CHAPTER
1 INTRODUCTION

Human beings today, thrive for technological advancement in the field of electric drives. Electric motors being the heart of any industry, energy-efficient drives have become the need of today. The advent of power electronic converter technologies has made the use of permanent magnet motors popular in many applications. Earlier the motors used in textile industries and automation industries were three-phase squirrel cage induction motors because of rugged construction. Now-a-days they are replaced by permanent magnet motors due to the advancement in control techniques, reduced size of the motor with reduced copper losses. The Permanent Magnet (PM) motors available in two variants, popularly known as Permanent Magnet Synchronous Motor (PMSM) and Brushless DC (BLDC) motors. These motors had gained popularity in electrical drives owing to the amelioration in semiconductor switches with Very Large-Scale Integration (VLSI) technology which makes its operation smooth and provides an open path for variable frequency variable speed applications. Both motors have their rotor made up of base metal materials like Samarium Cobalt and Neodymium magnets. The discrepancy between the two lies in the stator winding current and the form of back emf. The control techniques used for motor control play a key role in the performance of the overall drive. The vector control techniques are generally used for PMSM motors with sinusoidal currents and back emf to provide constant torque operation and are modelled and implemented using the Park transformation theory. Contrarily, the BLDC motor stator is wound with three-phase concentrated winding to produce trapezoid back emf and quasi square wave currents with only two phases conducting at a time. The Clarke transformation or abc reference frame theory is used for its modelling and implementation. Pulsating torque is produced due to quasi-square wave currents and non- sinusoidal back emf. The BLDC motors possess greater torque to weight ratio, improved efficiency due to the absence of rotor copper losses, and reduced maintenance due to electronic commutation which makes them suitable for applications like electric vehicles, aerospace, medical equipment, textile industries, air conditioners, PCs and many more is quoted by [1-4]. The only disadvantage for BLDC motor is slow dynamic response and increased torque ripple which can be overcome using advanced control techniques for its operation.

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The closed-loop control of the BLDC motor improves the performance of the drive which provides the scope of controlling the output by comparing it with the reference quantity. Mainly, the BLDC motor performance is bounded by the use of (i) Hall Effect Sensors(HES) (ii) torque pulsations. The hall sensors help to perform easily the closed-loop operation with the added cost. The performance of the BLDC motor can be enhanced by eliminating these sensors for cost reduction and increased reliability. The sensorless control is the only feasible choice for applications that require high performance and are operated in a barbarous environment. Various sensorless techniques have been discussed in [5] to eliminate the position sensors to increase the reliability of the drive. The disadvantage with the sensorless drive is increased control complexity to operate the drive with closed-loop control. The BLDC motor control requires the use of position sensors, such as shaft encoders or HES to detect the permanent magnet rotor position. These hall sensors enable the motor operation with closed-loop control without any complexity. The disadvantage with this sensored drive is that it completely relies on these sensors which are highly affected by environmental conditions such as dust, moisture, vibrations, etc.

Despite the many advantages of BLDC motor such as lack of periodic maintenance due to absence of brushes and mechanical commutator, low mechanical wear out, reduced copper losses, etc over to DC motor [1-4], the BLDC motor performance is bounded by the torque pulsations. This torque pulsation affects the use of the BLDC motor for applications where precise control is required. In BLDC motor, with two-phase operation(2-ΦO), only two phases are conducting at a time. The variation in the rise and fall rate of the incoming and outgoing phase current results in dips in the commutation torque. To generate constant torque the turn on and turn off of the incoming and outgoing phase should be equal which results in smooth torque at every commutation interval has been discussed in [5][6][11]. In the BLDC motor drive the phase current which is the quasi square wave in nature should be in phase with the trapezoidal phase back emf. But, due to motor dynamics, there is a mismatch between the back emf and phase current resulting in the production of torque ripple is given by [6-9]. Torque ripple in BLDC motor appears due to the structure of motor, control techniques used to drive electronic commutator, and controller design. Cogging torque and commutation torque are the two types of torque produced in BLDC motors. Cogging torque ripple is originated due to the variation in reluctance due to the change in airgap length between the stator slot openings and the permanent magnet rotor as the rotor rotates. This type of torque ripple can be reduced by undergoing changes in the motor design such as: by skewing the stator slots, using fractional slot winding design, or by choosing a width of the magnet relative to the slot pitch as suggested by[10]. The torque pulsation affects the use of the BLDC motor for applications where precise control is required.

1.1 State of art

The BLDC motor performance with quasi square wave currents and trapezoidal back emf is mainly affected by the torque ripple. The torque ripple in BLDC motor is produced mainly due to the three components (a) Structure of motor (b) Nature of motor and (c) Control of motor.

a) Structure of motor: The structure of the particular motor depends upon its design parameters such as shape, specific loadings, rating, speed, dimensions, etc. Choice of specific loading affects the motor design and as per its application considering the cost factor.

b) Nature of motor: The behavior of motor can be known from the parameters and characteristics of the material used in its manufacturing. The selection of proper material also leads to improved performance of the motor.

c) Control of motor: Various control techniques have been introduced to mitigate torque ripples. By proper selection of the control technique, better performance of the motor under steady-state as the well transient condition can be achieved.

A highlight of various torque ripple minimization techniques to enhance the motor performance from the motor control side is provided to improve the BLDC motor performance. The commutation in a BLDC motor disturbs the voltage of a non-commutated phase. This generates a dip in the non-commutating phase current resulting in torque ripple[9]. By improving the motor control techniques commutation torque ripple can be improved. To mitigate commutation torque ripple there are mainly four methods: (1) Direct Torque Control (DTC) and Field Oriented Control(FOC) to control the torque directly (2)Changing the input voltage (3)Current control techniques and (4) Employing advanced controllers.

1.1.1 Techniques for torque ripple mitigation

The BLDC motor performance is highly influenced by the torque ripple produced during its operation. Here, various methods are discussed for the reduction of torque ripple to improve the motor performance.

1.1.1.1 Field oriented control and direct torque control

Optimum torque control is obtained when the angle between the stator and rotor flux linkages is 90º. In FOC, the motor current and voltage vectors are obtained from the calculation based on current feedback. The motor phase quantities (currents, voltages and flux) which are represented by space vectors can be controlled using FOC [12,13]. In this, the three-phase stator currents are transformed into two quantities (i) torque and (ii) flux. Both can be controlled separately. The various frame transformation in FOC is given by [13]. Using Clarke transformation one can convert the three-phase abc variables into two-phase α, β system. Then using Park transformation the α, β variables are transformed into d, q coordinate system, where the d-axis represent the motor flux and the q-axis represents motor torque. As compared to the Sinusoidal Pulse Width Modulation(SPWM) technique, the utilization of the bus voltage is efficiently done by the Space Vector Modulation Technique(SVM), which results in smooth motor performance.

The DTC as compared to FOC is achieving recognition due to its, non-complex control arrangement and easy operation. In DTC, the variation relating the set variable and the actual variable of flux linkage and torque is used to select the voltage vectors. The errors thus produced are given to the hysteresis controllers. The hysteresis controller processes the error with respect to the set value and based on its output a vector proportional to voltage is chosen from a look-up table. Using DTC, the electromagnetic torque and flux linkages can be directly controlled by the selection of the proper voltage vector from either six or eight sectors considered.[14] discussed the structure simplicity of DTC as no Pulse Width Modulation(PWM) and coordinate transformation is required.[15] compared DTC and PWM techniques for the performance of BLDC motor drives. Comparatively less low-frequency torque ripples are produced by direct torque control.[16] proposed a technique to minimize the error between commanded and estimated torque. A controller is designed to maintain the phase current near to the reference current to maintain constant torque to eliminate the commutation torque dips at high speeds. A DTC for BLDC motor drive to eliminate torque ripple has been suggested by[17]. A DTC for BLDC motor with non-sinusoidal back emf using a four-switch inverter is proposed by [18-19]. The proposed technique gives improved torque response for non-ideal trapezoidal emf waveform with the elimination of torque oscillations at low frequency. The author [20] suggested employing direct torque control to maintain constant current by controlling the torque. This can be done by measuring the back emf and phase current. A comparison between two-level and three-level flux controllers is provided by [21]. It is suggested that by using a flux comparator of three-level for direct torque control there is a considerable reduction in torque ripple harmonics.

1.1.1.2 **Dynamically changing the input voltage**

Similar to the DC motor the speed of the BLDC motor is directly proportional to its terminal voltages. Unlike the DC motor, the conventional commutator is replaced by an electronic commutator. For the BLDC motor, a 3-phase voltage source inverter is used to provide electronic commutation. The Voltage Source Inverter (VSI) controls the current in the three phases of the motor using the exact rotor position derived from the hall sensors or some sensorless control technique. The two methods commonly used for controlling the inverter output are variable DC link voltage control and PWM switching technique. [22] compared the above two methods for high-speed sensor less control of BLDC motor to obtain performance comparison of VSI.

1.1.1.2.1 Various PWM schemes

The commutation of the BLDC motor occurs every 60º causing a jump in the stator magnetic field. This results in six torque ripples for every 360º electrical due to the occurrence of six current transitions. A jump in the stator magnetic field produces torque ripple. The torque ripple produced due to the mismatch between the stator and rotor magnetic field can be reduced by a control algorithm using the PWM technique is given by [23]. As at any time only two phases are conducting, the freewheeling of the diode in the inactive phase causes torque ripple. A new PWM technique (PWMONPWM) is proposed by [24] in which the conducting device of the electronic commutator is operating in the PWM mode during the first 30˚ and the last 30˚ of the half-cycle, and is in continuous ON state in the middle 60˚ of the half-cycle. The author [25] had discussed the influence of PWMON, ONPWM, H_PWM-L_ON, H_ON-L_PWM techniques in sensorless BLDC motor. This technique not only reduces the switching losses but results in reduced torque ripple. The effect of the outgoing phase's back emf on current and the current produced by phase inductance is identified by [26-27]. The work reported how the back emf of the outgoing phase is affected by operating the motor using the PWM mode technique. Two methods are proposed by [28] at higher speed for reducing the effects of commutation torque ripple. As the delay in current is caused by torque dips of the next in-coming phase before the current in the out-going phase has perished to zero. The proposed method makes an effort to remove this delay by giving the incoming phase an advance lead in building up the current. The torque dip reduction method introduces modulated pulses during the intervals when each motor phase usually will not be carrying any current. Due to this effect, the current flows all together in all three phases of the motor, which allows the building up of current gradually in each in-coming motor phase as per commutation logic obtained from rotor position during high-speed operation. For very small motors, he proposed a pulse width chopping method to reduce ripple in torque during commutation. By comparing both the methods he concluded that the pulse width chopping method has lower torque variation as compared to the current prediction method. An efficient and cost-effective digital pulse width modulation control scheme for BLDC motor is suggested by [29]. He used the concept to develop a low-cost controller which can replace the single-phase induction motor with a BLDC motor for certain applications.

1.1.1.2.2 Variable DC-link Voltage

A DC-link voltage control is proposed in [30] using a buck converter to reduce the commutation torque ripple. In this method, the torque ripple was reduced only at low speed as the bandwidth of the converter was not considered. The author [31] proposed a super lift Luo topology circuit for high-speed operation with a more complex and proficient structure to produce desired dc-link voltage. The work presented by [32] employed a SEPIC topology circuit to control the dc-link voltage with additional three switches and their resultant inductances, capacitances, and diodes. A method of varying the input voltage to reduce the torque ripple in the conduction region by maintaining the current in the conduction region is reported in [33]. A cascaded buck converter method is also suggested to eliminate torque ripple in the conduction region.

1.1.1.3 **Current control techniques**

An improved predictive current control method is presented in [34]. Using this method the torque and current dips are suppressed during commutation intervals. He had drawn the following conclusion: the ripple in torque is declining during the commutation conditions at low speed, during high speed, the torque tipple is rising, the ripple in the torque is nullified when the speed of the rotor is equal to $U_d/4\Psi_m$ where U_d is the supply voltage and ψ_m is the flux linkage which is directly proportional to the back emf. A new technique is suggested in [35] for equalizing the slope of two currents during commutation. This method removes torque ripple over a wide range of values below the present limit point. V= 4E. The proposed technique is developed for modes two, four, and six, with the developed relations being the same for all other modes. A novel technique is proposed in [36] to cancel the pulsating torque ripple component in the phase current by using programmed excitation waveforms. In this method, each phase current waveform is programmed as predictive functions of the reference torque and rotor position to generate the desired average torque which cancels the pulsating torque components. [37] proposes a torque management method for BLDC motors with non-ideal back emf waveforms to minimize torque ripple. The action time of pulses is calculated regarding actual back emf waveforms and the influence of finite dc bus supply voltage is considered in the commutation period. In the experiments, two current sensors and one voltage sensor were used. DSP TMS320F240 is used to make the torque feedback follow the torque reference. For low-speed situations, a Four Switch Three Phase Inverter (FSTPI) BLDC motor drive using the direct phase current (DPC) control approach with two current sensors may effectively regulate the currents. As a result, the current and torque have no more ripple than the hysteresis band. However, according to the author [38], the DPC control strategy is unable to eliminate commutation torque ripple at high speeds. Advanced controllers help in speed control and torque control of BLDC motors. Conventional Proportional & Integral (PI) and Proportional Integral & Derivative (PID) controllers are commonly used in industries according to the applications due to their simple operation and control[39]. In linear system design, tuning of the PID controller is easy and results in better performance of the designed model. But, for nonlinear system design such as closed-loop control of BLDC motor drive, the tuning of PID controller is difficult and results in poor performance of the drive is quoted in [40]. It is suggested in [41] that the use of smart controllers like Fuzzy Logic Controllers (FLC) will result in improved performance of the BLDC drive. It finds many advantages compared to conventional PID controllers. By using linguistic rules the controller can be developed without requiring any mathematical expressions. This makes the implementation of the controller easy. The optimal control techniques have achieved a major relevance in contemporary brushless DC motor speed control developments as an instrument for coping with the increasing problem complexities and as a methodological tool for design techniques systemization. A class of this optimal control approach that has received a wide acceptance is the H_2/H_∞ norm minimization is discussed in [42-43]. In particular, the H_∞ norm-based optimal control method facilitates the incorporation of the performance objectives into control design problems by defining appropriate weighing functions. The Genetic Algorithm (GA) based best possible parameter search algorithms contrasting other gradient-based searching algorithms will not assume the parameter space as differentiable and there is very little probability that the search may be trapped in the local minimum is proposed in [44-45]. The GA approach is based on the natural phenomenon which is said to be the survival of the fittest in a tough environment. To solve complex design problems it uses direct correlation to do global optimization as suggested in [46]. The controller must be adaptive to the changes that appear in the drive's dynamic characteristics to obtain improved performance. Due to this GA has found its interest in various drives applications to achieve high efficiency and provide global optimal solutions in problem space such as the search of optimal PI controller parameters presented in[47]. An Artificial Neural Network (ANN) and a Model Reference Adaptive System (MRAS) are used for finding a zero-crossing of back emf in sensorless BLDC motor in which the performance of the estimation is based on the properties of the motor [48]. The relation between the size of back-EMF voltage and the motor speed is applied to control the speed of the motor using FLC in a high-speed range (more than 10,000 rpm) is suggested in [49]. The ANN is deployed to estimate the back emf from voltage and current of each phase in the low-speed range is conceptualized in [50]. The interior-loop current control and load disturbance rejection is discussed by [51] using a Sliding Mode Control(SMC) technique for speed control of BLDC motor. Discrete Wavelet Transform (DWT) is a useful tool to detect the disturbances of time-varying signals. As the induced emf has an irregular shape in the commutation region and input current would carry the hidden properties of back emf and other signatures of rotor position. The wavelet theory is applied to detect these signatures and deduce the de-noised rotor speed as well as acceleration. The number of peak appearing in wavelet is the unique feature for transient classification is proposed in [52]. If the right values of the controller tuning constants are not employed, the control structure performs poorly in terms of characteristics and even becomes unstable. As a result, it becomes required to tweak the controller parameters in order to achieve good control performance, as recommended in [53]. The Particle Swarm Optimization (PSO) and Bacterial Foraging (BF) techniques are used to find the optimal values of parameters Kp, Ki, and Kd for the PID controller of the BLDC motor speed control system. By comparing PSO method with the BF technique, it seems that the PSO method can improve the dynamic performance of the system in a better way is reported in [54].

1.2 Objective and scope of work

The objective of the research is as follows:

To investigate the issues related to BLDC motor performance, various control techniques for torque ripple mitigation and analyze the effect of speed on the commutation torque ripple when operating the motor with conventional six-step control, hysteresis current control technique with two phase operation (2-ΦO), twelve-step direct torque control with two and three phase operation (2-3ΦO) hence, devise a control strategy with three phase operation (3-ΦO) for improved BLDC motor performance with reduced control complexity. Further, the control scheme must ensure improved DC bus utilization, torque ripple attenuation, and reduced stator copper losses for the BLDC motor besides providing the closed-loop speed control under varied speed and load conditions as compared to conventional six-step control.

Following objectives are achieved in the proposed research work reported in the thesis are:

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1. To analyze the phenomena of current commutation with 2-ΦO responsible for the generation of commutation torque ripple with variation in motor speed using conventional Six-Step Control (SSC) of BLDC motor.

2. Modeling of hysteresis current controller for closed-loop speed control of the BLDC motor is carried out to investigate BLDC motor performance with 2-ΦO.

    - A Hysteresis Current Control Technique (HCCT) is employed to validate the BLDC motor model with closed-loop speed control.
    - The interior current loop and exterior speed loop ensure correct commutation logic for the electronic commutator.
    - Control strategy ensures a simple closed-loop speed control with only two-phase conduction.
    - Validation of simulation results utilizing the hardware implementation for closed-loop speed control operation of BLDC motors using hysteresis current control technique.

3. Modeling of Six-Step Direct Torque Control (SSDTC), Modified Six-Step Direct Torque Control (MSSDTC), Twelve-Step Direct Torque Control (TSDTC), and Modified Twelve Step Direct Torque Control (MTSDTC) technique for closed-loop speed control of the BLDC motor is carried out to investigate BLDC motor performance with 2-3ΦO. This technique ensures reduced switching losses and commutation torque ripple with improved motor performance.

    - A Conventional SSDTC and MSSDTC technique is developed and analyzed with MATLAB®/SIMULINK for closed-loop control of BLDC motor with 2ΦO. The MSSDTC technique reduces the switching losses and improves drive efficiency.
    - A TSDTC technique is developed and analyzed with MATLAB®/SIMULINK for closed-loop control of BLDC motor with 2-3ΦO. It incorporates the switching of the third switch in the commutation region by the selection of the appropriate voltage vector thereby reducing the commutation torque ripple compared to conventional SSDTC operation.

- A MTSDTC technique with ONPWM and PWMON is proposed (referred to MTSDTC PWMON and MTSDTC ONPWM) where PWMON stands that the upper and lower switches are provided with pulse width modulated pulses for 60^{0} and the switches are in continuously ON state for rest 60^{0} during the 120^{0} conduction period and vice-versa for ONPWM). The MTSDTC ONPWM and MTSDTC PWMON techniques are developed and analyzed with MATLAB®/SIMULINK for closed-loop control of BLDC motor with 2-3ΦO.
- The MTSDTC ONPWM technique ensures reduced commutation torque ripple as compared to all the above techniques with reduced switching losses. A comparative analysis of all the DTC techniques is presented which provides the best DTC technique to improve the BLDC motor performance in 2-3ΦO.

4. Modeling of Modified Sinusoidal Pulse Width Modulation (MSPWM) technique is proposed for closed-loop speed control of the BLDC motor to investigate BLDC motor performance with 3ΦO.

- A MSPWM technique is developed and analyzed with MATLAB®/SIMULINK for closed-loop control of BLDC motor with 3ΦO. It incorporates the generation of a three-phase modulating reference wave which are compared with the triangular carrier signal to produce the switching signals for the three-phase inverter acting as an electronic commutator.
- The proposed control scheme introduces sinusoidal currents with trapezoidal back emf to improve BLDC motor performance. The effectiveness of the MSPWM technique is verified by analyzing its performance with conventional SSC.
- The comparison of the proposed technique with conventional SSC provides improved DC bus utilization, reduced stator copper losses, and reduced commutation torque ripple. The commutation torque ripple attenuates up to 50% with the proposed technique than the conventional SSC.
- The hardware implementation for closed-loop speed control of BLDC motor using MSPWM validates the simulation results.

5. The comparison of the proposed approaches for torque ripple attenuation for BLDC motor with the existing 2-ΦO, 2-3ΦO and 3-ΦO is provided to prove the effectiveness of the proposed technique.

1.3 Thesis Organization

A brief description of the research work reported in the thesis is given below:

Chapter 1: This chapter provides a brief introduction of the BLDC motor with a comprehensive survey based on the issues related to motor performance and a review of various control techniques used for motor speed and torque control. The motivation and objective behind the research are deduced and a road map of the thesis organization is provided.

Chapter 2: In this chapter, a mathematical model of BLDC motor is developed using the motor dynamic equations. Analysis of the phenomena of current commutation with 2-ΦO responsible for the generation of commutation torque ripple with variation in motor speed with conventional SSC of BLDC motor closed-loop control is provided which leads to the requirement of the BLDC motor operation with 2-ϕO, 2-3ϕO and 3-ϕO.

Chapter 3: This chapter provides a detailed discussion on modeling and analysis of the HCCT for closed-loop control. Simulation of 2-ϕO of BLDC motor using HCCT using MATLAB®/SIMULINK. Validation of the simulation results is carried by implementing the HCCT on a prototype BLDC motor using the STM32F407VG ARM controller.

Chapter 4: This chapter provides a detailed discussion on modeling of DTC technique for closed-loop control, simulation of conventional SSDTC, MSSDTC with 2-ϕO, TSDTC with 2-3ϕO and MTSDTC technique with PWMON and ONPWM switching technique for reduced switching losses and torque ripple with 2-3ϕO using MATLAB®/SIMULINK. A comparison of the MTSDTC technique with PWMON and ONPWM with the other DTC techniques is performed.

Chapter 5: This chapter provides a detailed discussion on modeling of MSPWM using MATLAB®/SIMULINK. It provides comparison of the simulation results of the proposed MSPWM technique with conventional SSC of BLDC motor. The experimental verification of proposed 3-ϕO of BLDC motor using modified sinusoidal pulse width modulation technique is carried on a prototype BLDC motor using STM32F407VG ARM controller.

Comparison of the proposed control technique for torque ripple attenuation of BLDC motor with the existing 2-ΦO, 2-3ΦO and 3-ΦO is provided to prove the effectiveness of the proposed technique.

Chapter 6: It provides the summary, conclusions, and scope of future work.

The thesis ends with a complete Bibliography.