance ripples are reduced by the proposed asymmetry compensation function and the disturbance ripple created by the back EMF is compensated by feed forward control. Second, the disturbance torque has been observed and compensated through the improved disturbance torque controller.

Torque Estimator

The methodology for detecting absolute position of a BLDC motor using inexpensive analog Hall sensors and allow computation time algorithm to extract position information. Further, this algorithm can be implemented in tandem with simple block commutation, sinusoidal commutation, or direct torque control.

Hall Sensor: The main components of the method consist of mounting the sensors in a regular pattern around the motor. One sensor is required per coil.

The sensors are simply measures field strength in a linear axis nearly orthogonal to the coil field. This can be verified theoretically and experimentally. The other implication of this is that the orientation of the Hall Effect sensors relative to the coils and rotor magnets must be carefully determined in order to avoid interference from the time-varying magnetic field generated in the coils. The reluctance of the air is far higher than the reluctance of the motor components, so most of the flux field density due to coil currents remains within the motor.

By measuring the analog Hall sensor signal directly, a high resolution rotor position can be extracted from that data. The notion of extracting an angular position from sinusoidal waveforms in general is not new. The concept is that of an older technology – the resolver. However, the present application differs in that the sensor and actuator are integrated and the measurement repeats with every electrical cycle.

Lint-to-line Back EMF: To eliminate the low-frequency torque oscillations, two actual and easily available line-to-line back EMF constants (k_{ba} and k_{ca}) according to electrical rotor position are obtained offline and converted to the dq frame equivalents. Coordinate transformations are done by the new line-to-line transformation that forms a2×2 matrix instead of the conventional 2 × 3 matrix. Therefore, rather than three line-to-neutral back EMF waveforms, in the motor easily accessible two line-to-line back EMF constants (kba(θre) and kca(θre)) are obtained offline and converted to the dq frame equivalents(kd(θre) and kq(θre)). The electrical rotor position is estimate during winding inductance and stationary reference frame stator flux linkages and currents.

SIMULATION RESULTS

The simulation was performed with conventional six switches fed BLDC motor. In order to get 120º square wave phase currents, two switches are turned on at a time. The hall sensors mounted on the motor shaft gives the information of rotor position. The parameters of the BLDC motor used for simulation are listed in table below.

The proposed DTC system structure also has resistant to changes in motor parameters as conventional DTC due to use of any additionally motor parameters. So, the proposed DTC system can easily applicable every size of motors. The simulation results validate that fuzzy logic based control strategy for stator flux optimization can be successfully cooperated with conventional DTC scheme and achieves a reduction of torque ripple.

Fig.4 Hardware Diagram

TABLE I

Parameters of the BLDC motor

Motor parameters	Motor characteristics Values(units)
Terminal resistance	0.323 Ω
Terminal inductance	0.389 mH
Voltage constant	6.99 V/ k rpm
Electrical time constant	1.205 m-secs
Rotor Inertia Jm	0.142e-3 Kg.m2
No load speed	3434 rpm
No load current	1.24 A
Rated Power	123W
Number of poles	8
Number of phases	3

Table.1 Motor Paramaters

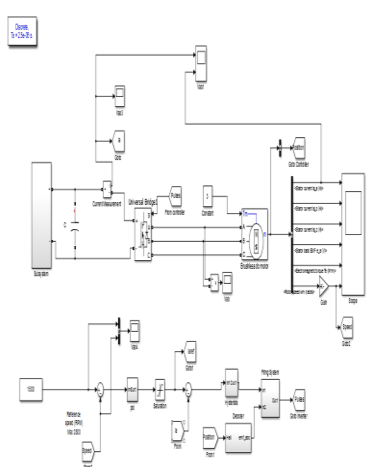

Fig.5 Simulation Diagram

The output ofBUCK BOOST converter waveform is shown below. In order to validate the performance of the brushless dc motor with proposed dc to dc BUCK converter, a simulation model is developed. The simulation is performed with MATLAB Simulink.

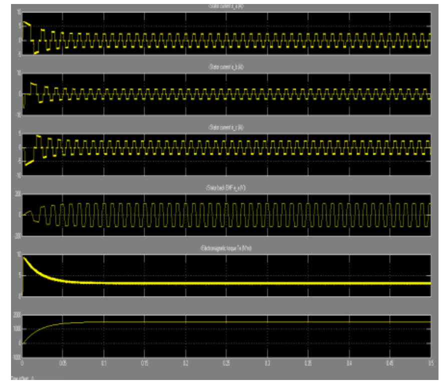

Fig.6 Simulation output

Some applications, such as an automobile (Windscreen wiper), require the motor to have a fairly constant speed for different loads. DC motors such as shunt and compound work reasonably well in these applications, but a BLDC with a PI controller improves the performance. The speed vs. torque and 10 show that the speed remains virtually constant across the torque range. These curves are more similar to a separately excited DC motor, but they are actually much better because of the feedback control.

CONCLUSION

The Various sensorless control techniques are being introduced and researched in order to replace the use of sensor control techniques in a BLDC system. By doing this, the cost of the system can be reduced and BLDC can be more affordable. Torque ripples due to phase current commutation is reduced by optimizing duty ratio of the active voltage vectors and by controlling error b/w command and estimated torque. Finally the instantaneous torque estimated with the help of line-to-line Back EMF acquirement, and hall sensor position calibration & compensation. With the help of PID controller and Back EMF feed forward control High torque in the conduction region is achieved. By controlling the outgoing phase current the torque ripple in commutation are reduced. This method of torque ripple reduction is analyzed and validated using MATLAB simulation results.

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