SYNOPSIS

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Degree for which submitted: Ph.D. Department: Electrical Engineering

Thesis Title: **Modified Sinusoidal Pulse width Modulation Technique for speed control of Permanent Magnet Brushless DC Motor**

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The global market today is heading towards advance permanent magnet motors as compared to the conventional DC and AC electric motors due to the advent of semiconductor devices. Around 60% of energy is consumed by electric motors used in industries. Energy efficient drives with improved performance is the universal demand. Generally the motors used previously in various industries were three phase squirrel cage induction motors because of rugged construction. Unlike DC motors, the BLDC motor do not require brushes and mechanical commutator. Nowadays the conventional motors are replaced by permanent magnet brushless DC motor (BLDC) due to the advancement in control techniques. The BLDC motor provides reduced maintenance, high torque to weight ratio, reduced copper losses, high power density with increase reliability, which makes it suitable for applications such as domestic, aircraft, automotive, medical, textile industry, military, spacecrafts etc.[1-3].

The closed loop control of BLDC motor improves the performance of the drive which provides the scope of controlling the output by comparing it with the reference quantity. This control helps to use the motor for wide range of applications. Mainly, the BLDC motor performance is affected by the use of (i) position sensors (ii) torque pulsations. The BLDC motor control requires the use of position sensors, such as shaft encoders or Hall-effect sensors (HES) to detect the permanent magnet rotor position. These hall sensors enables closed loop control of the drive without any complexity.

The disadvantage with this sensored drive is that it completely rely on this sensors which are highly affected by the environmental conditions such dust, moisture, vibrations etc with added cost. The performance of 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 which requires high performance and operated in barbarous environment. Various sensorless techniques have been discussed by [4] to eliminate the position sensors to increase the reliability of the drive. The disadvantage with the sensorless drive is increased control complexity required to operate the drive in closed loop control. (ii) the torque pulsation affects the use of BLDC motor for applications where precise control is required. Further, the effective performance of the electric motor can be achieved by two ways: a) by improving their geometry, and/or b) by modifying their control technique. The BLDC motor performance can be improved with improved stator slot design, winding design, choice of specific loadings, permanent magnet rotor design etc. The geometrical changes in the motor helps to reduce the cogging torque. 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 [5]. The finite element method is used for precise designing of the BLDC motor. The reluctance torque can be made ineffective with selection of surface mounted permanent magnet rotor. Since the BLDC motor is excited with quasi square wave currents and trapezoidal back emf with two phase operation (2-ΦO), it leads to commutation torque ripple due to finite winding inductance during commutation interval. The torque ripple increases with increase in speed of the drive which affects drive performance.

The BLDC motor stator wound with concentrated coils generates trapezoidal back emf in phase with quasi square wave currents. The rotor being a permanent magnet, it is important to know the rotor position for exciting the particular stator winding to procure synchronism between the stator and rotor magnetic field. The hall effect sensors are used for accurate position sensing. The BLDC motor has an arrangement of electronics commutator unlike the mechanical commutator required for the DC motor to supply the three phase stator winding resulting in reduced maintenance cost. The three phase inverter acts as an electronic commutator. At any instant of time with only two phases conducting, to ensure the correct rotation of the motor, the selection of the switching devices often known as commutation logic is of utmost importance. The speed of motor depends on magnitude of the applied voltage. Hence speed control with torque ripple attenuation can be achieved using various control techniques like current control, direct torque control, pulse width modulation control and field oriented control. For closed loop speed control operation, every time the motor speed is measured and compared with the set value to find the error speed. The error speed is processed in the PI controller, which in turn adjust the duty cycle to reduce error. The commutation logic circuit decides which of the two switches for two phase operation (2-ϕO) and three switches for three phase operation (3-ϕO) or combination of two-three phase operation (2-3ϕO) of the inverter bridge are to be switched on for proper commutation from the hall sensor signal.

The BLDC motor with trapezoidal back emf and quasi square wave currents is generally operated with 2-ϕO. The 2-ϕO requires three hall position sensor placed 120° apart on the stator rear end for detecting the exact rotor position. The BLDC motor with trapezoidal back emf and quasi square wave currents has six commutation instances in one electrical cycle. With only two phase operating at any time, the out-going phase current either decays at a faster rate or slower rate than the rise rate of the in-coming phase current due to the winding inductance resulting in the ripple in the non-operating phase current which is responsible for ripple in the motor torque. The back emf being directly proportional to the speed, at low speed its value being less is unable to decay the current instantly in the commutation region and during high speed operation, the value of back emf superimpose on the supply voltage which does not allow the incoming current to rise instantly, slowing down the rate in both the case which results in the occurrence of more intense commutation torque ripple at high speed.

The commutation of PMBLDC 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 transition. 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 pulse width modulation (PWM) technique is suggested by[6].The commutation torque ripple is practically produced due to the abrupt changes in the incoming and outgoing phase currents in commutation region which is influenced by stator winding inductance. The detailed behavior of the inverter switches and diodes in the conduction and commutation region and its influence on commutation torque ripple is explained by [7]. The dynamic performance of the BLDC motor drive is analyzed using an advanced simulation model is proposed by [8-9] with a switching function concept for three phase inverter using hysteresis current control technique. To reduce the commutation torque ripple, a closed loop hysteresis current control technique with a inner current control loop and outer speed loop is developed to reduce the current spike which in turn reduces the commutation torque ripple. The closed loop speed control of BLDC motor using hysteresis current control technique is developed in MATLAB/Simulink. The modeling consist of a generation of back emf, three phase current, motor torque, speed control and three reference currents. The inner current loop is incorporated using hysteresis current controller which provides the switching logic for the three phase inverter and outer speed control loop using a PI controller. The three reference currents are compared with the actual currents using a hysteresis current controller within a narrow hysteresis band. If the error is greater than the hysteresis band upper switch is ON and if error is less than the hysteresis band lower switch conducts to produce pulse width modulated gate pulses for the three phase inverter. A PI controller process the error produced by comparing the actual motor speed calculated from the rotor position with the reference speed to generate reference torque. The simulation results obtained using hysteresis current control technique are validated by implementing it on a prototype 36 volt, 4 pole BLDC motor.

The main flaw with 2-ϕO is surge in commutation torque ripple at high speed restricts the use of BLDC motor in certain applications which require a precise control [7]. In order to obtain optimum torque control the angle between stator flux linkage and rotor flux linkage should be 90° as given by $T_m = K_t |\psi_r||\psi_s| Sin\theta$, where, K_t is the torque constant, ψ_r is rotor flux linkage, ψ_s is the stator flux linkage, θ is the torque angle between the stator flux linkage and rotor flux linkage .The electromagnetic torque can be controlled effectively by controlling the amplitude and/or the rotational speed of stator flux vector (ψ_s). For DTC of BLDC motor in two phase conduction, a change in the torque can be achieved by keeping the amplitude of the stator flux linkage constant and increasing the rotational speed of the stator flux linkage as fast as possible. This helps to reduce the complexity of the drive. For this six/twelve active voltage vectors have to be defined for proper commutation of three phase stator winding as per the requirement of six step DTC or twelve step DTC technique.

DTC has found its impact in many industrial applications as well as in automotive industry due to its simple structure, no complex coordinate transformation requirement, less parameter dependency, no requirement of current regulator and fast torque response. The idea of DTC was first developed by [10] and [11] in the mid 1980s for induction motor drives. A DTC technique for BLDC and BLAC motor is proposed by [12] which implies the capability of DTC technique for instantaneous torque control. Two phase conduction is incorporated for BLDC motor and three phase conduction for BLAC motor. A direct torque control (DTC) technique with two phase conduction is suggested by [13] by designing a look up table for selection of voltage vectors operating the drive in constant torque region to eliminate the flux control as compared to the three phase DTC technique. An improved six step DTC technique with gating signals resembling unipolar PWM-ON technique over conventional six step DTC technique with reduced switching losses and improved motor performance is suggested by [14]. A hybrid two and three phase switching mode(2-3ϕO)DTC technique is proposed by [15] for high speed operation to reduce the distortion of electromagnetic torque which produces torsion vibration to improve the reliability of the motor. The three phase switching operation is suggested in the commutation region with positive torque error to equalize the rise rate and fall rate between the incoming and outgoing current. A two phase switching is incorporated with negative torque error in the commutation region apart from its operation in conduction region. To improve the reliability of the drive, [15,16] proposed a DTC technique using the null vectors for motor operation with the negative torque error for clockwise and anticlockwise motor operation in the conduction region and three phase switching mode with a three level torque controller for sector to sector transition for positive torque error. This method provides an equalized switching frequencies between the upper and lower switches of the three phase inverter bridge and eliminate the common mode voltage (CMV). The overlap region angle in the commutation region is not mentioned by [16-17]. The twelve step DTC technique with 2-3ϕO is discussed by [18], which allows the conduction of the third switch in the overlap region based on the selection of overlap angle depending on the applied load and speed of the motor**.**

To overcome the drawbacks of conventional DTC with 2ϕO, the proposed DTC technique with 2-3ϕO is developed to reduce the commutation torque ripple in the commutation region. In one electrical cycle, two phase conduction is used in the conduction region and three phase conduction is incorporated in the commutation region. This technique helps in minimizing the commutation torque ripple. Though the computational steps increases with this type of hybrid operation making the drive operation complex with reduced the commutation torque. By reducing the diode conduction time, the positive and negative ramp in the non-commutating current can be reduced to zero. This can be done by switching ON the third switch in the commutation region with three switch conduction. A modified twelve step DTC technique is developed to reduce the diode conduction to a great extent. This method requires the phase transformation from abc to αβ, torque and flux estimation, sector selection. By using Clarke transformation the three phase abc variables of voltage, current and back emf are converted to two phase αβ system. In Direct Torque Control (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 process the error with reference to the set value and based on its output as only two phases are conducting at any instant, the electromagnetic torque and flux linkages are directly controlled by selection of the proper voltage vector from a look up table. For twelve step DTC control, twelve voltage vectors for one electrical cycle are defined for the conduction region and commutation region comprising of six vectors for conduction region and six for commutation region. An overlap region is considered during the sector transition.

Based on the location of the reference vector, particular voltage vector is selected to produce optimum torque. The phase voltages V_{an}, V_{bn}, and V_{cn} are determined by the status of the six switches, S1, S2, S3, S4, S5 and S6. For this six non zero voltage space vectors are defined for BLDC motor. These voltage vectors are 60º apart. They are V1(100001) which represents, S1 and S6 are ON; V2(001001) i.e S6 and S3 are ON; V3(011000) i.e S3 and S2 are ON; V4(010010) i.e S2 and S5 are ON; V5(000110) i.e S5 and S4 are ON and V6(100100) i.e S4 and S1 are ON. In SSDTC only two switches are conducting in conduction as well as commutation region at any time. On the contrary, in TSDTC , to reduce torque ripple produced in the commutation region due to the mismatch in the slope of decaying current and incoming current, a third switch is made ON in the overlap region. Six voltage vectors in the overlap region are defined as V12(101001),V23(011001),V34(011010),V45(010110),V56(100110),V61(100101). In This reduces the equivalent winding inductance which results in reduced current ripple and hence torque ripple. For positive torque error, voltage vectors responsible for increasing the rotational speed of stator flux vectors in counter clockwise direction are selected for the six sectors and overlap regions and for negative torque error, flux vectors rotating in clockwise directions are selected.

The modified twelve step DTC (MTSDTC) technique with PWM_ON control and ON_PWM control is developed to reduce commutation torque ripple and the switching losses as compared to the TSDTC, SSDTC and modified SSDTC using MATLAB/Simulink. In the proposed technique, for negative torque error null vectors are considered for both the conduction and commutation region which results in reduced torque ripple with improved motor performance and reliability. The result analysis obtained clearly indicates reduced torque ripple with the proposed MTSDTC ON_PWM technique as compared with TSDTC technique.

To further enhance the BLDC motor performance, a 3-ϕO approach leads to improved motor performance with reduced commutation torque ripple at high speeds during which the commutation torque ripple becomes prominent. The control techniques used for 3ϕO requires shaft encoders or rotor position algorithm for obtaining continuous rotor position instead of hall effect sensor. The field oriented control (FOC), space vector modulation (SVM) technique are the likely control approach used to enhance the motor operation with improved drive efficiency. [19] focused on the modulation index(MI) which is said to be determining factor for the PWM techniques. The maximum MI obtained using sinusoidal PWM (SPWM) technique is 0.785 when a sinusoid reference signal is compared with a ramp signal. A flat toped reference signal whose peak value is less than fundamental can be generated by a adding third harmonic to obtain higher value of MI. [20] suggested that for all ranges of speed, the performance of the drive with sinusoidal supply currents outlays the drive performance using quasi square wave currents. The comparison of sinusoidal currents and square wave current at different speed is analyzed. The space vector modulation technique (SVM) is used to produce sinusoidal current to prove the performance improvement of the BLDC motor drive with respect to the conventional operation with square wave current. The BLDC motor when operated with modified sinusoidal PWM technique has 6 N harmonic torque instead of pulsating torque and the torque ripple are reduced up to 50% than conventional six-step control is suggested by [21]. The closed-loop operation is not performed which shows poor dynamic response of the drive which limits its application. The BLDC motor operating with any type of back emf whether sinusoidal or trapezoidal, the stator copper loss is increased by 10.2% when operated with quasi square wave currents as compared to the vectorial waveform currents as the RMS value of square wave current is greater than the vectorial currents is proposed by[22]. The sinusoidal currents with trapezoidal back emf for BLDC motor are most suitable for high speed operation of the drive is pointed out by [23].

The commutation torque ripple produces adverse effects on motor performance like jerks, unwanted noise, vibrations, etc. A modified sinusoidal pulse width modulation (MSPWM) technique is developed in MATLAB/Simulink with reduced complexity as compared to the FOC and SVM to improve motor performance and to reduce the commutation torque ripple as compared to the 2-ϕO is proposed. The proposed modified sinusoidal pulse width modulation (MSPWM) technique leads motor control in three-phase conduction mode(3-ϕO), which naturally offers three-phase conduction during commutation interval to reduce commutation torque ripple in BLDC motor. The proposed technique aims to develop closed loop speed control of

BLDC motor with reduced stator copper loss and torque ripple along with increased DC bus utilization by providing sinusoidal stator currents in synchronism with the trapezoid back emf.

In the proposed MSPWM technique, the BLDC motor with trapezoid back emf is operated with sinusoidal currents to generate optimal torque per ampere current. Maximum torque per ampere is produced when the rotor flux follows the stator flux by an angle of 90˚ termed as delta angle or load angle(δ). The stator flux is changed in accordance with the rotor position. The optimal delta angle (δ) is calculated by transforming the three phase stator currents in to rotating dq axis reference frame from abc reference frame using Park's transformation. The motor speed is calculated from the rotor position and compared with the quoted speed. The difference of the two speeds is fixed by a PI controller. The gain of controller controls the magnitude of the three phase voltages by the virtue of modulation index. Three-phase sinusoidal voltages are generated in the voltage generation block using the delta angle, modulation index and electrical rotor position. Three saddle shape modulating waves are generated which are matched with the triangular carrier wave to engender the gate pulses for the six inverter switches by the PWM modulator block. As variation in speed is in straight proportion to the applied voltage, motor control is inhibited by varying the duty cycle of the gate pulses. The simulation results of proposed MSPWM technique clearly indicates that the torque ripple are reduced by 50% with improved DC bus utilization as compared with conventional six step control. The motor dynamic response is improved using only one PI controller as compared to the FOC and DTC techniques which reduces the control complexity.

The simulation results of hysteresis current control technique (2-ΦO), proposed modified twelve step direct torque control technique with ON_PWM and PWM_ON control(2-3ΦO) and proposed modified sinusoidal pulse width modulation technique(3-ΦO) are validated through the experimental results to prove its effectiveness. The proposed concepts are validated in hardware prototype realized using ARM Cortex-M4 microcontroller. The overall system requirement for hardware implementation consist of a prototype BLDC motor of 36 volt, 4 pole with a belt pulley loading arrangement and inbuilt shaft encoder of 1250 ppr, STM32F407VG ARM controller card with a clock frequency of 168 MHz, a three phase voltage source inverter (VSI) with six insulated gate bipolar transistors (IGBTs), sensor card for current and voltage sensing, IGBT driver card to quarantine the low voltage controller circuit from the high voltage power circuit, a DC power supply circuit for the controller, driver card and inverter circuit.

Objective and Scope of work

The objective of the research is as follows:

To investigate the issues related to commutation torque ripple and analyze the effect of speed on the commutation torque ripple when operating the motor with conventional six step control and hysteresis current control technique (2-ΦO), twelve step direct torque control (TSDTC)(2-3ΦO) hence, devise a control strategy using 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 beside providing the closed loop speed control under varied speed and load condition as compared to conventional six step control.

Hence, to achieve this objectives, the research work reported in the thesis are:

1. BLDC motor modeling, Analysis of current commutation with 2-ΦO responsible for the generation of commutation torque ripple with variation in motor speed with conventional six step BLDC motor closed loop control.
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 is employed to validate the BLDC motor model with closed loop speed control.
    - Inner current loop and outer speed loop ensures correct commutation logic for the electronic commutator.
    - Control strategy ensures a simple closed loop speed control with only two phase conduction.

- The hardware implementation for closed loop speed control of BLDC motor using hysteresis current control technique validates the simulation results.

3. Modeling of conventional six step, modified six step, twelve step and modified twelve step direct torque control(DTC) for closed loop speed control of the BLDC motor is carried out to investigate BLDC motor performance with 2-3ΦO. These technique ensure better reduced torque ripple and improved motor performance.
    - A Conventional six step DTC(SSDTC) and modified six step DTC is developed and analyzed with MATLAB/Simulink for closed loop control of BLDC motor with 2ΦO. The modified six step DTC technique reduces the switching losses and improves drive efficiency.
    - A Twelve step DTC technique(TSDTC) is developed and analyzed with MATLAB/ Simulink for closed loop control of BLDC motor with 2-3ΦO. It incorporates the switching of third switch in the commutation region by selection of the appropriate voltage vector thereby reducing the commutation torque ripple compared to conventional six step SSDTC operation.
    - A modified twelve step DTC technique with ON_PWM and PWM_ON is proposed (referred MTSDTC PWM_ON and MTSDTC ON_PWM) where PWM_ON stands for upper switches are provided with pulse width modulated pulses and lower switch continuously ON and vice-versa for ON_PWM).The MTSDTC ON_PWM and MTSDTC PWM_ON techniques are developed and analyzed with MATLAB/Simulink for closed loop control of BLDC motor with 2-3ΦO.
    - The MTSDTC ON_PWM technique ensures reduced commutation torque ripple as compared with all the above technique with reduced switching losses. A comparative analysis of all the DTC technique is presented which provides the best DTC technique to improve the BLDC motor performance using 2-3ΦO.
    - The hardware implementation of the proposed modified twelve step DTC technique with ON_PWM and PWM_ON is carried out under varied speed and load condition to validate the simulation results.

4. Modeling of modified sinusoidal pulse width modulation technique is proposed for closed loop speed control of the BLDC motor to investigate BLDC motor performance with 3ΦO.
   - A modified sinusoidal pulse width modulation 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 saddle shaped modulating reference wave which are compared with the triangular carrier signal to produce the switching signals for the three phase inverter acting as electronic commutator.
   - The proposed control scheme introduces sinusoidal currents with trapezoidal back emf to improve BLDC motor performance. The effectiveness of modified sinusoidal pulse width modulation technique is studied by analyzing its performance with conventional six step control.
   - The comparison of the proposed technique with conventional six step control provides improved the DC bus utilization, reduced the stator copper losses and the commutation torque ripple up to 50% than the conventional six step control
   - The hardware implementation for closed loop speed control of BLDC motor using modified sinusoidal pulse width modulation technique validates the simulation results.
5. The comparison of the proposed control techniques 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.

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. It provides a comprehensive survey based on the issues related to motor performance with a review on various control techniques used for motor speed and torque control.

The motivation and objective behind the research and a road map of thesis organization is provided.

Chapter 2: In this chapter, mathematical model of BLDC motor using the motor dynamic equations and 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 closed loop control using six step operation for the BLDC motor is provided which leads to the requirement of the BLDC motor operation with more proficient control techniques using 2-ϕO, 2-3ϕO and 3-ϕO.

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

Chapter 4: This chapter provides detailed discussion on modeling and analysis of direct torque control(DTC) technique for closed loop control, simulation of conventional Six step DTC(SSDTC), modified SSDTC with 2-ϕO and 2-3ϕO of BLDC motor using TSDTC and MTSDTC technique with PWM_ON and ON_PWM switching technique with reduced switching losses and torque ripple. Comparison of the MTSDTC technique with PWM_ON and ON_PWM with the TSDTC technique is performed. The proposed MTSDTC technique with PWM_ON and ON_PWM control simulation results are validated on a prototype BLDC motor using STM32F407VG ARM controller to prove its effectiveness.

Chapter 5: This chapter provides detailed discussion on modeling and analysis of modified sinusoidal pulse width modulation technique using MATLAB/Simulink. Comparison of the simulation results of the proposed MSPWM technique with conventional six step control of BLDC motor and experimental verification of proposed 3-ϕO of BLDC motor using modified sinusoidal pulse width modulation technique on a prototype BLDC motor using STM32F407VG ARM controller.

Comparison of the proposed control techniques 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.

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

Thesis ends with a complete Bibliography.

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