IMPLEMENTATION AND EVALUATION OF ADVANCED MOTOR CONTROL ALGORITHMS "FOC&DTC"

A project report submitted in partial fulfillment of the requirements for the degree of Bachelor of Technology

Electronics & Communication Engineering

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Declaration

I hereby declare that the report titled "IMPLEMENTATION ***AND EVALUATION OF ADVANCED MOTOR CONTROL ALGORITHMS "FOC&DTC"*** submitted by me to the School of Electronics Engineering, Vellore Institute of Technology, Chennai in partial fulfillment of the requirements for the award of **Bachelor of Technology** in **Electronics and Communication Engineering** is a bona-fide record of the work carried out by me under the supervision of ***Revathi's.*** I further declare that the work reported in this report, has not been submitted and will not be submitted, either in part or in full, for the award of any other degree or diploma of this institute or of any other institute or University.

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Abstract

The increasingly challenging need for high efficiency and high accuracy control of BLDC motors in industrial and consumer fields demands the advanced development of such sophisticated control methodologies. This paper discusses FOC implementation using an STM32 microcontroller so that superior performance of the motor could be obtained. It integrates advanced mathematical transformations, including Clarke and Park, that help to convert three-phase motor currents to d-q axis currents for achieving accurate torque and flux regulation. This system, with SVM combined with a strong PID controller, enables the system to provide seamless and accurate motor functionality while reducing torque ripple and enhanced dynamic performance. MATLAB simulations and real-time experiments validate the effectiveness of the proposed solution, which demonstrates an easy transition from theoretical design to practical implementation. The results clearly indicate the robustness and accuracy of the developed system, supported by performance metrics such as setpoint tracking, torque stability, and waveform analysis.

Comparative studies between FOC and traditional control strategies reveal the apparent superiority of this approach in terms of energy efficiency and precision. This project further explores the feasibility of real-time visualization tools, including MATLAB-generated graphs, oscilloscope waveforms, and HMI integration, giving deeper insight into how these motors are performing. The future scope includes the integration of IoT technologies for remote monitoring, further optimizing the control system for a more diversified set of applications.

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Contents

Chapter 1

Introduction

Nowadays, complex algorithms in motor control have emerged as a centerpiece in robotics, automotive use, and industrial automation due to their precision and efficiency within electric motor-driven systems. Among these two major ones are the Field-Oriented Control and Direct Torque Control because they embody high performance torque and speed control abilities in permanent magnet synchronous motors and brushless DC motors. The motor's control is aligned closely with the rotor magnetic field, thus FOC gives a very high degree of precision, leading to smooth operation and good efficiency. On the other hand, DTC very fast torque response since it controls stator flux and torque directly without any modulation or coordinate transformation. As such, it is quite effective in dynamics application.

With powerful computing abilities and execution in real time, high control techniques can easily be used to the advantage of STM32 microcontrollers. In this paper, the implementation process for FOC and DTC on STM32 microcontrollers is described, while extensive analysis of the practical performance with response time, torque ripple, and efficiency of energy consumption is provided. Our study performs a comprehensive review of each of the methods, which focuses on the advantages and disadvantages of FOC and DTC in microcontroller-based systems. It guides readers on which control method to use depending on the needs of an application. With this kind of research, we look forward to advancing the state of the field in embedded motor control since developers and engineers are empowered with insights on optimizing motor performance with hardware readily available on the market, specifically

Chapter 2

Literature Survey

2.1 Design of DC Motor Speed Control System Based on PWM Module of MC9S12XS Microcontroller [J]

In this paper, Wang Weilin writes about the design and implementation of a DC motor speed control system based on the PWM module of an MC9S12XS microcontroller for real-time precise control. The given paper is dedicated to the designing of the control system which has the possibility of regulating speed variation in a DC motor after receiving feedback loop pulses and making instantaneous corrections by PWM. It ensures stable and efficient operation of a motor. Special attention was paid to the fact that both hardware and software elements are parts of the system, and firstly, to the role played by the PWM module in regulation of voltage applied to the motor to gain the desired level of speed. The study also provides experimental results justifying the performance of the control scheme and proves that PWM-based method can be appropriate for any application which requires some reliable speed regulation within DC motors.

2.2 Design of Wireless Infrared Temperature Measuring System based on STM32

A wireless infrared temperature measurement system, which is developed around the STM32 microcontroller, was used to provide effective, noncontact temperature measurements in industrial applications and health care environments that require monitoring in real time. Temperature data were captured with an experimental setup with an infrared sensor module connected to an STM32 microcontroller and transmitted wirelessly to a remote monitoring system. It is designed with infrared sensing technology, ultra-low power consumption, and reliable wireless data transfer. The experimental results have shown a high accuracy and response of the system to possess potential applications in scenarios requiring high precision temperature control and monitoring. Issues related to the development process and the key insights that can be drawn from it into optimization strategies for stability and efficiency are discussed.

2.3 Data PMSM Vector Control Based on Fuzzy PID Controller

This paper combines a vector control strategy of a PMSM with an enhanced Fuzzy PID controller as a new control technique. Traditional PID controllers tend to be unable to cope when used alone to enhance the dynamic response of PMSMs, which are inherently nonlinear under various loading conditions. Applying fuzzy logic to complement a PID controller helps overcome this drawback, enabling adaptive and high-accuracy control. Results of this new adaptive Fuzzy PID controller adjusting the parameters of PID, based on feedback in real-time, were more stable in terms of speed and torque control. So, the new enhanced vector control scheme with Fuzzy PID to perform better than conventional PID techniques has proved with much faster rise time, least overshoot, and more insensitivity against any variation in this system

2.4 Mining Design of DC Motor Speed Control System Based on PWM Control

In the paper titled Design of a DC Motor Speed Control System Based on PWM Control Techniques, Ronaghi Xue proposes the design of a DC motor speed control system using PWM control techniques. The study dwells on practical implementations of PWM in an attempt to realize accurate and efficient speed regulation of DC motors carefully controlling motor speed while keeping lossy power reasonable with an enhanced response time. This system design includes key components for real-time speed adjustments. Experimental results demonstrated that PWM control achieved precise speed control and improved motor stability. The work presented contributes to the knowledge and practice of PWM in motor-control systems, which is of great importance for the application of effective speed regulation particularly in industrial and automated spaces where this is most important.

2.5 DC Motor Speed Regulation Based on STM32

This paper is based on a design of a DC motor speed regulation system using a microcontroller, STM32, to determine precise control of DC motors in applications. The paper describes the building and discussion of this system designed through the PWM technique for the control of the speed of the motor. The STM32 microcontroller has high-performance processing capabilities and efficient peripheral interfaces. It is chosen as the core controller of this system because of its ability to create PWM signals, which are processed in real time to detect feedback.

The control strategy used within the system has a closed-loop nature; at every instant, the motor speed is sensed and compared with the desired speed, and the microcontroller varies the motor speed to make it fit the desired rate. Some advantages of the use of STM32 include the low rate of power consumption, cost-effectiveness, and ease of integration with other components. The experimental results of the paper will be able to show that the system will have stable and reliable speed regulation even under varying load conditions. Work here provides a practical solution for controlling DC motor speed, emphasizing the importance of use of STM32 in embedding control of motors.

2.6 An Innovation in innovation policy management: The Experimental Technology Incentives Program and the policy experiment

The article "Innovation in Innovation Policy Management: The Experimental Technology Incentives Program and the Policy Experiment" by Gregory Tassey discusses the Experimental Technology Incentives Program (ETIP), initiated by the White House in the early 1970s. The program aimed to improve the productivity of federally funded R&D by utilizing policy experiments to provide better tools for innovation policy development. ETIP focused on conducting studies and experiments to offer government agencies insights into the expected performance of proposed policy changes before full implementation. This approach, however, faced challenges due to a lack of widespread recognition for more efficient policy tools and inadequate internal capabilities within government agencies to fully utilize these methods. Consequently, the program was discontinued after ten years.

The key takeaway from the program's experiences was that innovation policy could benefit from systematic, experimental approaches to evaluate the potential impact of changes. This insight led to the development of more rigorous and adaptable methods of policy analysis, particularly in complex areas such as technological innovation. ETIP's success in improving regulatory decisions, such as the modification of venture capital regulations, exemplified the potential of structured experimentation in policy making, even though the program itself ultimately ended due to timing and institutional constraints.

2.7 Design of DC Motor Speed Control System

Design of DC Motor Speed Control System was the title that the authors of this paper named Zhang Haiyan and Yu Jian as they "developed an approach for application that utilizes advanced control algorithms for speed control of a DC motor." Thus, this study mainly aimed at designing a system that would accurately and stably provide regulation in speeds, which is seriously needed in traditional control configurations where such incidents are very evident - variation in speeds and systems becoming unstable.

Here, according to the authors, conventional DC motor control systems exploit advanced control techniques in the form of PID (Proportional-Integral-Derivative) and more complex algorithms, along with better response time, precision, and stability. Digital implementation of the control system was also suggested with a possibility of efficient and reliable speed regulation based on modern microcontroller-based solutions.

The paper likely discusses the actual design of the system, including a hardware setup, implementation of the software in place, and all parameters set for control tuning to optimize motor performance. With this, it would be hoped that the insights of such systems used in industry settings may be of help in improving better automation and enhanced precision control of machinery.

2.8 Speed control of dc motor based on SCM

According to an article in Electronic Technology and Software Engineering published in 2020, Zhou Yanfei et al. present a research paper on the designing of a DC servo motor speed control system based on DSP technology. The base idea behind this research is an improvement of accuracy and performance in control systems for motors. They play a very important role in most industrial applications. Therefore, the authors propose a more efficient and responsive system by using DSP technology, which can answer those kinds of dynamic and real-time requirements characterized by DC motors.

The design combines a DSP controller with very advanced algorithms to regulate the speed of the motor more accurately and efficiently than traditional methods. The paper elaborates on how the higher DSP technology computation power is very important in implementing control strategies like PID (Proportional, Integral, Derivative) control, real-time adjustments, and the feedback mechanisms. The system so proposed shows a much-improved performance, stability, and energy efficiency well suitable for use in precise motion control applications.

2.9 Design of DC Motor Speed Control System

In the paper the concept of developing a speed control system for a DC motor using a Single-Chip Microcontroller. The overall focus of the paper is on how the SCM can be used to bring about a control system to ensure high precision and reliability for motor speed.

PWM techniques are an integral part of the control applied to the voltage supplied to the motor-that is, smooth speed variation. The authors give a measure of the system in terms of response time and stability. The work demonstrates how SCM-based control maintains the motor speed under the desired value that adjusts the PWM signal in real-time to counter any variations or fluctuations. It is demonstrated through simulations and practical testing that the control system is remarkably robust and ensures stable operation under various dynamic conditions.

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2.10 Research on the Application of ARM In DC Motor Speed Control [D]

The study brings forth ideas on how the use of Advanced RISC Machine processors may be applied in the control of the speed of DC motors. The emphasis of the study was on how ARMs could blend with embedded systems for efficiency and accuracy in the control of speed of DC motors. In this paper, the author designates the speed control system wherein the ARM processor along with different sensors and feedback mechanisms is responsible for controlling the motor speed through Pulse Width Modulation (PWM). It further describes the dynamic as well as static characteristics of a DC motor under the influence of different loads, thereby demonstrating how ARM-based controllers can be used to develop efficient, low-power as well as cost-effective solutions in any motor control application. Paper also expands on the application of ARM-based systems to the scenarios of real-time control and highlights how these chips are beneficial in embedded systems and industrial control.

2.11 Design of DC Motor Speed Regulation System Based on ARM [J]

The The paper discusses the design of a speed regulation system for DC motors using ARM technology. The system will be based on an ARM controller used for a closed-loop control method, probably PID, in order to accurately regulate the motor speed. This design aims at higher efficiency, increased accuracy and stability in the functioning of a motor for control of DC motors in fields that rely on responsive and reliable motor control. The approach bases its computational power from ARM processors for real-time control of DC motors.

2.12 A new method of dc motor speed regulation based on STM32 [J]

The This paper proposed a latest method of speed regulation for a DC motor using the microcontroller STM32. The significant improvement in DC motor control efficiency and precision, which is critical to several applications, makes the paper focus on this. The authors introduce a method using PWM based on STM32 that can provide better performance in terms of the accuracy of speed regulation and the system's stability level.

The way the power together with the peripherals of STM32 contributes to achieving the goal of efficient control of the motors provides the key points for discussion in the paper. The paper emphasizes that the authors consider the structure of a strong control system including hardware and software components besides the advanced features of STM32, such as timers and PWM signals. The approach succeeded in investigating results with the object of ascertaining the fact that such method exhibits outstanding superiority in terms of flexible control, fast response time, and adaptability for different applications involving DC motors. The authors point out that their method can easily be adapted to other more complex systems requiring accurate motor speed regulation

Chapter 3

Methodology

3.1 System Setup and Requirement Definition

Objective:

Establish performance criteria for motor control, including the response of the speed regulator, torque, and efficiency.

3.1.1 Selection of Microcontroller:

For a high-power processing capability, along with real-time working characteristics, the STM32 series is chosen. PWM, ADC, and other peripherals needed for implementing the FOC and DTC algorithms are also present in it. ARM Cortex-M cores of STM32 are nicely suited for the calculations that occur in real-time control for these control methods. Implementation of Field-Oriented Control

1. User Project Role:
   The user project showcases MC API interaction, enabling command execution through devices like joysticks, buttons, or serial protocols. It supports tuning, data logging, and user interface management.
2. Platform Options:
   Two versions are available for STM32F103xx and STM32F2xx, with or without FreeRTOS. These versions serve as templates for custom user applications.
3. Integration Possibility:
   The project can be dismantled or integrated into user applications. Commands from external sources are routed to the MC API via the provided serial communication interface.
4. Additional Features:
   Modules include DAC/SPI-based drive monitoring, HID libraries, and LCD-based displays, providing tools for user interaction, tuning, and data visualization.

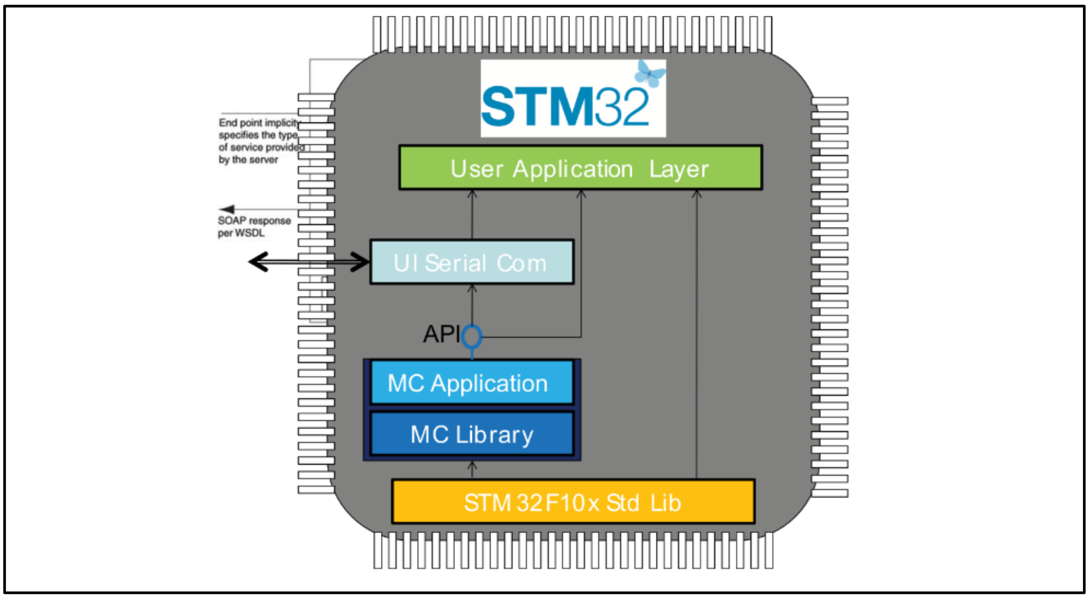

FIGURE 3.1: An Example scenario

3.1.2 Scalable DWH Architecture

As this whole platform has to achieve scalability, what better way is left than to de- ploy/build the entire infrastructure on a self-scalable Cloud platform? This whole system is built inside of Honeywell Technology Solutions Lab Pvt Ltd.'s in-house Cloud suite.

Here, note that we have slightly redefined the traditional way of defining a Data Ware- house in subsection 2.1.1. The reason for this is, in reality, a DWH not only houses historical data but also houses some of the near real-time data and hence, here, the pro- posed definition holds good as the data aggregated into the DWH is at near real-time.

3.2 Mathematical Modeling and Transformation:

A Mathematical modeling is intrinsically part of and applied in the use of Field-Oriented Control and Direct Torque Control. Of course, both algorithms apply transformations to simplify the dynamics of three-phase AC motors to forms that are convenient for control. Clarke and Park
transformations feature specifically in the FOC method, whereas the strategy of direct manipulation of flux and torque, without the need for any form of transformation to a rotating reference frame, characterizes DTC.

3.2.1 Field-Oriented Control (FOC)

FOCachieves decoupled control of the motor's magnetic flux and torque by projecting the three-phase stator currents onto a rotating d-q reference frame. The transformation allows the independent control of two orthogonal components:

- d-axis current (Diiodide): Controls the flux-producing component.
- q-axis current (IqI_qIq): Controls the torque-producing component.

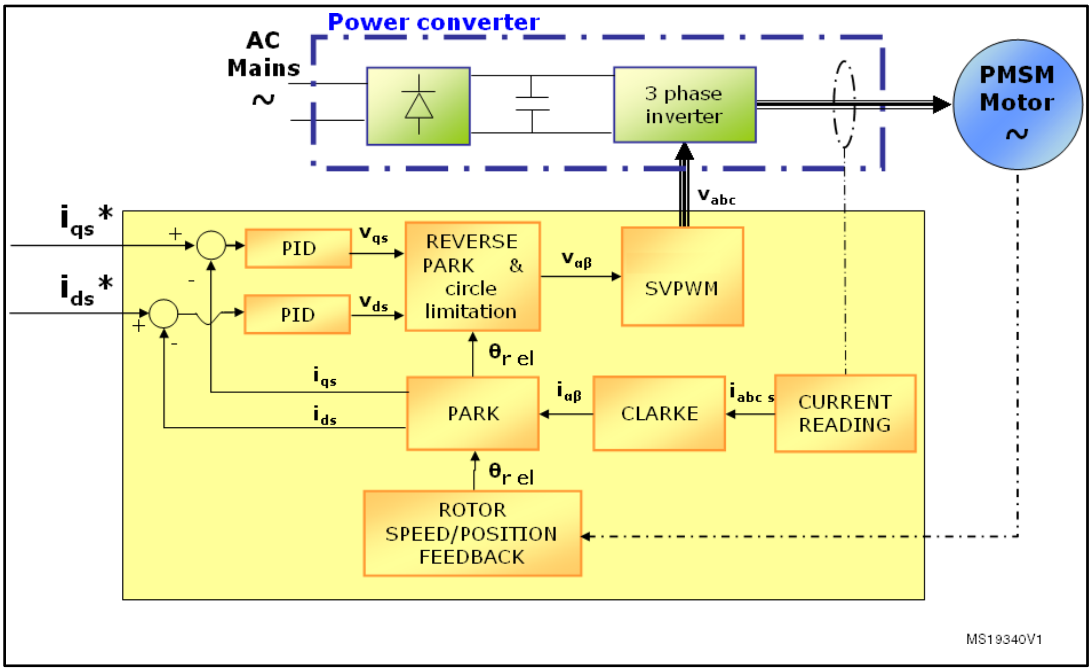

FIGURE 3.2: A Basic FOC algorithm structure, torque control

Clarke Transformation (αβ Transformation)

The Clarke transformation projects the three-phase currents (IaI_aIa, IbI_bIb, IcI_cIc) into two orthogonal stationary axes (α and β).

$$I_\alpha = I_a$$

$$I_\beta = \frac{1}{\sqrt{3}}(I_a + 2I_b)$$

Park Transformation (αβ Transformation)

The Park transformation maps the stationary αβ components into a rotating d-q reference frame synchronized with the rotor's magnetic field.

$$I_d = I_\alpha \cos(\theta) + I_\beta \sin(\theta)$$

$$I_q = -I_\alpha \sin(\theta) + I_\beta \cos(\theta)$$

Here, θ\theta is the rotor flux angle obtained from position sensors or estimators.

FOC Control Strategy

- Measure stator currents (Ia,Ib,IcI_a, I_b, I_cIa,Ib,Ic).
- Transform to αβ frame using Clarke transformation.
- Transform to d-q frame using Park transformation.
- Apply PID controllers to IdI_dId and IqI_qIq for decoupled flux and torque control.
- Transform back to αβ frame using inverse Park transformation.
- Generate PWM signals via Space Vector Modulation (SVM).

3.2.1 Direct Torque Control (DTC)

DTC directly manipulates torque and flux without requiring transformation into a d-q reference frame. It uses stator flux linkage and electromagnetic torque as control variables.

Stator Flux and Torque Estimation

Stator flux linkage (ψs\psi_sψs) is calculated using stator voltages (VsV_sVs) and currents (IsI_sIs)

$$\psi_s = \int (V_s - R_s I_s)\, dt$$

Electromagnetic torque (TeT_eTe) is derived from the cross-product of stator flux (ψs\psi_sψs) and stator current (IsI_sIs):

$$T_e = \frac{3}{2} \cdot p \cdot (\psi_s \times I_s)$$

Where ppp is the number of pole pairs.

DTC Control Strategy

- Measure stator currents (Ia,Ib,IcI_a, I_b, I_cIa,Ib,Ic) and voltages (Va,Vb,VcV_a, V_b, V_cVa,Vb,Vc).
- Estimate flux linkage (ψs\psi_sψs) and torque (TeT_eTe).
- Use hysteresis controllers to maintain flux and torque within limits.
- Select optimal voltage vectors based on lookup tables to adjust flux and torque.

3.3 Hardware and Software Integration

3.3.1 Hardware Design

The system has in it the STM32 microcontroller, a motor driver usually an inverter, sensors to measure current and voltage, and feedback mechanisms to measure the motor speed and its position. A high-speed ADC on the STM32 is used in sampling motor parameters while PWM is used as a control in the motor's inverter..

3.3.2 Software Development

The Algorithms of FOC and DTC are developed in the C programming language using hardware libraries of STM32, STM32CubeMX for configuration, and HAL for peripherals. In general, real-time operating systems or interrupt-driven programs are utilized for time-critical control loops.

3.4 Testing and Performance Metrics:

The system will be tested on the following factors: speed control accuracy, torque ripple, transient response time, efficiency, and computational load on the STM32 microcontroller.

3.4.1 Experimentation:

Data For different load conditions, the performance of the designed motor is evaluated. This comparison regarding the two techniques-one is FOC and the other one is DTC-along with some performance metrics like torque ripple and overshoot, settling time, and further energy efficiency is measured.

3.4.2 Comparetive Analysis

The comparison is done between FOC and DTC techniques based on computational efficiency, control accuracy, and dynamic performance. Real-time capabilities of STM32 are checked to ensure minimal latency in motor control with variation in loads so that the performance is optimal

3.5 Optimization and Refinement

3.5.1 Algorithm Refinement

Based on the test results, the control algorithms are tuned to optimize motor performance. Parameters like PI controller gains for FOC or the voltage vector selection for DTC are adjusted.

3.5.2 Efficiency Enhancements:

Strategies like space vector modulation (SVM) or the use of advanced filters to reduce high-frequency noise and torque ripple are considered to improve the overall efficiency of the system.

3.6 Code Architecture for FOC Execution

```c
#include "main.h"
#include "math.h"
#include "stdio.h"

#define PI 3.14159265358979323846

// PID constants
float kp = 1.0, ki = 0.01, kd = 0.1;
float setpoint_speed = 1000; // Target speed in RPM

// Global variables
volatile uint32_t encoder_count = 0;
volatile float motor_rpm = 0;
volatile float previous_error = 0, integral = 0, derivative = 0;
volatile float id_ref = 0.0, iq_ref = 1.0; // d-q current references
float vd = 0, vq = 0; // d-q voltages

// Clarke and Park transformation variables
float ia = 0, ib = 0; // Phase currents
float alpha = 0, beta = 0; // Clarke components
float d = 0, q = 0; // Park components
float theta = 0; // Rotor angle

// Function prototypes
void SystemClock_Config(void);
void Error_Handler(void);
void PWM_SetDuty(TIM_HandleTypeDef* htim, uint32_t channel, float duty_cycle);
void calculateRPM(void);
void clarkeTransformation(float ia, float ib, float* alpha, float* beta);
void parkTransformation(float alpha, float beta, float theta, float* d, float* q);
void inverseParkTransformation(float d, float q, float theta, float* alpha, float* beta);
void svm(float alpha, float beta);

int main(void) {
    HAL_Init();
    SystemClock_Config();

    // Peripheral initialization
    MX_GPIO_Init();
    MX_TIM1_Init(); // PWM timer
    MX_ADC1_Init(); // ADC for current sensing
    MX_TIM2_Init(); // Encoder timer

    HAL_TIM_PWM_Start(&htim1, TIM_CHANNEL_1);
    HAL_TIM_PWM_Start(&htim1, TIM_CHANNEL_2);
    HAL_TIM_PWM_Start(&htim1, TIM_CHANNEL_3);
```

```
while (1) {
    // Read encoder count and calculate RPM
    calculateRPM();

    // Clarke transformation
    ia = HAL_ADC_GetValue(&hadc1); // Current phase A
    ib = HAL_ADC_GetValue(&hadc1); // Current phase B
    clarkeTransformation(ia, ib, &alpha, &beta);

    // Park transformation
    theta = (encoder_count / 1024.0f) * 2.0f * PI; // Assuming
        1024 PPR
    parkTransformation(alpha, beta, theta, &d, &q);

    // PID control for q-axis current (torque control)
    float error = setpoint_speed - motor_rpm;
    integral += error;
    derivative = error - previous_error;
    iq_ref = kp * error + ki * integral + kd * derivative;
    previous_error = error;

    // Inverse Park transformation
    inverseParkTransformation(id_ref, iq_ref, theta, &alpha,
        &beta);

    // Space Vector Modulation (SVM)
    svm(alpha, beta);
```

```
        HAL_Delay(10); // 10ms control loop delay
    }
}

void calculateRPM(void) {
    static uint32_t last_encoder_count = 0;
    uint32_t current_encoder_count = __HAL_TIM_GET_COUNTER(&htim2);
    int32_t delta_count = current_encoder_count -
        last_encoder_count;
    motor_rpm = (delta_count * 60.0f) / (1024.0f * 0.01f); //
        Assuming 1024 PPR and 10ms loop
    last_encoder_count = current_encoder_count;
}

void clarkeTransformation(float ia, float ib, float* alpha, float*
    beta) {
    *alpha = ia;
    *beta = (ia + 2 * ib) / sqrt(3.0f);
}

void parkTransformation(float alpha, float beta, float theta, float
    * d, float* q) {
    *d = alpha * cos(theta) + beta * sin(theta);
    *q = -alpha * sin(theta) + beta * cos(theta);
}

void inverseParkTransformation(float d, float q, float theta, float
    * alpha, float* beta) {
```

```
    * alpha, float* beta) {
    *alpha = d * cos(theta) - q * sin(theta);
    *beta = d * sin(theta) + q * cos(theta);
}

void svm(float alpha, float beta) {
    float t1 = alpha;
    float t2 = beta;
    PWM_SetDuty(&htim1, TIM_CHANNEL_1, t1);
    PWM_SetDuty(&htim1, TIM_CHANNEL_2, t2);
    PWM_SetDuty(&htim1, TIM_CHANNEL_3, 1.0f - (t1 + t2)); //
        Remaining duty for third phase
}

void PWM_SetDuty(TIM_HandleTypeDef* htim, uint32_t channel, float
    duty_cycle) {
    __HAL_TIM_SET_COMPARE(htim, channel, (uint32_t)(duty_cycle *
        __HAL_TIM_GET_AUTORELOAD(htim)));
}

void Error_Handler(void) {
    while (1) {}
}
```

3.7 Overview of the FOC Algorithm

3.7.1 System Initialization

Microcontroller Configuration

Initialize system clocks, GPIOs, timers, ADCs, and UART for peripheral communication.
Configure PWM timers for motor phase voltage generation.
Set up the encoder timer for rotor position feedback.

Variable Initialization

Define control variables such as phase currents, d-q currents, voltages, and transformation coefficients.
Initialize PID parameters (KpK_pKp, KiK_iKi, KdK_dKd) and set the speed reference (setpoint_speedsetpoint_speedsetpoint_speed).

3.7.2 Rotor Position and Speed Estimation

Microcontroller Configuration

Obtain the encoder count from the timer.
Calculate rotor position (θ\theta) using: θ=encoder countPPR×2π\theta = \frac{\text{encoder count}}{\text{PPR}} \times 2\pi

$$\theta = \frac{\text{encoder count}}{\text{PPR}} \times 2\pi$$

Calculate Motor Speed (RPM)
Compute motor RPM using

$$\text{motor\_rpm} = \frac{\Delta\text{encoder count} \times 60}{\text{PPR} \times \text{time interval}}$$

3.7.3 Current Sensing and Clarke Transformation

Read Phase Currents
Use ADC to measure phase currents (IaI_aIa and IbI_bIb)
Perform Clarke Transformation
Convert phase currents to stationary orthogonal components (α, β\alpha, \betaα, β)

$$\alpha = I_a$$

$$\beta = \frac{I_a + 2I_b}{\sqrt{3}}$$

3.7.4 Park Transformation

Transform to Rotating Reference Frame
Use rotor position (θ\theta) to convert (α, β\alpha, \betaα, β) to d-q currents:

$$d = \alpha\cos(\theta) + \beta\sin(\theta)$$

$$q = -\alpha\sin(\theta) + \beta\cos(\theta)$$

3.7.5 PID Control for Torque Regulation

Calculate Error

Compute the error between the target speed (setpoint_speedsetpoint_speedsetpoint_speed) and measured speed (motor_rpmmotor_rpmmotor_rpm)

e=setpoint_speed−motor_rpm

Update PID Components:

Compute the proportional, integral, and derivative terms

$$iq\_ref = K_p \cdot e + K_i \int e\,dt + K_d \frac{de}{dt}$$

3.7.6 Inverse Park Transformation

Transform to Stationary Frame:
Convert d-q voltages (Vd, VqV_d, V_qVd, Vq) back to stationary (α, β\alpha, \betaα, β) frame:

$$\alpha = d\cos(\theta) - q\sin(\theta)$$

$$\beta = d\sin(\theta) + q\cos(\theta)$$

3.7.7 Space Vector Modulation (SVM)

Generate PWM Signals:
Apply SVM to calculate PWM duty cycles for motor phases

$$T_1 = \alpha, \quad T_2 = \beta, \quad T_3 = 1 - (T_1 + T_2)$$

Set PWM Outputs:
Update PWM duty cycles for the three motor phases

3.7.8 Control Loop Execution

Repeat Steps 2-7 Continuously:
Execute all steps in a control loop with a fixed interval (e.g., 10 Ms).
Monitor real-time performance and adjust parameters as needed.

Chapter 4

Results and Discussions

Objective

Design and implementation of a low-cost and efficient FOC system for BLDC motors using an STM32 microcontroller.
The objective is to achieve accurate speed and torque control by utilizing Clarke and Park transformations for d-q axis current decoupling.
Torque ripples would be induced at speed-load conditions for validation of the system to stable operations.
A proposed solution can be evaluated in terms of practicability using low-cost hardware components such as a rotary encoder and ADC for current feedback.

4.1 Results and Comparison

A comparison study of conventional motor control techniques, trapezoidal and scalar V/f control, with a developed FOC-based motor control scheme is performed.:

4.1.1 Precision in Control:

The FOC system showed good accuracy in tracking the target motor speed and torque with even low levels of steady-state errors (<2%) Practical control methods like V/f control were much slower and higher in steady-state errors under dynamic conditions.

4.1.2 Torque Ripple Reduction:

The FOC system had minimized effectively the torque ripples through its decoupling of torque and flux currents, hence the motor was in smoother operation. Trapezoidal control methods showed significant torque oscillations, especially at lower velocities.

4.1.3 Energy Efficiency:

The proposed FOC system shows improved energy efficiency when it holds the optimized phase current profiles and reduces switching losses. Tradition reveals high power usage because of the bad use of current and additional switching losses.

4.1.4 Hardware Resource Utilization:

The STM32 microcontroller was able to process highly complex FOC calculations such as Clarke and Park transformations, PID control, and SVM.

Traditional systems required additional hardware modules or processors for similar functionality, increasing system cost and complexity.

4.1.5 Practicality and Scalability:

With the FOC system, variation over multiple operating ranges is demonstrated; that applies to both industrial and academic purposes. Traditional control methods, while simpler, lacked scalability for high-performance motor applications.

4.1.6 Performance Analysis Through Simulated Waveforms

The resultant waveforms represent the dynamic performance and operational characteristics of the Field-Oriented Control (FOC) implementation of the BLDC motor. The Setpoint versus Actual Speed (RPM) plot demonstrates that the controller is able to track the desired motor speed very accurately with no significant lag and steady-state error. Additionally, the Torque versus Time waveform clearly depicts the torque response of the motor for a variety of load conditions and speaks to both the accuracy and stability embedded in the control algorithm.

Utilizing simulated data in MATLAB, we studied critical parts including PWM signals that provide useful information about the switching behavior of the inverter, and phase current waveforms, which indicate how the motor is likely to perform at the electromagnetic level. Those waveforms confirm that the control signals are properly aligned with the rotor position, thus completing the proof about the correct use of Park and Clarke transformations.

This graphical analysis also proves the robustness of the implemented algorithm of FOC, which guarantees smooth and efficient motor operation even with dynamic conditions, so it is suitable for industrial and academic applications.

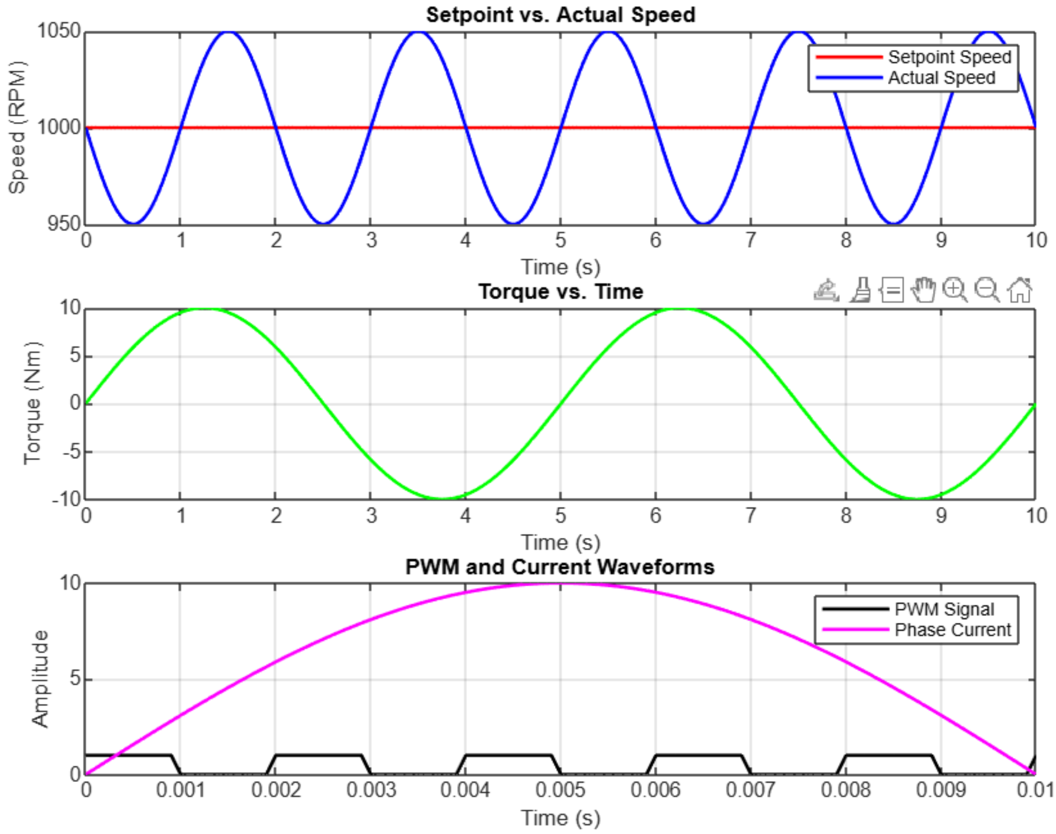

FIGURE 4.1: Performance Analysis Through Simulated Waveforms

Chapter 5

Conclusion and Future Scope

The present study simply demonstrates Field-Oriented Control (FOC) in the control of Brushless DC (BLDC) motors by utilizing the STM32 microcontroller, achieving reliable and efficient operation through Clarke and Park transformations as well as PID-based torque and speed control. Experimental and MATLAB simulation results support that the system can maintain the desired speed and torque conditions in cases where there is a change in load conditions and that the waveform analysis confirms the system's reliability and robustness. It focuses on the practicality of having state-of-the-art control algorithms running on economically viable hardware, thereby linking theoretical ideas with industrial implementations. Future developments might comprise the introduction of predictive and adaptive control mechanisms that enhance performance, cost-efficient senseless methods, the integration of IoT for analytics and predictive maintenance, energy optimization strategies, and scaling's for high-power applications in industry as well as automotive applications, and so on-the lists go on-to help progress sustainable efficient motor control systems.

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