

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**DESIGN AND IMPLEMENTATION OF TRACTION CONTROL
UNIT ON SOC FOR RAILWAY SYSTEMS**



MUSA ERGEN

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ELECTRONICS ENGINEERING

ADVISOR: ASSOC. PROF. ENGİN AFACAN

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

RAYLI SİSTEMLER İÇİN ÇEKİŞ KONTROL
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On behalf of my beloved son...

ABSTRACT

The process of development includes a number of important steps, one of which is the verification of a complicated system. This stage is especially important in the case of applications where safety and energy efficiency have greater importance, such as railway transportation systems. Therefore, a series of tests and simulations must be conducted before the natural operation of the train on the rails. This study investigates the implementation of an advanced control strategy within a hardware-in-the-loop (HIL) environment in order to maximize the performance of a railway traction motor and achieve optimal results. At beginning, a comprehensive investigation into a variety of control systems, including vector and scalar control approaches, was carried out. Field-oriented control (FOC) and direct torque control (DTC) were investigated from the perspective of the vector control method. Moreover, both direct current (DC) and alternating current (AC) motor types were researched in the field of traction motors. Within the realm of alternating current (AC) motors, particular focus was placed on both induction motor and permanent magnet synchronous motor (PMSM) types. As a consequence of these experiments, the FOC approach, when combined with an AC induction motor, was shown to be the most suitable option for the control of railway traction motors. The PLECS RT Box 3 simulator device and the F28379 development board make up the HIL setup, which offers a robust test environment. The F28379 development board contains the TMS320F28379 microcontroller unit (MCU) from the C2000 family of integrated chip manufacturer Texas Instruments (TI). This setup enables real-time simulation and validation of the proposed FOC algorithm under a variety of loads and dynamic conditions. The study's method includes building the control algorithm into a microcontroller (MCU) and the traction motor model with a three-phase voltage source inverter (VSI) on the RT Box 3 simulator. This provides real-time and hardware-in-the-loop simulation easier. The controller gives a 400Nm reference torque value to the 120kW AC induction motor. This makes for efficient and accurate torque control with a peak-to-peak deviation of 10% when used with a 1000V DC-link supply and a 1 kHz switching frequency, which are suitable parameters for light railway vehicles.

Keywords: Field-Oriented Control, Railway Traction Motor, Hardware-in-the-loop, F28379 Launchpad, PLECS RT Box 3, AC Induction Motor

ÖZET

Karmaşık sistemlerin geliştirme süreci, bir dizi önemli adım içerir ve bunlardan en önemlisi sistemin doğrulanmasıdır. Bu aşama özellikle güvenlik ve enerji verimliliğinin büyük önem taşıdığı uygulamalarda, örneğin demiryolu taşıma sistemlerinde, önemlidir. Bu nedenle, trenin raylarda normal çalışmasından önce bir dizi test ve simülasyonun yapılması gerekir. Bu çalışma, bir Hardware in the Loop (HIL) yani döngü içindeki donanım ortamında demiryolu çekiş motorunun performansını optimize etmek amacıyla gelişmiş bir kontrol yönteminin uygulanmasını içermektedir. İlk olarak, vektörel ve skalar kontrol yaklaşımlarını içeren çeşitli kontrol sistemlerinin kapsamlı bir incelemesi yapıldı. Vektörel kontrol metotlarından hem alan odaklı kontrol (FOC) hem de doğrudan tork kontrolü (DTC) metotları incelendi. Ayrıca, çekiş motorları alanında hem doğru akım (DC) hem de alternatif akım (AC) motor tipleri araştırıldı. Alternatif akım (AC) motorları alanında, özellikle indüksiyon ve kalıcı mıknatıslı senkron motor (PMSM) tiplerine odaklanıldı. Bu araştırmaların sonucu olarak, FOC yaklaşımının, AC indüksiyon motoru ile birleştirildiğinde, demiryolu çekiş motorlarının kontrolü için en uygun seçenek olduğu gösterildi. PLECS RT Box 3 simülatör cihazı ve üzerinde Texas Instrument (TI) entegre çip üreticisine ait mikro denetleyici birimini (MCU) bulunduran, F28379 kodlu geliştirme kartı tarafından sağlanan HIL kurulumu, gerçek zamanlı simülasyon ve FOC algoritmasının çeşitli yükler ve dinamik koşullar altında doğrulamasına izin veren sağlam bir test ortamı oluşturmuştur. Çalışmanın yöntemi, FOC algoritmasını MCU'ya ve üç fazlı gerilim kaynaklı invertör (VSI) modeli ile raylı araçlara uygun parametrelere sahip AC indüksiyon motorunun modelini RT Box 3 simülatörüne entegre edip gerçek zamanlı ve donanımsal olarak simülasyon yapmayı içermektedir. Hafif raylı araçlar için uygun parametreler olan 1000V DC-bara beslemesi ve 1 kHz anahtarlama frekansı ile, 120kW alternatif akım (AC) indüksiyon motoru üzerinde kontrolcüden gönderilen 400Nm referans tork değerine göre tepeden tepeye %10 sapma ile verimli ve hassas tork kontrolü sağlanmıştır.

Anahtar Kelimeler: Alan Odaklı Kontrol, Raylı Araç Çekiş Motoru, Döngü İçi Donanım, F28379 Geliştirme Kartı, PLECS RT Box 3, AC İndüksiyon Motor

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	: Alternating Current
ADC	: Analog Digital Converter
BLDC	: Brush-less DC
CPSR	: Constant-Power Speed Ratio
CPU	: Central Processor Unit
CSI	: Current Source Inverter
DC	: Direct Current
DFOC	: Direct Field Oriented Control
DSP	: Digital Signal Processor
DTC	: Direct Torque Control
EV	: Electric Vehicle
FOC	: Field Oriented Control
FPGA	: Field Programmable Gate Array
HIL	: Hardware in the Loop
HVAC	: Heating, Ventilation, and Air Conditioning
IEEE	: Institute of Electrical and Electronics Engineers
IFOC	: Indirect Field Oriented Control
IGBT	: Insulated-Gate Bipolar Transistor
IM	: Induction Motor
IPMSM	: Interior Permanent Magnet Synchronous Motor
LTI	: Linear Time-Invariant
MCU	: Micro Controller Unit
MOSFET	: Metal Oxide Semiconductor Field Effect Transistor
MPC	: Model Predictive Control
PMSM	: Permanent Magnet Synchronous Motor
PI	: Proportional Integral
PM	: Phase Margin
PWM	: Pulse Width Modulation
SCIM	: Squirrel Cage Induction Motor
SiC	: Silicon Carbide
SOC	: System on Chip
SPMSM	: Surface Permanent Magnet Synchronous Motor
SVM	: Space Vector Modulation
SVPWM	: Space Vector Pulse Width Modulation
TI	: Texas Instrument
UPS	: Uninterruptible Power Supplies
VFD	: Variable Frequency Drive
VSI	: Voltage Source Inverter
WRIM	: Wound Rotor Induction Motor

i_a	: A-phase Stator Current
i_b	: B-phase Stator Current
i_c	: C-phase Stator Current
i_α	: Alpha Axis Current
i_β	: Beta Axis Current
i_d	: Direct Axis Current
i_q	: Quadrature Axis Current
i_{dref}	: Reference Direct Axis Current
i_{qref}	: Reference Quadrature Axis Current
i_s	: Stator Current
i_r	: Rotor Current
V_d	: Direct Voltage Component
V_q	: Quadrature Voltage Component
V_α	: Alpha Axis Voltage Component
V_β	: Beta Axis Voltage Component
V_a	: Phase A Voltage
V_b	: Phase B Voltage
V_c	: Phase C Voltage
V_s	: Stator Voltage
L_d	: Direct Axis Inductance
L_q	: Quadrature Axis Inductance
L_s	: Stator Inductance
L_r	: Rotor Inductance
L_m	: Mutual Inductance
L_σ	: Inductance along the σ (sigma) axis of the magnetic field
θ, θ_e	: Rotor Angle of Motor
K_p	: Proportional Gain
K_{lim}	: Limit Gain
T_i	: Integral Time Constant
K_i	: Integral Gain
f_{sw}	: Switching Frequency
T_{sw}	: Switching Period
e_o	: Saturated Output
e_i	: Error Input
ω_c	: Crossover Angular Speed
ω_r	: Rotor Angular Speed
ω_m	: Mechanical Angular Speed
ω_s	: Synchronous Angular Speed
N_s	: Motor speed in rpm
$G(jw)$	: Transfer Function Magnitude
D	: Duty-cycle
T_{on}	: ON-time
T_{period}	: Time of Period

Y_s	:	Stator Flux
Y_r	:	Rotor Flux
R_s	:	Stator Resistance
R_r	:	Rotor Resistance
p	:	Number of Poles
B	:	Motor Viscous Friction
J	:	Motor Inertia
P	:	Motor Power
V_{DC}	:	DC-link Voltage
δT	:	Torque Error
δY_s	:	Flux Error
Y_{ref}	:	Reference Flux
T_e	:	Electromagnetic Torque
T_{ref}	:	Reference Torque



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1. INTRODUCTION

The verification of a complex system is a significant step in the development process that occurs during the design phase of the system. The verification stage is particularly vital in the case of applications where safety is more critical, like railway and air transportation systems, because the life of a human being could be put at risk if acceptable safety arguments are not presented. It is helpful to perform verification during the early phases of development in order to prevent integration issues later on. Due to several factors, such as the high cost of rail vehicle components and the complexity of integration, it is necessary to perform a series of tests and simulations before the natural operation of the train on the rails. Hardware and software-in-the-loop testing, as well as fault injection, are examples of techniques that are typically utilized in significant systems [1].

Many simplifications are thought to cut down on the time it takes to run software simulations. Hardware-in-the-loop (HIL) simulations, on the other hand, can be more realistic because they take into account the real limitations of the hardware [2].

The use of electric vehicles, which provide energy efficiency, high performance, and do not contribute to environmental pollution, is becoming increasingly widespread in rail transportation systems [3]. Moving away from fossil fuels that deplete reserves and continually increase in price is what is driving this shift in order to reduce air pollution and mitigate climate change [4].

There are two widely favored electric motor types: DC (direct current) and AC (alternating current) motors. While DC motors use direct current, where the direction of electric current remains constant, AC motors use alternating current, where the direction of electric current continuously changes. In electric vehicle (EV) applications, AC motors are widely preferred due to their uncomplicated structure, reliability, durability, minimal maintenance needs, cost-effectiveness, and ability to operate effectively in challenging environmental conditions. On the other hand, DC motors are characterized by higher operating temperatures and a comparatively lower capacity for torque [5]. In EVs, DC motors are unpreferable due to their limited constant power range [6]. The propulsion

technologies that are commonly chosen for electric vehicles (EVs) are brushless DC motors (BLDC), induction motors (IM), and permanent magnet synchronous motors (PMSM) [7]. High ratios of torque to inertia and power to weight, high maximum torque capability, high speed, low audible noise level, low maintenance, small size, low weight, reasonable cost, high efficiency over low and high speed ranges, energy recovery on braking, and non-sensitivity to acceleration forces are basically desirable features of the propulsion system for electric vehicles [8]. The industry uses IM extensively because of its robustness, reliability, and ease of control technique [9]. Moreover, in railway systems, PMSM is generally not preferred due to the short lifespan of the magnets and their difficult maintenance. High temperatures can decrease the magnetic field of magnets or even cause them to lose it entirely; therefore, the performance of permanent magnets may decrease in applications operating at high temperatures. For all these reasons, IM is mostly used in the traction of railway systems instead of DC motors or PMSM. The electric motor types are shown in **Fig. 1.1**.

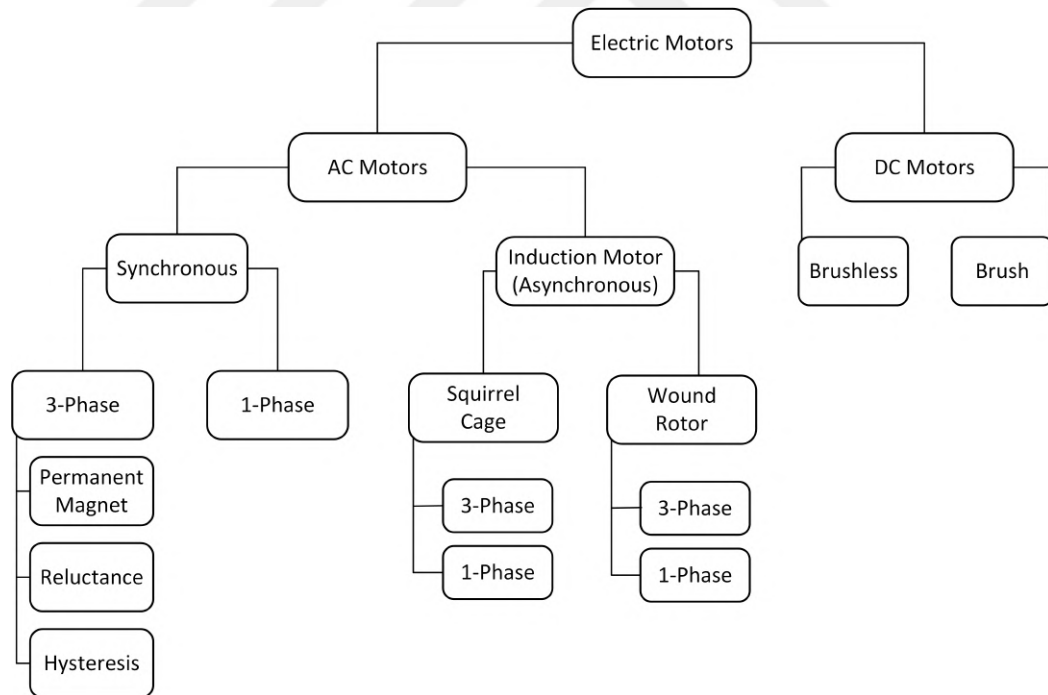


Figure 1.1: Taxonomy of the electric motors.

Toshiba and Skoda are two companies that produce high-power traction motors and traction inverters for the railway industry. The catalog called "Toshiba Traction and

Auxiliary Power Systems” on Toshiba’s website and the catalog called ”Skoda Traction Motors Product Catalog,” published by Skoda in 2012, provide information regarding the many types of train motors that are available for purchase. There are a total of 14 AC traction motors that TOSHIBA manufactures. Nine of these motors are AC induction motors, while five of them are permanent magnet synchronous motors (PMSM). The ”Skoda Traction Motors Product Catalog” gives a full description of the different types of AC motors that Skoda makes for mainline locomotives, metros, and trams. It also says that of the 25 traction motors that are manufactured, 24 are AC induction motors (ACIM) and only one is a permanent magnet synchronous motor (PMSM). The alternating current induction motor is the most suitable choice for train motors, as can be observed from the references described above. Considering the factors mentioned above, the AC induction motor has been utilized as a railway traction motor in the course of this research.

There are basically two control methods in the literature for AC induction motors: scalar and vector control methods. As the name suggests, scalar control ignores the coupling effect in the machine and just modifies the magnitude of the control variable. In scalar control, closed-loop V/F control is the most frequently employed speed control technique. It involves varying both the supply voltage and frequency while maintaining a constant V/f ratio. Scalar control is an inexpensive and easily applicable technique. However, it falls short of effectively managing drives characterized by rapid dynamic behavior, as it tends to exhibit sluggish responses to transients. Essentially, it represents a control method with suboptimal performance [10]. Scalar controls are simple to implement and offer efficient steady-state responses, but due to a lack of control, slow transients impair their dynamics. In contrast, for achieving superior precision and dynamic performance, vector control methods have been developed specifically for integration with closed-loop feedback systems [11]. Vector control’s primary purpose is the independent regulation of a motor’s flux and torque. Despite its increased complexity and the need for numerous calculations compared to other standard control techniques, vector control boasts various advantages. Some advantages of vector control are listed below [12] [13].

- Full and separate control over both flux and torque
- Better dynamic response and overall performance
- Efficient operation across a wide speed range
- Low energy loss
- Higher precision in motor control applications
- More stable systems
- The ability to quickly and accurately change torque
- Good performance in changing and dynamic conditions
- Overall flexibility in motor control strategies

There are two widely used vector control methods in traction control. They are field-oriented control (FOC) and direct torque control (DTC) methods. Field-oriented control is a technique used to enhance the control of an AC motor. This method works by separating the magnetic field of the motor into two distinct components: the rotating magnetic field and the fixed magnetic field. Direct torque control is another technique used for the control of AC motors. DTC focuses on directly controlling the torque and current of the motor. Out of all the strategies that are used for industrial railway traction applications that are based on induction motors, FOC is the most extensive and recommended technique [14]. SKODA, which operates tramways in Czechia and Latvia [15], and ALSTOM, which is responsible for the manufacture of high-speed trains, are examples of companies that have previously adopted and verified the FOC method [16] in their applications. A study [17] looks at the differences between field-oriented control (FOC) and direct torque control (DTC) for induction motors (IM) and permanent magnet synchronous motors (PMSM). For both motor types, enhanced steady-state behavior is found in the FOC method. It is highlighted that, in comparison to the induction motor (IM), the lower inductance of the permanent magnet synchronous motor (PMSM) resulted in increased torque fluctuations with the DTC method. To mitigate these fluctuations to an acceptable level, the use of lower sampling intervals was suggested in this study. A comparison is made between field-oriented control (FOC) and direct torque control (DTC) techniques in a different research paper [18]. It was established, on the

basis of the findings, that the field-oriented control approach demonstrates greater control performance in comparison to the direct torque control method. For the purpose of speed control, both DTC and FOC control displayed quick responses to disturbances. The findings suggested that the DTC approach gives a quicker reaction in transient settings, whereas the FOC method displays greater control performance against disturbances during motor operation. In comparison to field-oriented control (FOC), direct torque control is distinguished by a configuration that is less complicated. This is due to the fact that it does not require pulse width modulation or a specific rotor location, with the exception of when the rotor is being started up. The presence of substantial stator current ripples in steady state makes this technique unsuitable for high-precision systems, despite the fact that it is straightforward and exhibits a dynamic behavior that is advantageous [19]. Due to the aforementioned benefits that the FOC method offers in comparison to the DTC method, the FOC approach has been preferred in this study to regulate the railway traction motor.

Comprehensive testing is necessary before the train naturally runs on the rails. Developing and testing control systems for power electronics applications can incur significant costs and time investments. An efficient method for quickly prototyping and assessing power electronics systems and electric drives involves real-time hardware-in-the-loop (HIL) simulation [20]. Moreover, since numerous simplifications are made to expedite computation in software simulations, more authentic simulations are conducted using hardware in the loop to consider its actual constraints [2]. In the process of developing a system, hardware-in-the-loop (HIL) simulations are extremely important since they require usage of individual bits of hardware or the full hardware itself in the simulated loops. It is not necessary to perform extensive testing of the control algorithms because the simulation loop makes use of the actual hardware. The controller can also be simulated in the HIL simulations. These simulations are essential to the automobile, space, railway, defense, and marine industries. The simulation is linked to the simulation rather than the actual equipment that is being operated, making it an appropriate tool for testing a component such as an electronic control unit (ECU) or traction control unit (TCU) [21].

When considering the testing of railway systems, many studies have been conducted in literature. In [22], a digital real-time simulation is conducted for the motor control systems of rail vehicles using the field-weakening direct self-control method. In [23], an anti-slip control method for traction systems is validated through the hardware-in-the-loop (HIL) simulation approach. Another study [24] used the HIL method to calculate the admittance parameters in the control loop of railway traction motors. Using a fault-injection method and a hardware-in-the-loop (HIL) platform, the paper [25] looks into the effect that sensor flaws have on the performance of traction drives on a quantitative level. The proposed approach allows for the early detection and diagnosis of fault modes, as well as the comparison of performance levels. Through the utilization of hardware-in-the-loop and software-in-the-loop approaches, the article [1] provides a detailed explanation of the process of injecting an error into the safety-related Ethernet communication system of the train, thereby enabling the identification of the fault. Using instantaneous current and voltage data, the research presented in [26] develops an HIL simulation setup for a DC electric railway system. This setup takes into account the interaction between superconducting hardware and a real-time digital simulator. Additionally, the study considers the utilization of a current source rather than a voltage source at the time of simulation. The paper [27] presents a hardware-in-the-loop (HIL) test bench and a fuzzy PID-based traction control method. The test bench is used to validate the control algorithm, and the test results demonstrate the program's effectiveness in controlling the spin of the driven wheels. The work in the [28] introduces a FPGA-based real-time simulation platform for the electrical traction system of high-speed trains. The platform utilizes several simulators and supports many simulation steps, known as hardware-in-the-loop (HIL) simulation. An optimization approach of discrete-time switch admittance parameter is suggested for the ADC modelling method. The validity of the suggested modelling technique is confirmed by a comparison of the simulation results. A study [29] is introduced for control of AC railway induction motor with hybrid real time hardware-in-the-loop (HiL) simulator using FPGA and real time processor. The simulation is conducted with 1 KHz switching frequency and results show that there are approximately 20% deviation for speed when compared to reference inputs.

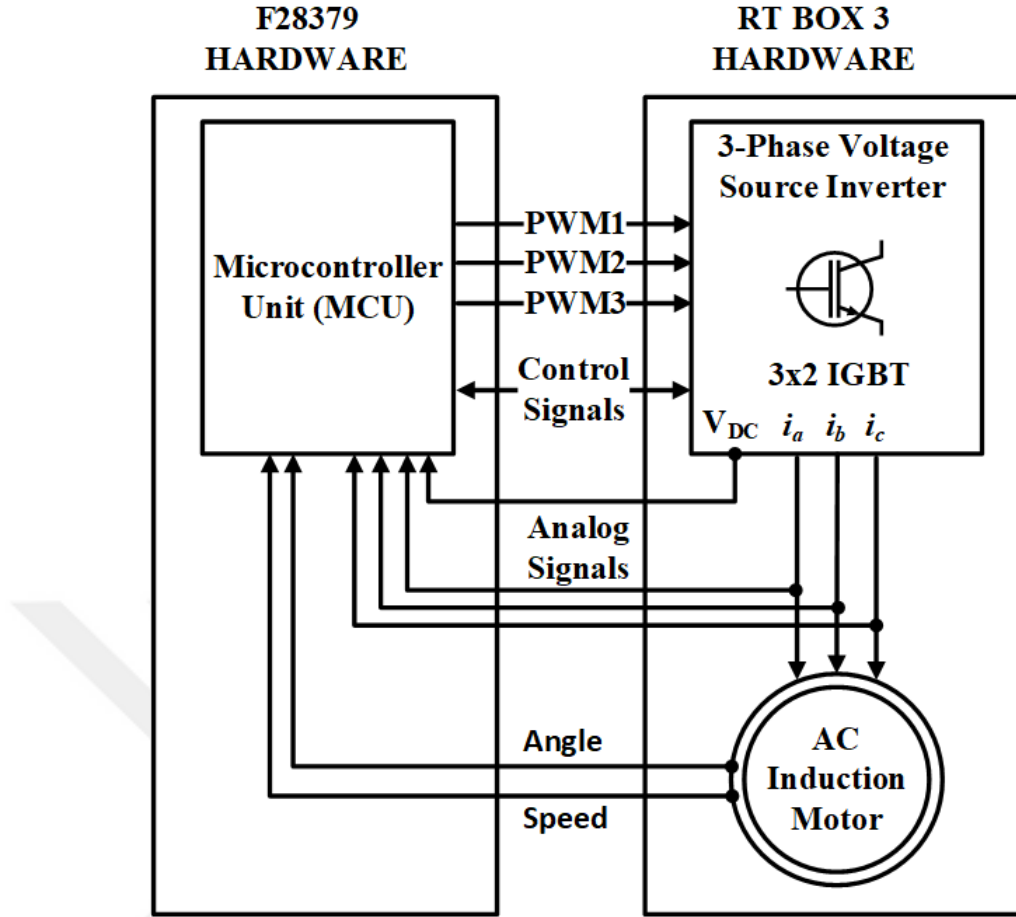


Figure 1.2: Block level schematic of the proposed HIL environment.

An examination of the hardware implementation of an advanced control method known as field-oriented control (FOC) is presented in this work. The goal of this analysis is to provide efficient and accurate control of torque over an AC induction motor, which is widely used as a traction motor in railway applications. Even though there are several articles discussing the control of AC induction motors using the field-oriented control (FOC) method, a few studies have been published in the literature that focus on implementing AC induction motor control with the FOC method in a hardware-in-the-loop (HIL) environment for railway vehicles. As a result, the design and implementation of the traction control unit for rail vehicles on the system on chip will be achieved. The block-level schematic of the proposed HIL environment is depicted in **Fig. 1.2**.

The methodology involves the integration of the FOC algorithm into the MCU, along with the incorporation of models representing the inverter and traction motor into the RT Box 3 simulator. Key factors, like a 1000V DC supply and a 1 kHz switching fre-

quency for the voltage source inverter (VSI), are carefully thought through to show that the proposed control strategy is both possible and effective. Understanding how FOC can be optimized and implemented in an HIL environment for railway traction motors is the main goal of this study. It hopes to help improve control strategies for making electric propulsion systems for railways more efficient, reliable, and long-lasting. The remainder of the thesis is as follows. In Section 2, an in-depth exploration of variable frequency drive control methods is presented. Following a comparison between vector and scalar control methods, the focus shifts to the field-oriented control (FOC) method—a vector control approach, with detailed insights. Additionally, the direct torque control (DTC) method is briefly outlined. Moving on to Section 3, a comprehensive examination of electric traction motor types employed in rail vehicles is provided. This includes a detailed analysis of AC induction motors and permanent magnet synchronous motors. Furthermore, the operating logic and various types of the inverter circuit, responsible for converting DC voltage to the required AC voltage for the traction motor, are explained. Section 4 demonstrates the efficient and precise control achieved through Hardware-in-the-loop real-time simulation, utilizing the proposed FOC method, AC Induction motor type, and Voltage source inverter structures. The parameters are suitable for optimal performance in train motors and inverters. Finally, in Section 5, the thesis concludes with general remarks and suggestions for future work.

2. VARIABLE-FREQUENCY DRIVE CONTROL

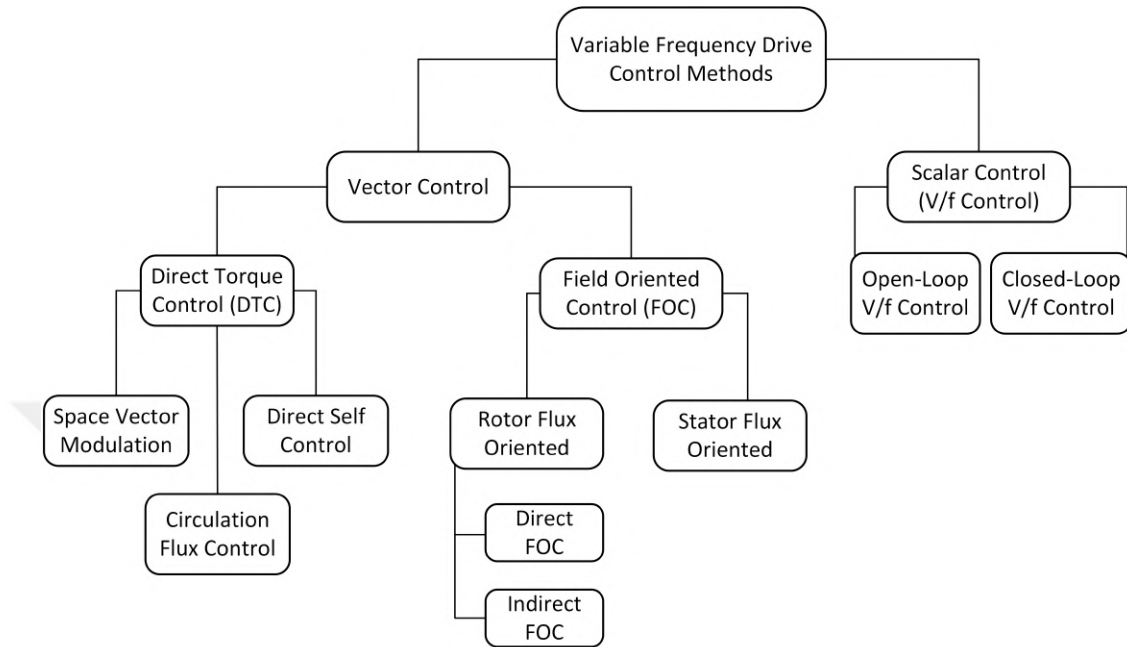


Figure 2.1: VFD control methods.

A variable frequency drive (VFD), also known as an adjustable frequency drive (AFD) or inverter drive, is a motor controller that allows for precise control over the speed and torque of an electric motor by adjusting the frequency and voltage supplied to the motor. VFDs enhance process control by providing accurate regulation of motor speed, and they can be employed in various applications, including pumps, fans, conveyors, and HVAC systems. These drives offer features such as dynamic braking, torque control, adjustable acceleration and deceleration rates, and automatic voltage regulation. Specifically considering AC induction motors, widely utilized in industrial automation and control, they have some significant features such as high durability, robustness, reliability, and low maintenance [30]. Variable frequency drive (VFD) control techniques can be broadly categorized into two types, as shown in **Fig. 2.1** scalar control and vector control methods.

2.1. Scalar Control

Scalar control, also called V/f, V/Hz, or constant voltage/hertz control, has a simple structure. The V/F ratio directly relates to the torque that the induction motor produces. If the voltage and frequency are adjusted while maintaining a constant ratio, the induction motor's torque will be consistent over the whole speed range [31]. However, this controller has disadvantages in achieving optimal accuracy in speed and torque responses. This is primarily because there is no direct control over stator flux and torque [32].

2.1.1. Open-Loop V/F Control

Because induction motors are so commonly used in industry and their open-loop V/F control is so straightforward, it is the most popular way to regulate speed. The affordability, ease of use, and resistance to feedback signal faults are some of the benefits of this kind of motor control. There are a few issues that arose when using this open-loop drive. These issues include the inability to regulate the motor's speed due to the rotor speed being marginally slower than the synchronous speed and the fact that the sole controllable variable in this design is the synchronous speed due to the stator frequency [31]. A block diagram of open-loop V/F control is shown in **Fig. 2.2**.

2.1.2. Closed-Loop V/F Control

Applying a variable magnitude and variable frequency voltage to the motor is the foundation of closed-loop voltage/frequency speed control for induction motors [31]. Compared to the open-loop approach, the closed-loop method provides a more accurate means of regulating the speed. Moreover, the torque is also controlled via the closed-loop method. The fact that the open-loop control system does not regulate torque and can only achieve the necessary torque at the nominal operating point is a significant drawback. The motor's speed will vary in response to variations in the torque of the load [33]. The block diagram of closed-loop V/F scalar control is depicted in **Fig. 2.3**.

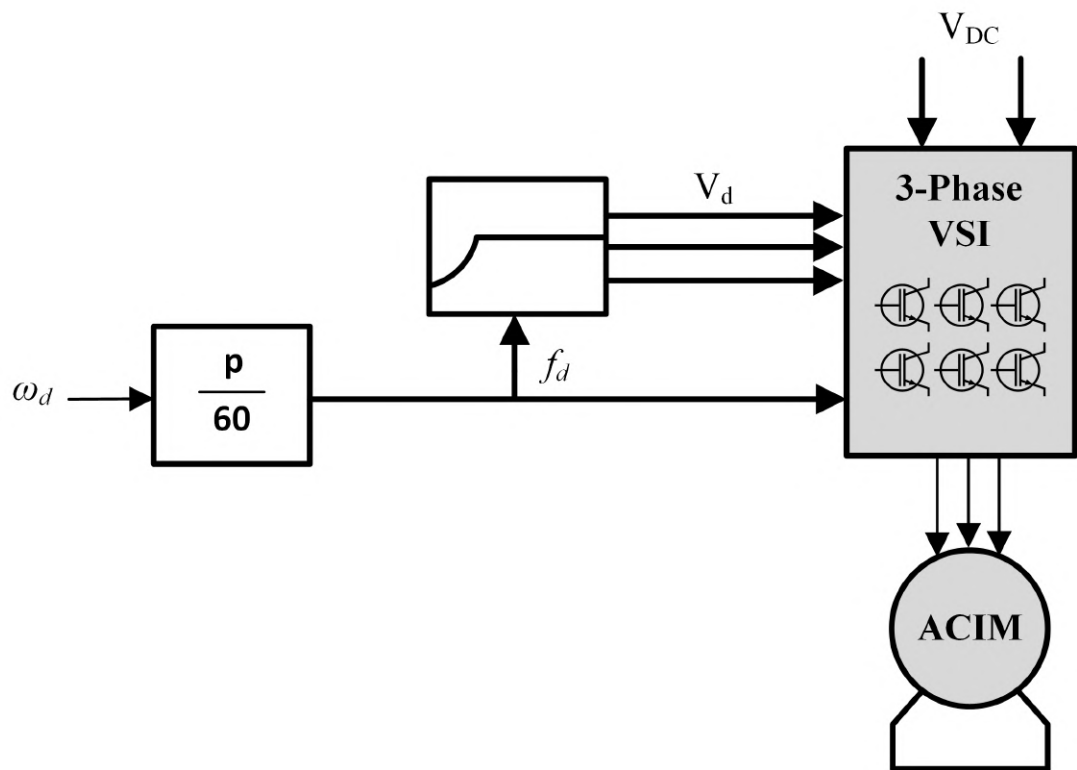


Figure 2.2: Open-loop V/F control block diagram.

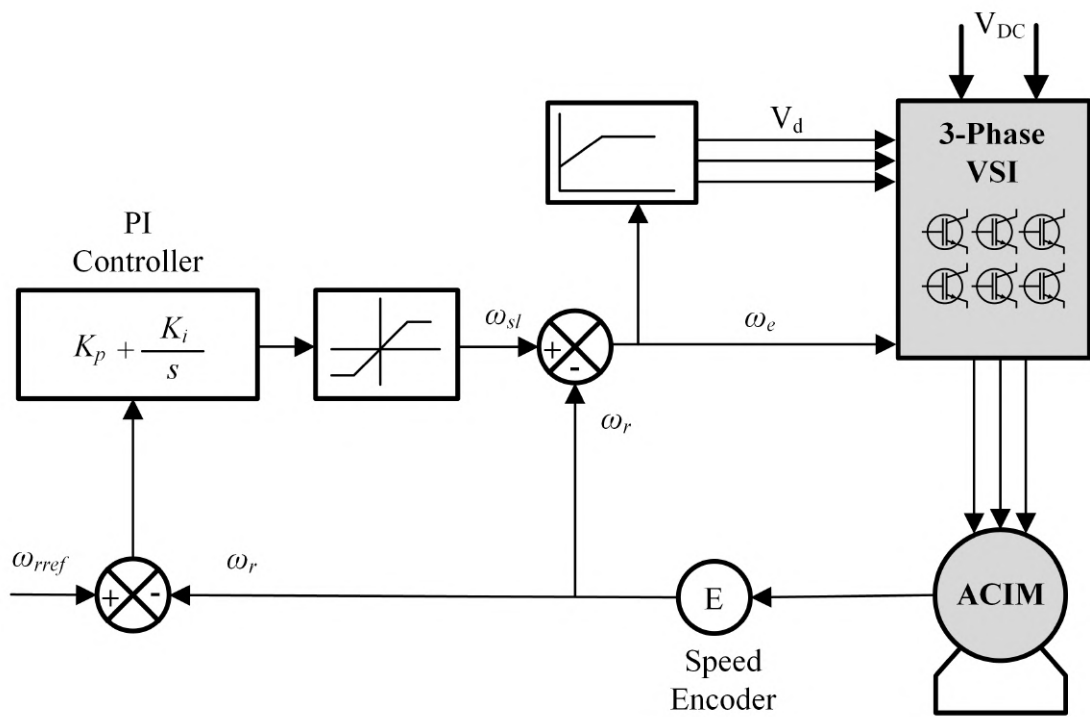


Figure 2.3: Closed-loop V/F control block diagram.

2.2. Vector Control

An induction motor's speed may be changed over a large range using a method known as vector control, which was first founded by Blaschke in the early 1970s [34]. Two quadrature components—one that regulates the motor's flux level and the other that regulates its torque production—combine to form a complicated current in the vector control scheme. In essence, the control issue is rewritten to seem like a DC motor's control. Speed control across a broad range, accurate speed regulation, quick dynamic reaction, and operating above base speed are only a few advantages of vector control [35].

2.2.1. Field Oriented Control

Field-oriented control (FOC) stands out as a preferred strategy for controlling electric motors in rail vehicles, offering a range of advantages in these applications. Enabling enhanced torque response and precise control at low frequencies and speeds, FOC ensures dynamic speed accuracy while simultaneously reducing motor size, cost, and power consumption [36]. Additionally, FOC improves energy efficiency by optimizing voltage and current balance, minimizing unnecessary energy losses, extending range, and reducing overall energy consumption. Understanding the rotor flux position and two stator currents is necessary for the FOC. The key component of the FOC is the understanding of the rotor flux position. Actually, if there is a mistake in this variable, the current components are computed wrongly and the rotor flux is not aligned with the d-axis. Since the rotor speed and rotor flux speed in an induction machine are not identical, a unique approach must be used to determine the rotor flux position (in other words rotor flux angle) [35].

When it comes to electric machines, especially AC induction or synchronous motors, the terms rotor flux orientation and stator flux orientation refer to the alignment of magnetic fields inside the revolving and stationary components, respectively. In other words, the terms are used to describe the orientation of the magnetic fields. Rotor flux orientation is shown by the rotor, which is the component of the motor that rotates. This is because the winding of the rotor creates a magnetic field that is generated by the revolving field of the stator, which in turn causes the rotor to follow suit owing

to electromagnetic induction. Stator flux orientation, on the other hand, refers to the alignment of the magnetic field that is generated by the stationary stator winding. This magnetic field forms a spinning magnetic field when it is powered with alternating current power or direct current. These ideas are essential for gaining an understanding of motor dynamics, since the rotor flux has an effect on the torque and speed of the motor, while the stator flux is responsible for defining the speed at which the motor operates as a whole. Within electric motors, the transformation of electrical energy into mechanical energy is in large part accomplished by these orientations, which work together to perform a crucial function. The FOC architecture of a three-phase AC induction motor (ACIM) is shown in **Fig. 2.4**, and the working principle of the algorithm is explained in the following subsections.

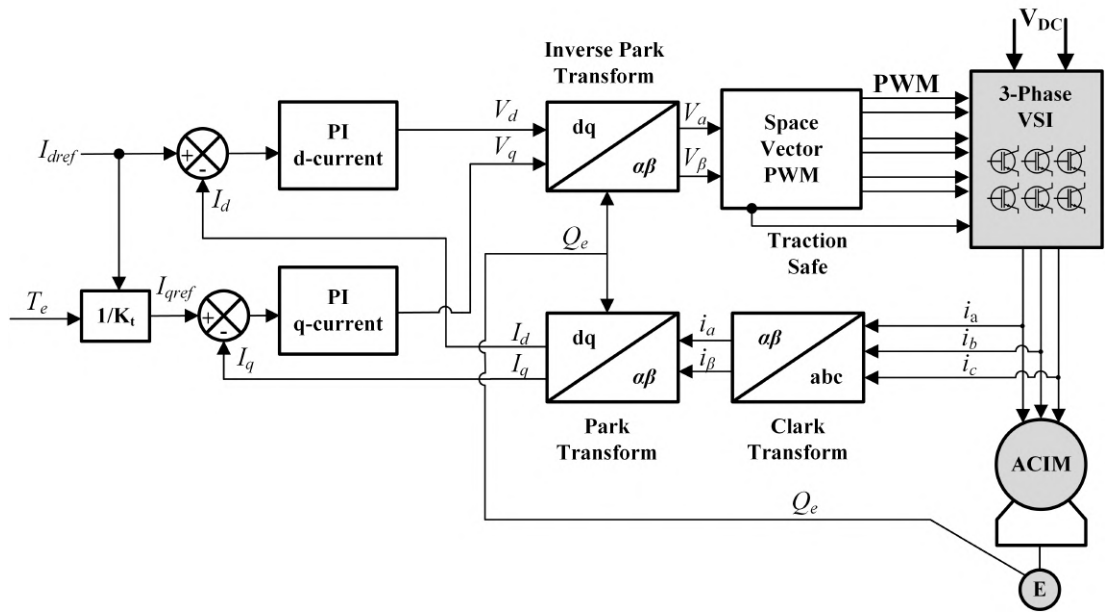


Figure 2.4: FOC structure of a 3-PH AC induction motor.

2.2.1.1. Clarke Transformation

Upon measuring the 3-phase stator currents i_a , i_b , and i_c , the three-phase stator currents are transformed into two-axis currents i_α and i_β through the application of a Clarke transformation, as illustrated in **Fig. 2.5**. The Clarke transformation equations are shown in Equation 2.1, Equation 2.2, and Equation 2.3.

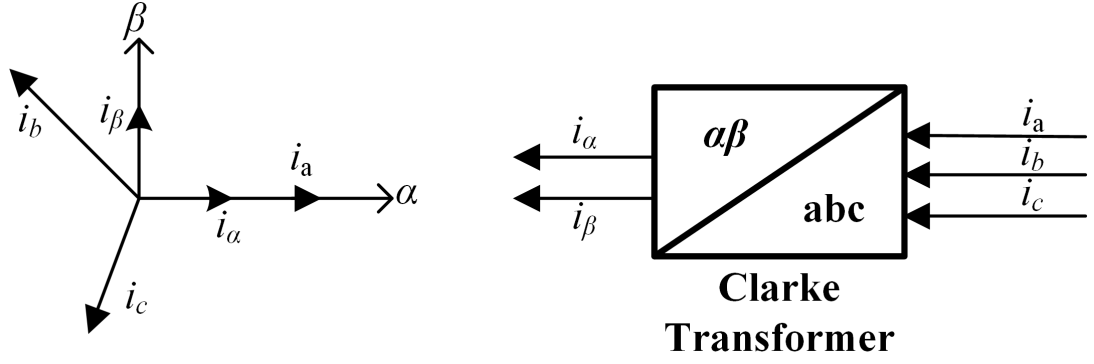


Figure 2.5: Clarke transformation vector.

$$i_a + i_b + i_c = 0 \quad (2.1)$$

$$i_\alpha = i_a \quad (2.2)$$

$$i_\beta = \frac{i_a + 2i_b}{\sqrt{3}} \quad (2.3)$$

Clarke transformation matrix:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{1}{\sqrt{3}} & \frac{2}{\sqrt{3}} & 0 \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

where,

- i_a , i_b and i_c are three-phase stator currents.
- i_α , i_β are stationary orthogonal reference frame currents.

2.2.1.2. Park Transformation

The two-axis currents i_α and i_β undergo transformation into another set of two-axis currents i_d and i_q , achieved through the utilization of a park transformer as shown in **Fig. 2.6**. This park transformation facilitates the derivation of a two-coordinate linear time-invariant (LTI) system. Consequently, the LTI system enables the implementation of straightforward and easily applicable proportional-integral (PI) controllers, streamlining the control of torque and flux-producing currents.

The Park transformation equations are shown in Equation 2.4 and Equation 2.5.

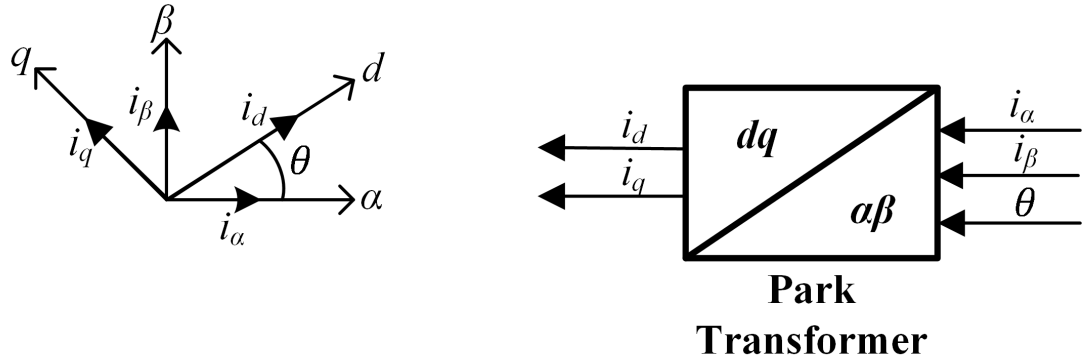


Figure 2.6: Park transformation vector.

$$i_d = i_\alpha \cos \theta + i_\beta \sin \theta \quad (2.4)$$

$$i_q = -i_\alpha \sin \theta + i_\beta \cos \theta \quad (2.5)$$

Park transformation matrix:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

where,

- i_d and i_q are rotating reference frame currents.
- i_α, i_β are orthogonal stationary reference frame currents.
- θ is the rotor angle of motor.

2.2.1.3. PI Controller

The proportional-integral (PI) controllers are employed to regulate the d-axis and q-axis currents to reach desired values, ensuring the desired flux and torque are achieved at the motor. FOC continuously calculates and updates these values, swiftly adapting to any changes in motor speed or torque, effectively achieving the desired performance [11]. The algorithm utilizes feedback from sensors, such as encoders, to monitor the motor's real-time state, aiding in the adjustment of the PI control algorithm.

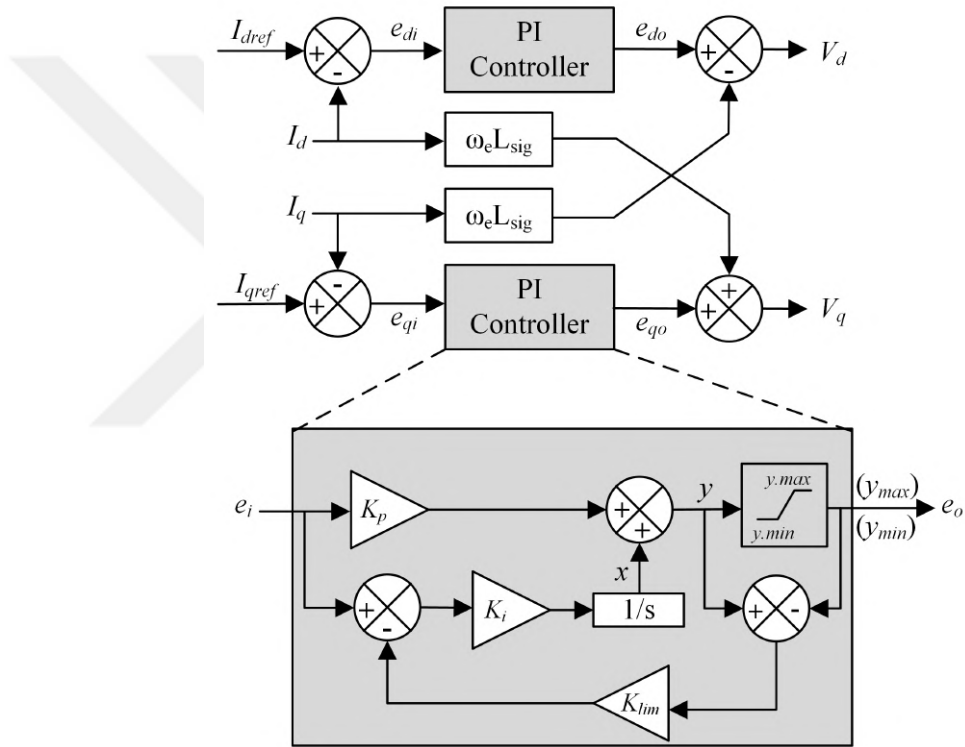


Figure 2.7: PI controller scheme.

In this study, we employ an advanced Anti-windup proportional-integral (PI) controller recognized for its superior performance and enhanced safety features. Inner current loop control and the proposed PI control algorithm scheme are depicted in **Fig. 2.7**. The open-loop transfer function of a typical PI controller is given following equation.

$$G(s) = K_p \left(1 + \frac{1}{T_i s} \right) \quad (2.6)$$

However, our approach involves the utilization of an Anti-windup PI controller, which is characterized by higher performance and a more robust operational structure. This controller is specifically designed to mitigate issues related to integral windup, ensuring not only improved overall performance but also a safer and more reliable operation.

Anti-windup PI Controller

According to the Anti-windup PI controller illustrated in the bottom of **Fig. 2.7**, the output value e_o is constrained within the minimum and maximum values of the saturation block. Additionally, the feedback loop incorporates the difference between the actual output y and the saturated output e_o , which is then adjusted through a gain K_{lim} to diminish the amount of error input e_i entering the integrator. A greater K_{lim} value maintains the proximity of the actual output y to the saturated output e_o , facilitating a prompt exit from saturation for the controller when the error direction changes [37].

Assuming the actual output y of the proposed Anti-windup PI controller surpasses the saturated output e_o and x represents the output of the integrator. If we consider that the actual output y is greater than the maximum value of the saturation block, then Y_{max} can be a representation of saturated output e_o . Then, we can establish a relationship between the input and output using the following set of six equations:

$$\frac{dx}{dt} = K_i [e_i - K_{lim}(y - Y_{max})] \quad (2.7)$$

$$y = x + K_p \times e_i \quad (2.8)$$

Hence,

$$\frac{dx}{dt} = -K_i K_{lim} x + K_i (1 - K_{lim} K_p) e_i + K_i K_{lim} Y_{max} \quad (2.9)$$

Equation 2.10 is the result of solving Equation 2.9 for a constant error input, denoted as $e_i(t) = E_i$.

$$x(t) = \left(X_0 - \frac{E_i}{K_{lim}} - Y_{max} + K_p \times E_i \right) \exp^{-K_i K_{lim} t} + \left(\frac{E_i}{K_{lim}} + Y_{max} - K_p \times E_i \right) \quad (2.10)$$

X_0 at Equation 2.10 represents the initial value of variable ' x '. The expression for the output ' y ' can now be formulated as Equation 2.11 with the help of Equation 2.8.

$$x(t) = \left(X_0 - \frac{E_i}{K_{lim}} - Y_{max} + K_p \times E_i \right) \exp^{-K_i K_{lim} t} + \left(\frac{E_i}{K_{lim}} + Y_{max} \right) \quad (2.11)$$

If the steady-state value of variable ' y ' is denoted as ' Y_{ss} ', then

$$Y_{ss} = Y_{max} + \frac{E_i}{K_{lim}} \quad (2.12)$$

As can be observed from Equation 2.12, a high value for K_{lim} is essential. This ensures that Y_{ss} approaches Y_{max} , allowing the controller to swiftly recover from saturation when the error input ' e ' changes direction. Additionally, achieving a rapid steady state under saturation conditions requires a very high value for K_{lim} .

PI Maximum Gain

The following equations were established to get the maximum gain from the proposed PI controller. The phase margin (PM) is changeable and chosen at 50 degrees. Switching frequency f_{sw} is 1 kHz. Hence,

$$T_{sw} = \frac{1}{f_{sw}} = 1ms \quad (2.13)$$

$$T_{pe} = \frac{3}{2} \cdot T_{sw} = 1,5ms \quad (2.14)$$

Table 2.1: Anti-windup PI controller parameters

Parameters	Abbreviation	Value	Unit
Switching Frequency	f_{sw}	1	kHz
Switching Period	T_{sw}	1	ms
Crossover Frequency	ω_c	47.15	rad/sec
Sigma-axis Inductance	L_σ	984	μH
Proportional Gain	K_p	0.0464	—
Integral Time Constant	T_i	4.571	—
Integral Gain	K_i	0.218	—
Limit Gain	K_{lim}	4.717	—

$$\omega_c = \frac{90 - PM}{180\pi T_{pe}} = 47,15 \text{ rad/sec} \quad (2.15)$$

The crossover frequency, denoted as ω_c , is the frequency at which the magnitude of the transfer function $G(jw)$ is equal to 1. In other words, it's the frequency at which the gain of the system is 0 dB (decibels).

The sigma axis is referred to as the axis around which the rotor rotates. The inductance along the sigma axis of the magnetic field L_σ indicates how much resistance the motor's magnetic field presents along this axis. L_σ could be found by Equation 2.17 with the inductance parameters of the motor at **Table 4.1**.

$$K_p = \omega_c L_\sigma = 0,0464 \quad (2.16)$$

$$L_\sigma = L_s - \frac{L_m^2}{L_r} = 984\mu H \quad (2.17)$$

$$T_i = \frac{10}{\omega_c^2 L_\sigma} = 4,571 \quad (2.18)$$

$$K_i = \frac{1}{T_i} = 0,218 \quad (2.19)$$

$$K_{lim} = \frac{K_i}{K_p} = 4,714 \quad (2.20)$$

2.2.1.4. Inverse Park Transformation

The output values V_d and V_q of the PI controllers undergo transformation into the stationary reference frame using an inverse park transformer. Consequently, voltage values V_α and V_β are derived as illustrated in **Fig.2.8**.

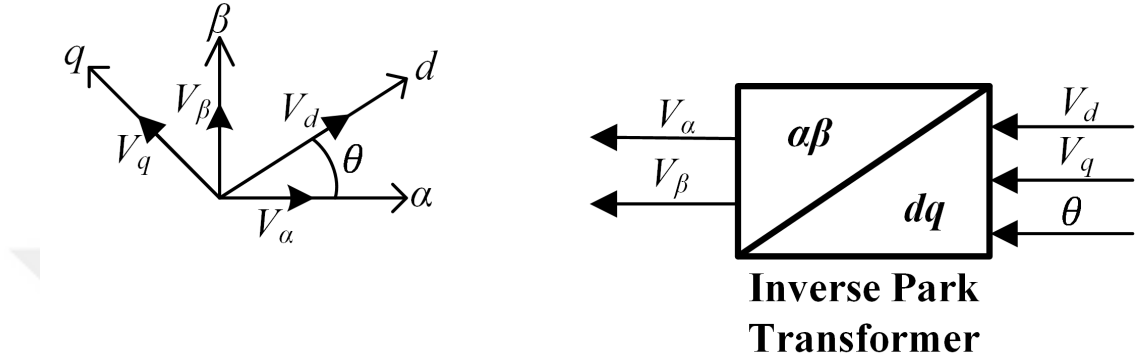


Figure 2.8: Inverse park transformation vector.

The Inverse-park transformation equations are shown in Equation 2.21 and Equation 2.22.

$$V_\alpha = V_d \cos \theta - V_q \sin \theta \quad (2.21)$$

$$V_\beta = V_d \sin \theta + V_q \cos \theta \quad (2.22)$$

Inverse park transformation matrix:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

where,

- V_α and V_β are orthogonal stationary reference frame voltages.
- V_d, V_q are rotating reference frame voltages.

2.2.1.5. Inverse Clarke Transformation

The Inverse-clarke transformation block is embedded in the SVPWM block in **Fig. 2.4**. The values V_α and V_β undergo a transformation into three-phase voltage values through the utilization of an Inverse-clarke transformation, as illustrated in **Fig. 2.9**. These transformed values are then employed in the computation of SVPWM (Space Vector Pulse Width Modulation) duty cycle values.

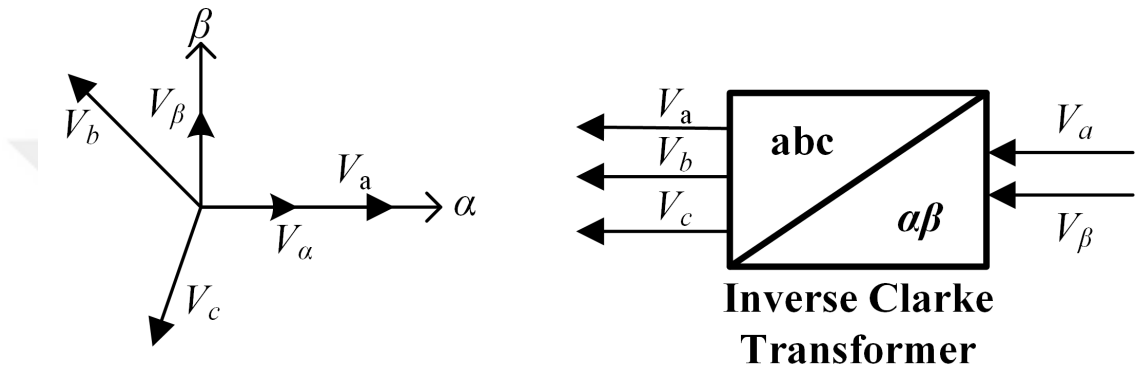


Figure 2.9: Inverse clarke transformation vector.

The Inverse-clarke transformation equations are shown in Equation 2.23, Equation 2.24, and Equation 2.25.

$$V_a = V_\beta \quad (2.23)$$

$$V_b = \frac{-V_\alpha + \sqrt{3}V_\beta}{2} \quad (2.24)$$

$$V_c = \frac{-V_\alpha - \sqrt{3}V_\beta}{2} \quad (2.25)$$

Inverse-Clarke Transformation Matrix:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}$$

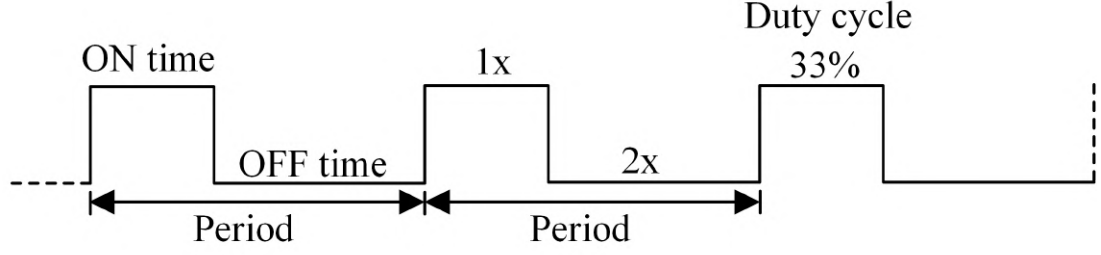


Figure 2.10: PWM duty cycle.

where,

- V_a , V_b and V_c are three-phase voltages.
- V_α , V_β are stationary orthogonal reference frame voltages.

2.2.1.6. Space-Vector PWM Generation

Power electronic circuits that switch between on and off states use pulse width modulation (PWM) to control the transmission and cutoff states of switching elements. This approach includes the determination of duty cycles, which can be described as the ratio of the duration of active time to the period and simply shows the amount of "on time" or "off time.". Equation 2.26 shows the duty cycle formula. A sample PWM signal and duty cycle representation are illustrated in **Fig. 2.10**.

$$Duty\ cycle\ (D) = \frac{T_{on}}{T_{period}} \times 100 \quad (2.26)$$

Space vector pulse width modulation is a technique developed to enable the generation of switching signals by utilizing the lengths and orientation angles of space vectors in determining the duty cycles of pulse width modulation signals. One of the most significant advantages of space vector pulse width modulation is its ability to leverage the direct current bus voltage in voltage-source inverters more effectively compared to other modulation techniques. The voltage level of the direct current signal obtained by rectifying the alternating current signal applied to the input of the inverter determines the effective value of the waveform that can be generated at the output of the inverter. The effective value of the alternating current signal that can be generated at the output

of the inverter will vary proportionally with how much benefit can be derived from the direct current bus voltage. Since the alternating current signal produced at the inverter's output is directly applied to the motor, maximizing the utilization of the direct current bus voltage is crucial for achieving the highest performance the motor can deliver [38]. Another advantage of using space vector pulse width modulation with field-oriented control is the direct utilization of space vectors expressed in the two-phase plane (stator reference plane) in modulation-related calculations. This advantage eliminates the need for an additional transformation, reducing the processing load introduced by the field-oriented control algorithm [38] [39]. **Fig. 2.11** illustrates a three-phase system featuring three switches consisting of six transistors. The primary objective in system control is to appropriately switch the transistors based on the current measurement levels within the system. When the top switch is on, the bottom one is off, or vice versa. With the presence of 6 transistors, there are 8 potential combinations, where each phase potential can be either positive or negative, resulting in a total of 8 combinations [39]. Each combination is illustrated in **Fig. 2.11**. Depending on the condition of the switches, line voltages may be found using the following matrices: The first matrix calculates line-to-line voltages, while the second matrix calculates line-to-neutral voltages.

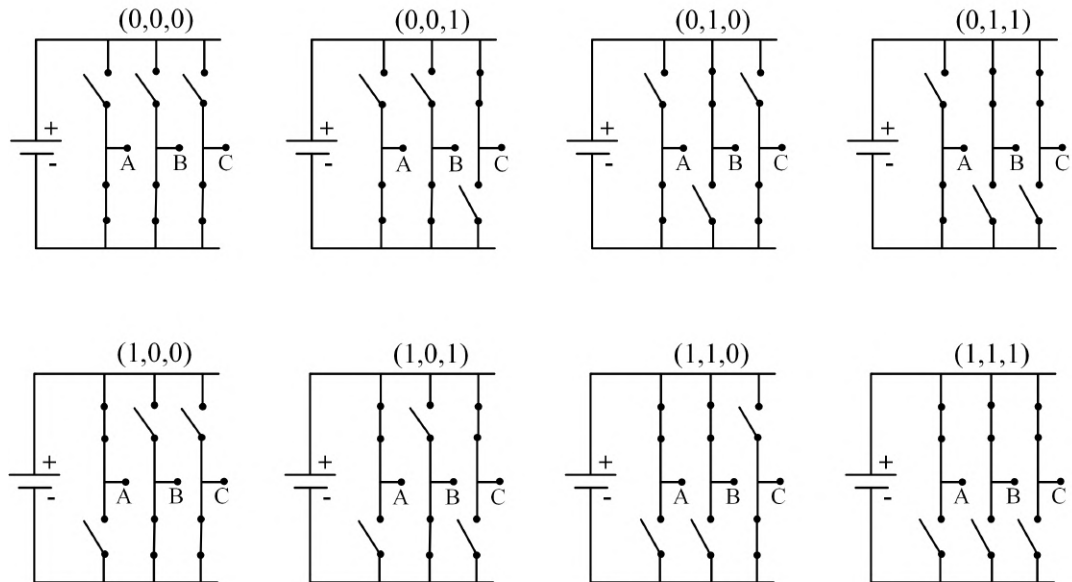


Figure 2.11: SVPWM switch states.

Line-to-line voltages:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ac} \end{bmatrix} = V_{DC} \cdot \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 1 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} S_1 \\ S_3 \\ S_5 \end{bmatrix}$$

Line-to-neutral voltages:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{DC}}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} S_1 \\ S_3 \\ S_5 \end{bmatrix}$$

The vectors $[0, 0, 0]$ and $[1, 1, 1]$ are termed zero vectors as they have no impact on the output voltage. This lack of influence is attributed to the absence of any potential difference. Each state is denoted by a vector ranging from V_0 to V_7 , as depicted in **Fig.2.12**, featuring a 60-degree phase difference between successive vectors. Additionally, V_0 and V_7 are positioned at the center of the star, symbolizing the fully open bottom and the fully open top configuration, respectively [40].

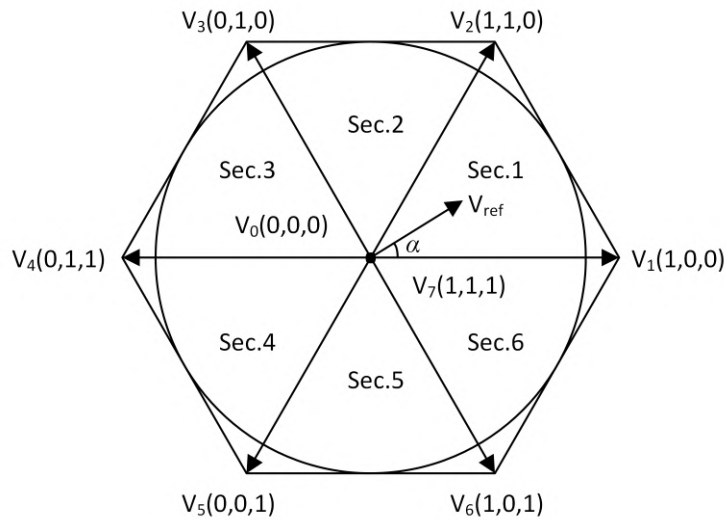


Figure 2.12: Space vector hexagonal star diagram.

2.2.1.7. Direct and Indirect Field-Oriented Control

Field-oriented control can be divided into two main categories: direct field-oriented control (DFOC) and indirect field-oriented control (IFOC). In vector control, having information about the rotor angle is crucial. Utilizing Hall sensors or estimating it using an adaptive scheme are two ways to determine the rotor angle [41]. In direct field-oriented control (DFOC), the rotor field angle is directly measured through a search coil or Hall sensor and subsequently derived. In IFOC, the rotor magnetic field is estimated, and the stator current is aligned with this estimated magnetic field. Even though DFOC has a more intricate and expensive structure, it produces very precise results. Furthermore, the dynamics of speed control in induction-machine (IM) drives with IFOC are effective during low-speed operation, but during rated-speed operations, DFOC provides superior dynamic performance when compared to IFOC [41]. Because rail transportation is safety-critical, the DFOC approach is used in this study to provide exact findings, as the cost was not taken into account.

2.2.2. Direct Torque Control (DTC)

In the late 1980s, the DTC idea was first presented to the public. Beginning in the middle of the 1990s, ABB has been producing a direct torque-regulated induction motor drive for commercial use. In the direct torque controller that was created by ABB, the optimal switching pattern for the inverter is calculated during each and every sample interval. A subsystem that contains torque and flux hysteresis controllers as well as appropriate inverter switching logic is the most important component of the control system of a direct current converter (DTC). Because the calculation of the stator flux and motor torque is reliant on the machine model as well as the measurement of the machine input stator voltages and currents, it is also necessary to have an accurate machine model. There is no need for the measurement of real speed. DTC theory is developed with the use of a machine model that is based on a stationary reference frame [11]. This method aims to optimize motor performance by utilizing a tight control loop for rapid responses to changing parameters. DTC maintains the motor's magnetic flux balance through the volt-second balance principle, ensuring the desired magnetic flux levels. Noteworthy for its ability to provide fast and accurate torque control, DTC excels at

delivering high torque at low speeds. While it boasts advantages such as simplicity in hardware requirements, it may introduce ripple in current and torque profiles in specific scenarios, and vibration issues can arise at lower speeds [42]. Overall, DTC proves effective in various applications, but consideration of its advantages and disadvantages is crucial based on specific application needs and motor characteristics. A block diagram of DTC is shown in 2.13.

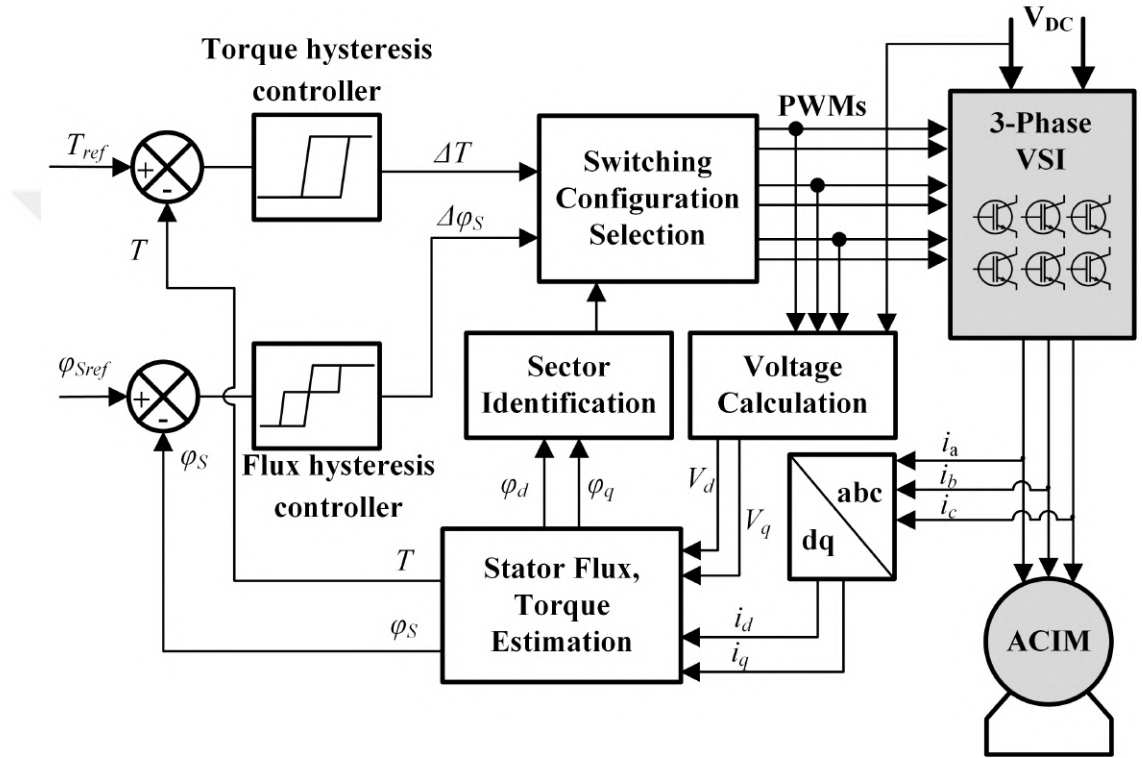


Figure 2.13: Block diagram of DTC.

In addition to direct torque control (DTC), direct self control (DSC), which is a subclass of DTC, was initially introduced in the late 1980s for use in induction motors with a hexagonal stator flux path. A number of high-power and low-frequency applications, like railway traction, were able to effectively utilize this technology [43].

Direct self control (DSC) is a more advanced control approach that is utilized in the field of AC induction motors. It is classified under the more general category of direct torque control (DTC). DSC was developed to overcome the issues that are presented by conventional DTC, specifically the problem of torque and flux ripple. The goal of DSC is to achieve more precise control. The fundamental goal of this structure is to

achieve optimal torque and flux management while simultaneously limiting changes that are not desirable [44]. The most important aspect of DSC is the careful selection of the voltage vector for the forthcoming sampling period. This decision is based on real-time assessments of the torque and flux of the motor. In order to facilitate the strategic selection of the voltage vector for increased control, the stator flux space is segmented into sectors, and the condition of the motor is determined within these sectors. Using hysteresis controllers, the DSC computes the switching states of the inverter by comparing the estimated and reference values of torque and flux. This helps to reduce the number of errors that occur. There are even some implementations of DSC that incorporate optimization techniques in order to determine the ideal voltage vector. This results in a significant reduction in torque and flux ripple. One of the most significant benefits of DSC is its ability to reduce torque ripple, which ultimately results in an improvement in the overall performance of AC induction motors. Nevertheless, it is of the utmost importance to acknowledge the difficulties that are linked with DSC, such as the needs for real-time processing and the complexity of the computations involved. As the field of motor control technology continues to improve, DSC continues to be at the forefront of the field. It represents a refined and sophisticated way to attain torque and flux management in electric motors that is smoother and more precise [45].

3. TRACTION MOTOR AND INVERTER

In rail propulsion systems, the traction motor and the inverter are essential components. It has the greatest significance to effectively regulate these components in order to achieve the highest possible levels of efficiency, performance, and range in electric vehicles. The development of more sophisticated motor control algorithms and power electronics technologies is continuing, which is contributing to the continual enhancement of the capabilities and efficiency of electric propulsion systems.

3.1. Traction Motor

The traction motor is the component of the rail vehicle that is responsible for converting the electrical energy that is supplied by the battery or any other source of power into the mechanical energy that is required to drive the vehicle. Brushless permanent magnet synchronous motors (PMSMs) or asynchronous induction motors are frequently employed as traction motors in the electric propulsion systems of rail vehicles. The design of the motor affects performance variables like efficiency, power density, and torque. Other important performance elements include torque characteristics. There is a direct correlation between the performance and efficiency of the traction motor and the overall efficiency and range of the electric vehicle. Motor control technologies such as direct torque control (DTC) or field-oriented control (FOC) are fundamentally important in order to achieve the highest potential levels of performance and energy economy. Types of electric motors are shown in Fig. 1.1 at Chapter 1.

3.1.1. AC Induction Motor (ACIM)

Modern electric traction employs asynchronous motors to propel railway vehicles, as these motors offer numerous advantages over traditional direct-current motors. Minimizing the consumption of active and reactive electrical energy is a priority with these motors, leading to a considerable reduction in operational costs [46]. When motor is connected to an AC power source, the stationary component called the stator creates a rotating magnetic field. Based on the principle of electromagnetic induction, the rotor,

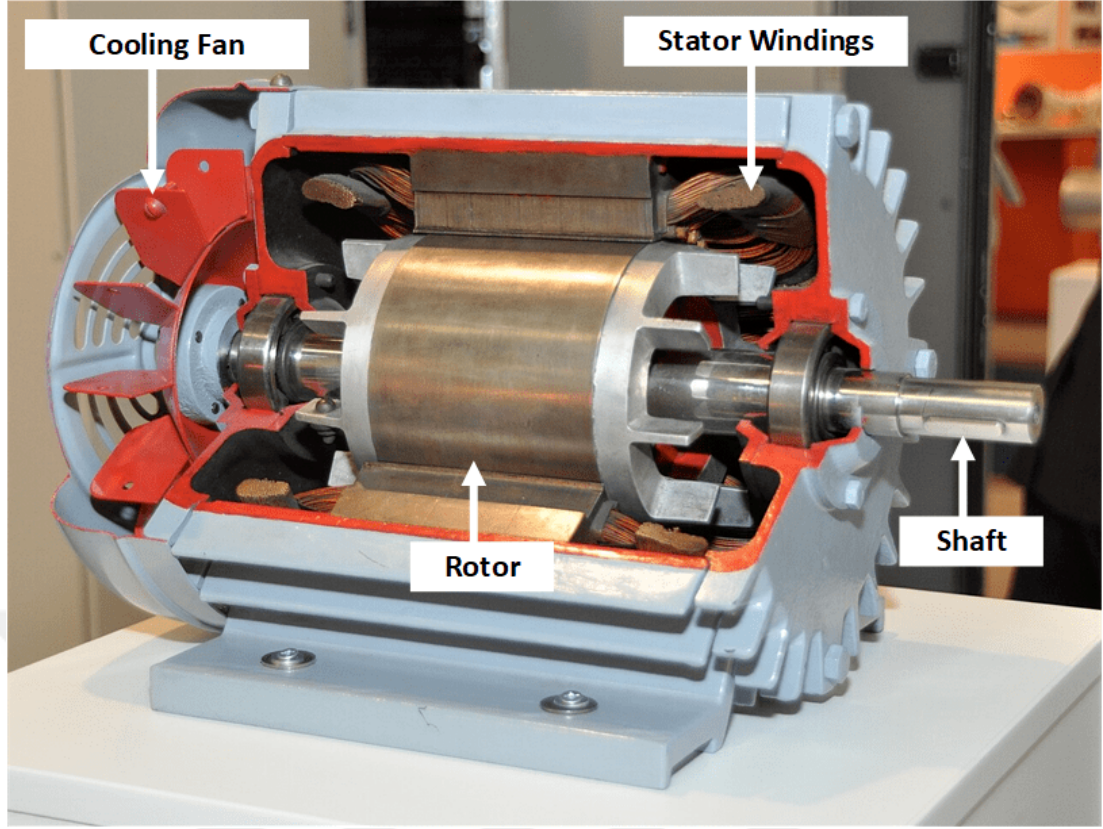


Figure 3.1: A photo of sample AC induction motor.

equipped with conductive bars, engages with the stator's magnetic field as per Faraday's law. This interaction induces torque, resulting in the rotation of the rotor. The induction motor exhibits the capability to quickly attain the desired speed reference while achieving efficient energy gains within the safe current limits in both generator and motor modes [47]. A sample photo of an AC induction motor is shown in **Fig. 3.1**. The equivalent circuit of the AC induction motor is depicted in **Fig. 3.2**. Three-phase induction motor equations in the stator reference frame are as follows:

$$V_s = R_s i_s + \frac{d}{dt} Y_s \quad (3.1)$$

$$0 = R_r i_r + \frac{d}{dt} Y_r - j\omega Y_r \quad (3.2)$$

$$Y_s = L_s i_s + L_m i_r \quad (3.3)$$

$$Y_r = L_r i_r + L_m i_s \quad (3.4)$$

$$T_e = \frac{3}{2} p \frac{L_m}{L_r} (Y_r i_s) \quad (3.5)$$

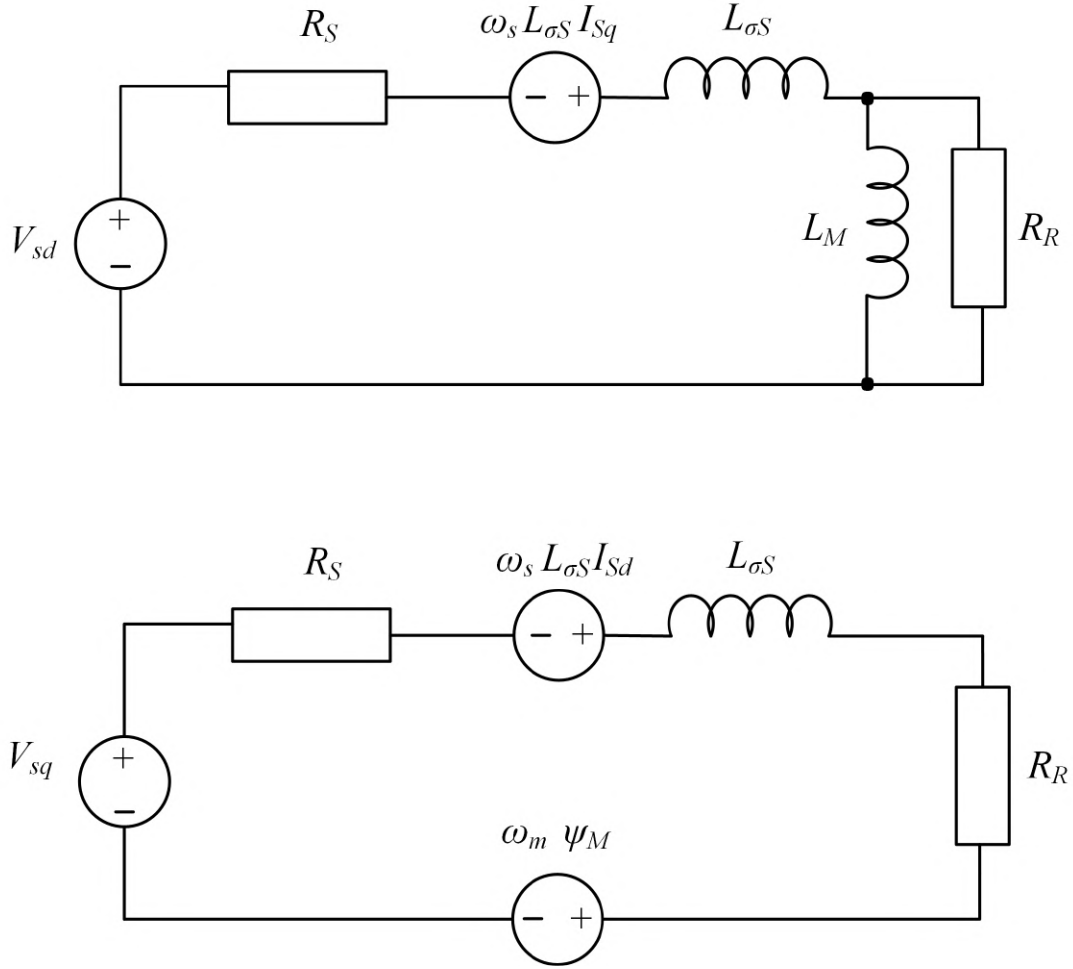


Figure 3.2: Equivalent circuit of the induction machine.

where,

- V_s denotes the stator voltage.
- Y_s and Y_r represent the stator and rotor flux.
- i_s and i_r are the stator and rotor currents.
- R_s and R_r are the stator and rotor resistances.
- L_s , L_r , and L_m are stator, rotor, and mutual inductances, respectively.
- ω is the electrical speed and p is the number of pole pairs.
- T_e denotes the electromagnetic torque.

Squirrel cage and wound rotor are two types of induction motors, which are explained in the following subsections. Comparisons of them are listed in **Table 3.1**.

Table 3.1: Comparison of induction motor types

Parameter	Motor Type	Feature
Design	Wound Rotor	Complex, with windings, slip rings, and brushes
	Squirrel Cage	Simple, with shorted conducting bars
Functionality	Wound Rotor	Variable speed and torque control
	Squirrel Cage	Primarily constant speed
Energy Effic.	Wound Rotor	Optimized for high starting torque and varying loads
	Squirrel Cage	High efficiency at a constant speed
Maintenance	Wound Rotor	High maintenance (slip rings, brushes)
	Squirrel Cage	Low maintenance
Usage Area	Wound Rotor	Heavy machinery, pumps, generators
	Squirrel Cage	HVAC systems, appliances, small to medium motors

3.1.1.1. Squirrel Cage Induction Motor (SCIM)

A widely utilized electric motor is the Squirrel Cage Induction Motor (SCIM), renowned for its simple design, robust construction, and reliable performance. The squirrel cage rotors consist of conductor bars arranged in slots carved into the face of the rotor. Large shorting rings are employed to short the conductor bars at either end of the rotor. This design is referred to as a cage rotor, resembling the exercise wheel used by squirrels or hamsters. Users of a squirrel cage motor supported by a variable-speed drive can smoothly start the motor and efficiently modify its speed [48]. The stationary element, known as the stator, generates a rotating magnetic field when connected to an AC power source. Operating on the principle of electromagnetic induction, the rotor, with its conductive bars, interacts with the stator's magnetic field, producing torque and causing the rotor to turn. Squirrel cage motors are generally self-starting, eliminating the need for external assistance during startup. Commonly employed in applications such as pumps, fans, compressors, and conveyors where constant-speed operation is sufficient, these motors are valued for their robust and reliable design, low maintenance requirements, and cost-effectiveness. Despite their advantages, squirrel cage induction motors have limitations, such as limited speed control compared to other motor types, making them less suitable for applications requiring variable speed. Despite these limitations, squirrel cage induction motors play a crucial role in powering a diverse range of industrial and commercial machinery. A sample photo of a SCIM is shown in **Fig. 3.3**.

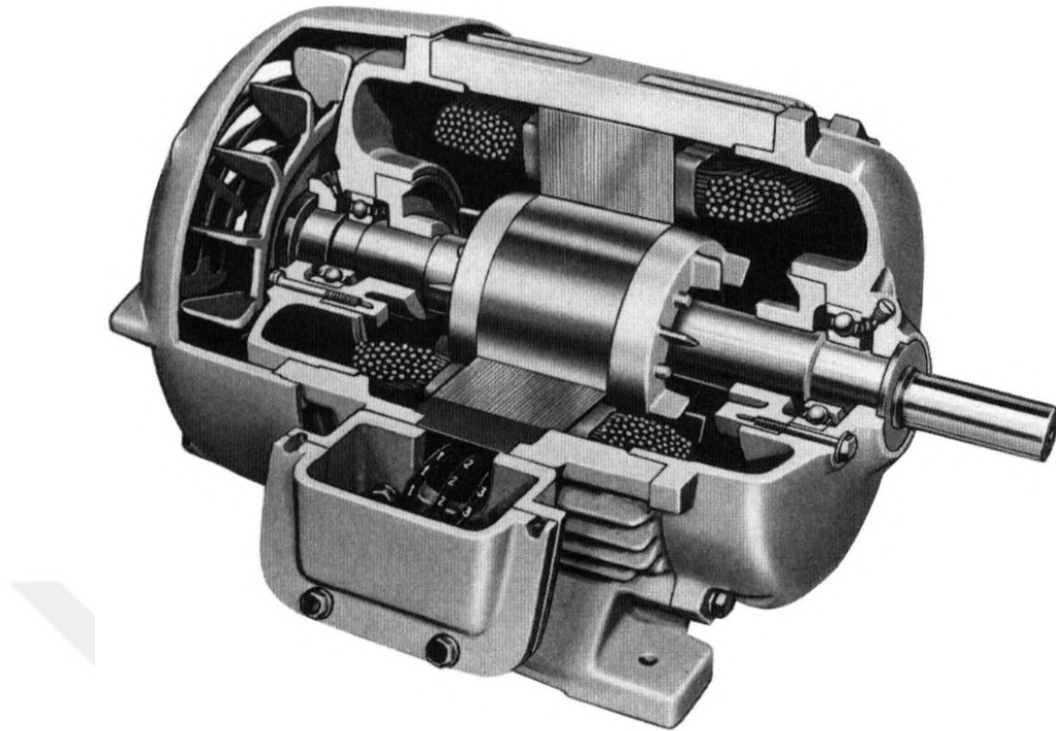


Figure 3.3: A photo of squirrel-cage induction motor [49].

3.1.1.2. Wound Rotor Induction Motor (WRIM)

A wound rotor induction motor (WRIM), commonly known as a slip ring motor, distinguishes itself from squirrel cage motors by featuring a rotor with multiple winding coils instead of a short-circuited design. In the WRIM, electrical power is directed to the stator circuit, while the rotor circuit remains short-circuited [50]. The three-phase winding in a slip ring motor resembles that of the stator, but slip ring brushes within the motor reduce the length of the rotor windings. These brushes enable access to rotor currents, increasing resistance and facilitating adjustments to torque and speed-current characteristics [48].

By connecting to external resistors, the rotor windings provide improved control over torque and speed characteristics. Similar to typical induction motors, the stator comprises a layered iron core with windings linked to the power source. During startup, external resistors in the rotor circuit contribute to smooth acceleration and speed control, making WRIMs particularly advantageous in applications requiring adjustable speed and torque, such as heavy industries like mining and steel mills. Despite offering

enhanced control over starting and speed, these motors entail higher maintenance demands due to external resistors and are generally more complex compared to squirrel cage motors. Nevertheless, the distinctive features of wound rotor induction motors make them well-suited for specific industrial settings that demand precise control over motor performance. In comparison to squirrel-cage rotor motors, wound-rotor motors are typically more expensive, require greater maintenance, and necessitate a more complicated automatic control circuit [49].

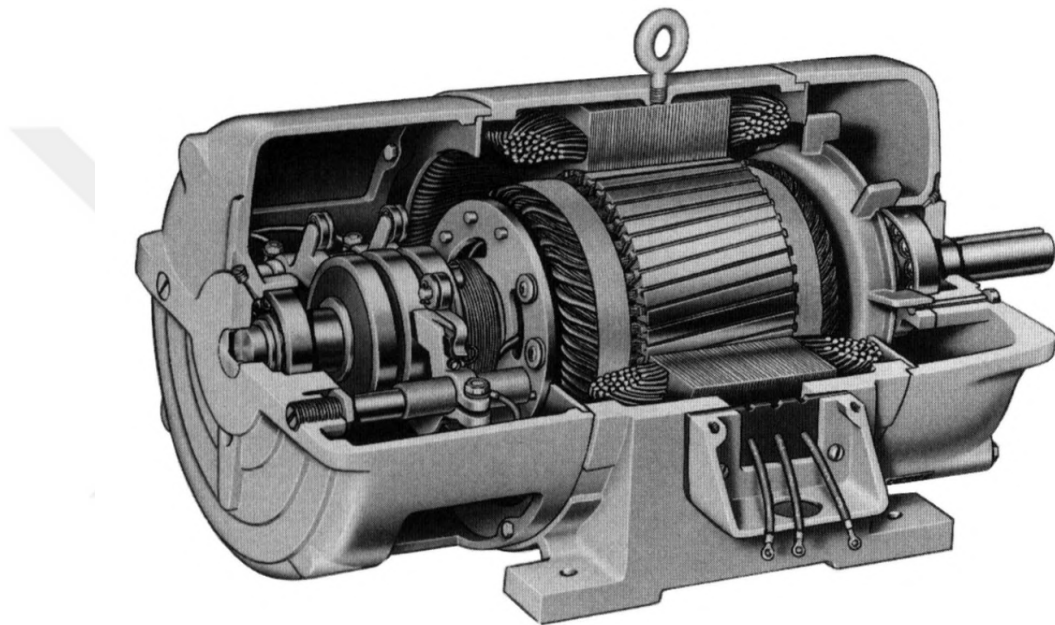


Figure 3.4: A photo of wound-rotor induction motor [49].

3.1.2. Permanent Magnet Synchronous Motor (PMSM)

One of the many varieties of synchronous motors is the permanent magnet synchronous motor (PMSM). Permanent magnet synchronous motors (PMSM) have permanent magnets integrated in the rotor of the PMSM, while conventional three-phase windings are enclosed within the stator of the PMSM. The function that the field windings in conventional synchronous machines carry out in PMSM is the responsibility of the permanent magnets. In contrast to the PMSM, which depends entirely on an AC source for its operation, the ordinary synchronous machine necessitates the presence of both an AC and a DC supply in order to maintain its functionality. One of the most notable advantages

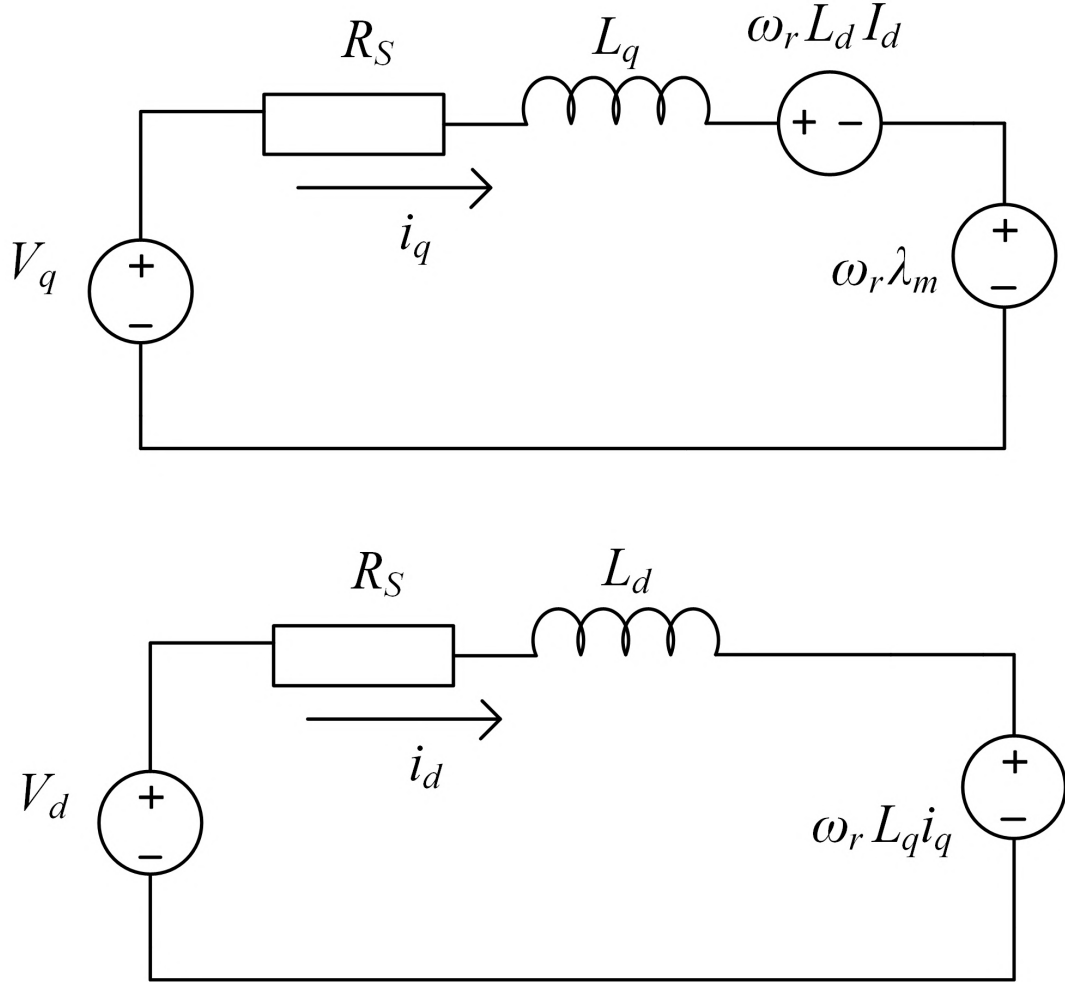


Figure 3.5: Equivalent circuit model of PMSM.

of PMSM in comparison to its counterpart is that it does not require a direct current supply for field excitation [51]. The arrangement of the rotor permanent magnets determines the classification of permanent magnet synchronous motors (PMSM) into two main categories: Interior permanent magnet synchronous motor (IPMSM) and surface permanent magnet synchronous motor (SPMSM), which are explained in the following subsections. The equations of PMSM are given in the following six equations:

$$\lambda_q = L_q i_q \quad (3.6)$$

$$\lambda_d = L_d i_d + \lambda_m \quad (3.7)$$

$$V_q = (r_s + pL_q)i_q + \omega_r L_d i_d + \omega_r \lambda_m \quad (3.8)$$

$$V_d = (r_s + pL_d)i_d + \omega_r L_q i_q \quad (3.9)$$

$$T_e = \frac{3}{2} \frac{P}{2} [\lambda_m i_q + (L_d - L_q) i_q i_d] \quad (3.10)$$

$$T_e = T_1 + B\omega_m + J \frac{d\omega_m}{dt} \quad (3.11)$$

where,

- $\lambda_q, \lambda_d; V_q, V_d;$ and i_q, i_d are fluxes, voltages, and currents on the q-axis and d-axis, respectively.
- $r_s, \omega_r,$ and ω_m are stator winding resistance, rotor electrical angular speed, and rotor mechanical angular speed, respectively.
- λ_m defines rotor magnetic flux linkage and p defines a differentiator of time.
- T_e and T_1 express developed and load torque, respectively.
- $B, P,$ and J represent the motor viscous friction, the number of poles, and the motor inertia, respectively [52].

3.1.2.1. Surface PMSM (SPMSM)

Due to the fact that all of the permanent magnets are positioned on the surface of the rotor, surface-mounted permanent magnet synchronous motors (SPMSM) are very easy to design. Additionally, particularly skewed poles can be magnetized on this type of surface mount with ease in order to reduce cogging torque. Cogging torque is the result of the interaction between the permanent magnets on the rotor and the slots on the stator. This design is only appropriate for low-speed applications because the magnets have a tendency to become dislodged when they are subjected to high-speed activities. The inductances of these motors in the d-axis (L_d) and q-axis (L_q) are considered to be identical due to the fact that it is believed that their saliency is insignificant [54].

3.1.2.2. Interior PMSM (IPMSM)

In the context of an interior permanent magnet synchronous motor, the term "Interior PMSM" refers to a motor in which the rotor, which is the part that rotates, is fitted with a permanent magnet that is physically located inside the motor. In most cases, this design

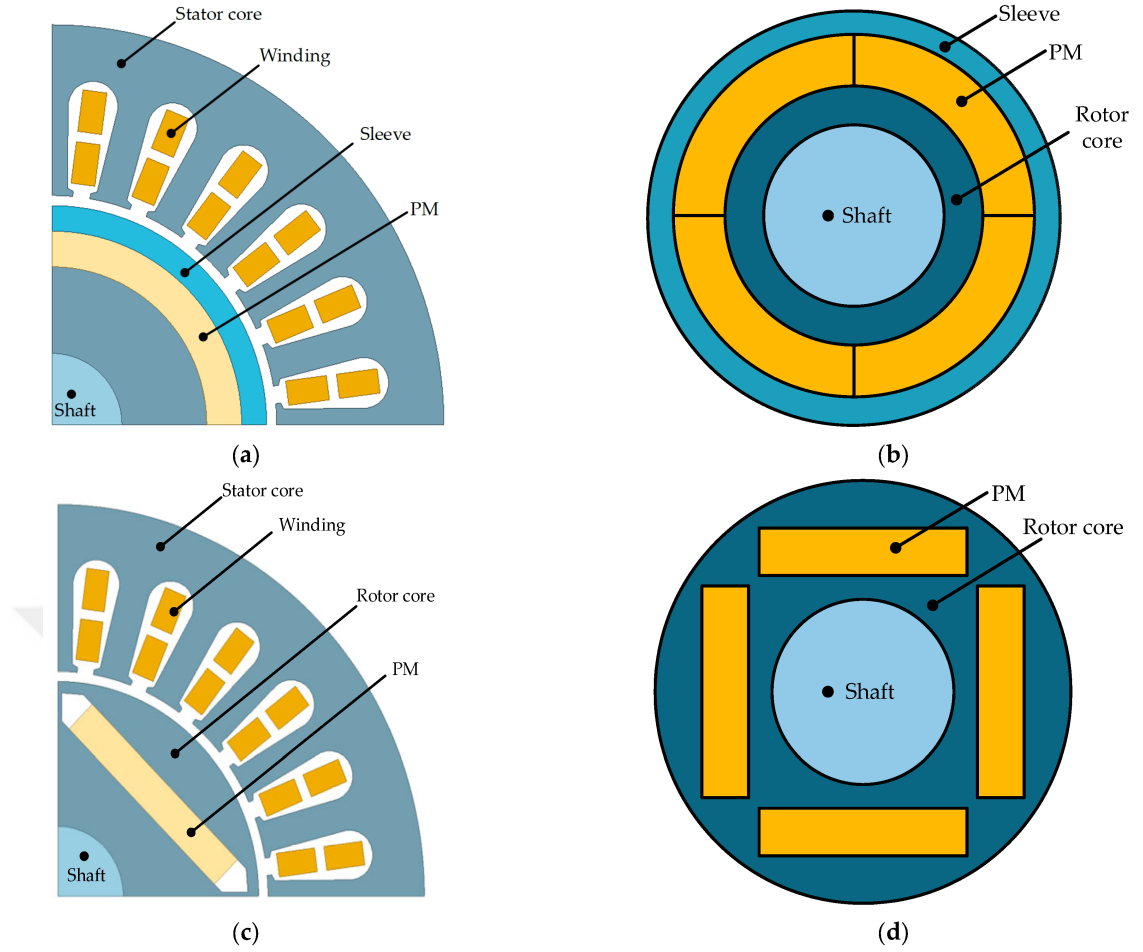


Figure 3.6: Two distinct motor models: (a) SPMSM model; (b) SPMSM rotor structure; (c) IPMSM model; and (d) IPMSM rotor structure [53].

provides benefits such as reduced weight, increased torque density, and accelerated response times. The use of this particular type of motor is frequently recommended for applications that have space limitations and for systems that have high-performance requirements. It works well at high speeds due to the rotor magnets' internal location. Because the q-axis inductance L_q is larger than the d-axis inductance L_d , these motors are salient [54]. A comparison of surface and interior PMS motors in terms of model and rotor structure is shown in **Fig. 3.6**.

3.2. Inverter

The inverter is a crucial electrical component that converts direct current (DC) power that is obtained from the battery into alternating current (AC) power for the traction motor. The frequency and amplitude of the AC waveform can be adjusted, which enables

the motor to be controlled with a high degree of precision. PWM (Pulse Width Modulation) signals drive the switches in the inverter, allowing for operation at maximum voltage and frequency at all times. This ensures efficient operation of AC motors. Directly driving AC motors with AC power sources can also be considered as a method, but it may complicate achieving maximum power at low-voltage points of the single phase AC signal. Therefore, adding a buffer may be necessary to achieve maximum power. However, to utilize this buffer, a DC power source is required once again. Hence, the most effective control method for trains involves first converting the AC voltage to DC voltage with the assistance of a rectifier, then converting this DC voltage back to AC signals with the control of PWM signals in the inverter, thereby driving the motor. In order to transform direct current (DC) power into alternating current (AC) waveforms, inverters make use of power semiconductor devices. These devices include silicon carbide (SiC) MOSFETs and insulated gate bipolar transistors (IGBTs). The switching frequency and the modulation methods (such as pulse-width modulation, or PWM) are significant aspects that have a significant impact on the efficiency and performance of the motor. The inverter is a significant component that plays a role in determining the dynamic response and the efficiency of the system. Advanced inverter control techniques include space vector modulation (SVM) and model predictive control (MPC), both of which help optimize motor operation, reduce losses, and improve system efficiency. Both of these techniques are examples of advanced inverter control techniques. The current source inverter (CSI) and the voltage source inverter (VSI) are two main types of inverters.

3.2.1. Current Source Inverter (CSI)

A current source inverter (CSI) is an inverter that maintains a constant current input by pulling a continuous and consistent current from its DC source. The output voltage of a CSI is variable due to its dependence on the load impedance, unlike voltage source inverters. It is possible to get high CPSR (constant-power speed ratio) values with reduced inverter and motor current ratings by using the CSI, which acts naturally as a boost-type inverter. This inverter has the ability to raise the motor terminal voltage over the dc-link voltage [55]. CSIs are commonly utilized in applications where pre-

cise control of current is essential, such as high-power drives and specific motor control applications. They exhibit advantages in scenarios with large inductive loads and possess inherent short-circuit protection. However, CSIs may require additional circuitry for voltage control, making them less suitable for applications where a constant output voltage is a primary requirement.

3.2.2. Voltage Source Inverter (VSI)

Voltage source inverters are typically employed in high-power applications, such as in the industrial sector for driving induction motors. Single-phase and three-phase are the two main types of VSI. An electronic power device that converts single-phase alternating current (AC) from direct current (DC) is known as a single-phase voltage source inverter (VSI). Unlike three-phase VSIs commonly used in industrial applications, single-phase VSIs are often employed in residential, small-scale commercial, and low-power electronic systems. The key characteristics of a single-phase VSI include a constant DC input voltage and the ability to generate a single-phase AC output waveform. These inverters find applications in various areas, such as domestic power supplies, small motor drives, and single-phase renewable energy systems like solar inverters for residential use. Single-phase VSIs are characterized by their simpler control schemes compared to their three-phase counterparts, making them suitable for low-power applications where a straightforward AC power source is needed.

The fundamental characteristics of a three-phase VSI include a constant DC input voltage and the generation of a three-phase AC output waveform. The inverter achieves this conversion through the controlled switching of semiconductor devices, such as insulated gate bipolar transistors (IGBTs). Three-phase VSIs offer advantages in terms of efficiency, power quality, and compatibility with three-phase loads, making them essential components in electric drives for motors, uninterruptible power supplies (UPS), renewable energy inverters (such as solar inverters and wind turbine converters), and other applications requiring precise and dynamic control of three-phase AC power. These inverters play a pivotal role in modern power systems, ensuring the efficient and reliable distribution of electrical energy across various industries and sectors.

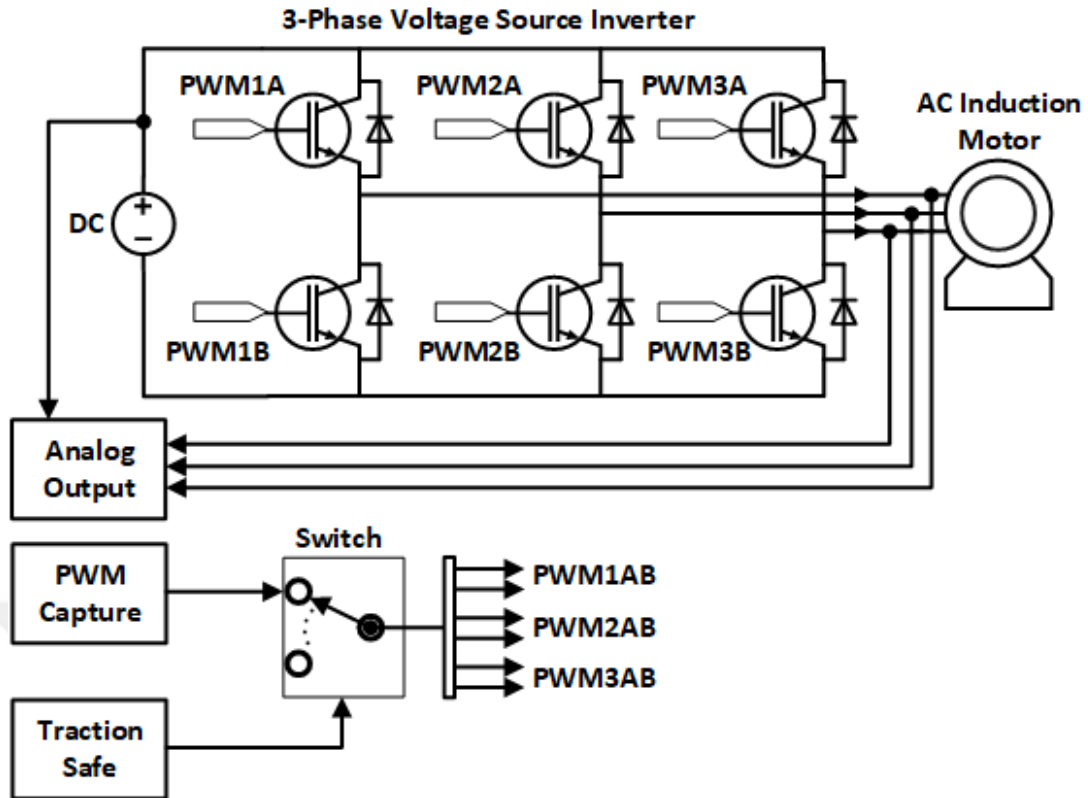


Figure 3.7: Voltage source inverter and AC induction motor.

A three-phase inverter is structured with three legs, each leg containing two IGBTs used as switches, resulting in a total of six IGBT, as shown in **Fig. 3.7**.

The Insulated Gate Bipolar Transistor (IGBT) is a semiconductor device that is extensively utilized in applications requiring high power and high frequency. Combining the advantages of both Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) high-speed switching and bipolar transistors' high power-carrying capabilities, IGBTs are utilized in various applications such as energy conversion, power inverters, and industrial motor drives. Their dual-semiconductor characteristics enable low energy losses and efficient power transmission. Notable for their high switching speed, IGBTs facilitate fast switching and high-frequency operation. With a capacity for handling high power levels similar to bipolar transistors, they find preference in industrial power electronics applications. IGBTs are commonly employed in power inverters for converting alternating current (AC) to direct current (DC), industrial motor control systems, and energy conversion systems like solar inverters and wind turbines. Their advanced thermal performance and versatility make them pivotal components in contemporary

applications requiring energy efficiency and precise power control, contributing significantly to advancements in the field of electrical power electronics. Therefore, IGBTs are used in this study for switching devices with PWMs coming from microcontrollers. An equivalent circuit model of IGBT is shown in **Fig. 3.8**.

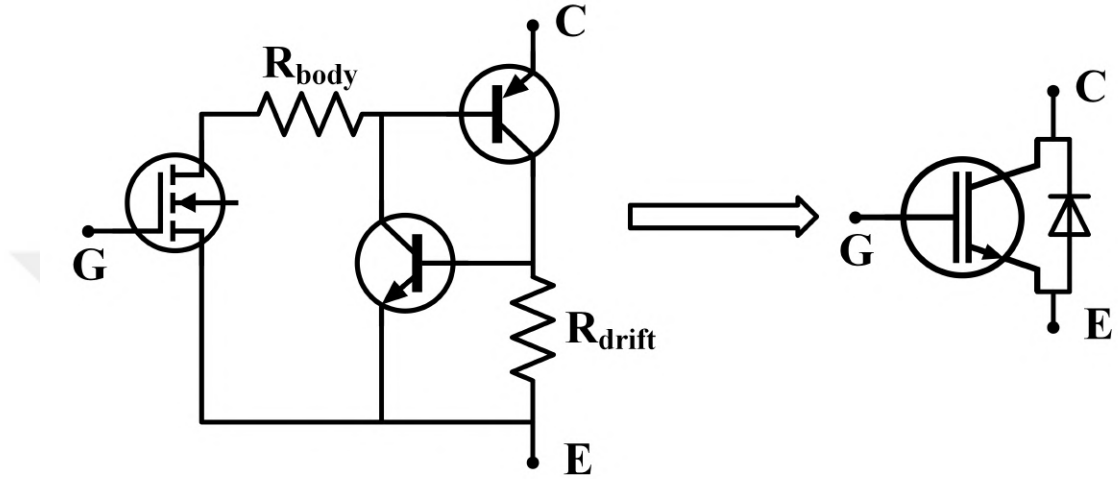


Figure 3.8: Basic structure and equivalent circuit of an IGBT.

In critical situations, it is necessary to cut off pulse width modulation (PWM) signals. A PWM cut-off signal is typically employed in various control systems under specific circumstances. Among these situations, firstly, when the operating temperature of a device exceeds a certain threshold, the PWM signal is cut off, aiming to prevent overheating and protect the system. Secondly, in the event of a detected overcurrent, the PWM signal is interrupted, which is essential for safeguarding system components or equipment from excessive loads. Additionally, under low-voltage conditions, the PWM signal can be cut off to protect the power source and mitigate issues arising from low voltage. This signal is also utilized in cases of error conditions, excessive speed or torque, and user-defined protection scenarios. Overall, the cut-off PWM signal serves the purposes of protecting the system, ensuring safety, and intervening in fault conditions, contingent upon specific conditions within the control system. As a result, when the aforementioned events take place, controller sends a traction-safe signal to safely shut down the PWM signals by closing switches, as shown in **Fig. 3.7**.

4. EXPERIMENTAL RESULTS

The PLECS RT Box is a specialized real-time simulator tailored for power electronics applications. Equipped with a multitude of analog and digital input and output channels as well as FPGA-embedded CPU cores, it serves as a flexible processing unit suitable for real-time hardware-in-the-loop (HIL) testing and swift control prototyping. In this study, the RT Box 3 device features a model of a voltage source inverter and an AC induction motor. The RT Box 3 simulator is shown in left side of the **Fig. 4.1**.

The TMS320F28379 DSP is used as a microcontroller unit (MCU) for this study. This MCU belongs to the TI C2000 MCU family and serves as the real-time controller. It is specialized in digital power and motor control for industrial and automotive applications. The F28379 launchpad, including the TMS320F28379 MCU and peripheral components, is shown in right side of the **Fig. 4.1**.



Figure 4.1: RT Box 3 simulator and development board.

The field-oriented control (FOC) structure, voltage source inverter (VSI) structure and AC induction motor (ACIM) model were designed in the PLECS design tool, specified for control and power electronics circuits. Then, the FOC model in **Fig. 2.4** was loaded onto the MCU at the F28379 launchpad. The VSI model in **Fig. 3.7** and the ACIM model in **Fig. 3.2** were loaded into the RT Box 3 simulator. The devices and the HIL test setup are depicted in **Fig. 4.2**.

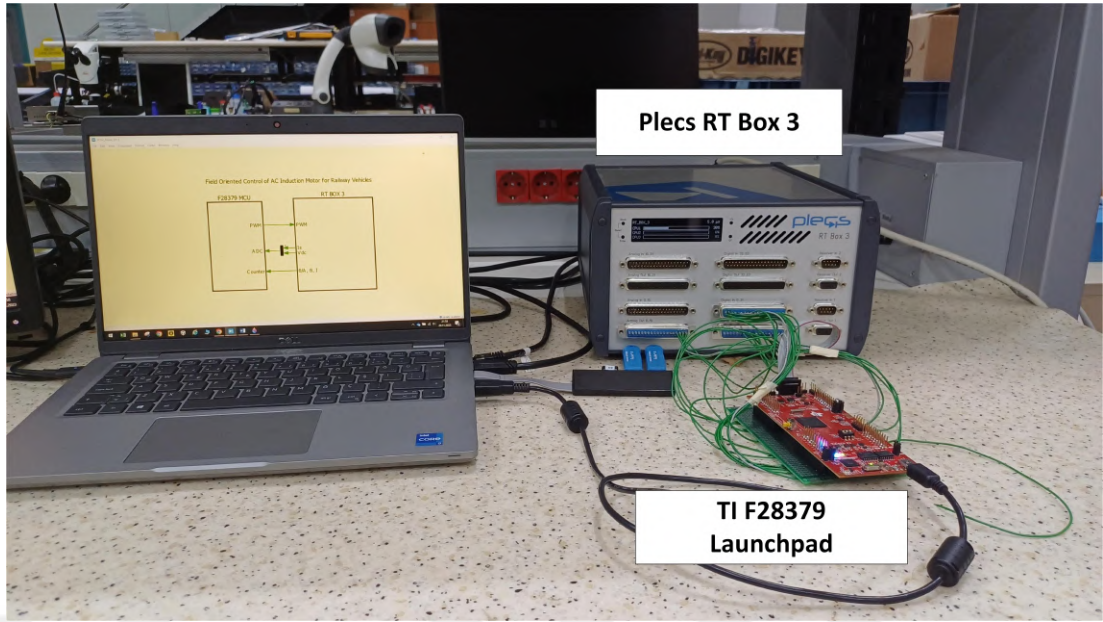


Figure 4.2: Test setup.

Motor and three-phase VSI parameters are chosen as suitable for railway applications. In trains, there is a need for high voltage in their motors because trains require high torque and power. This is due to the fact that trains carry heavy loads and sometimes need to ascend steep gradients. High voltage can assist in obtaining the required torque and power by providing more power to the motors. In this study, a 1000V DC-link voltage for the voltage source inverter has been utilized. In large systems like trains, fundamental or low-frequency switching modulation techniques are the most popular switching method, mainly because of the better compromise between voltage quality and power losses [56]. For this reason, the 1 kHz frequency is utilized for switching IGBTs. The resistance and inductance values of the rotor and stator of an AC induction motor are special values that are suitable for light railway train motor systems. AC induction motor and 3-phase VSI parameters are listed at **Table 4.1**.

According to the parameters outlined at **Table 4.1**, the simulation is conducted using the F28379 launchpad and RT Box 3 through the hardware-in-the-loop (HIL) method. Then, the values of the motor and controller were measured in real time with the start of the HIL simulation. 1 kHz PWM outputs used to switch IGBTs generated from the MCU were investigated and they are shown in **Fig. 4.3**. PWM signals that drive the control terminal of top-side IGBTs are only shown. PWM signals driving the bottom

Table 4.1: AC motor and VSI parameters

Parameters	Value	Unit
Number of Poles (p)	2	-
Stator Resistance (R_S)	0.1062	Ohm
Stator Inductance (L_S)	0.0160	Henry
Rotor Resistance (R_R)	0.0764	Ohm
Rotor Inductance (L_R)	0.0160	Henry
Mutual Inductance (L_M)	0.0155	Henry
Inertia (J)	2.8	Kg.m2
DC-link Voltage (V_{DC})	1000	Volt
Switching Frequency (F_{sw})	1000	Hertz

sides are inverting the top-side PWMs. This signifies that the PWM signals controlling the bottom-side IGBTs are the opposite of the signals used for the top-side IGBTs. When the top-side IGBT is on, the bottom-side IGBT is off, and vice versa. This inversion ensures the generation of the complete AC waveform. Due to the inverting form of top-side PWMs, bottom-side PWMs are not shown in **Fig. 4.3**.

The 3-phase AC voltages produced by the voltage source inverter (VSI) are the source of the stator currents of a 3-phase AC induction motor. Connected to each phase of the stator winding, the stator currents vary synchronously. These currents are designed to facilitate the rotational motion of the motor. Each phase's stator current is sequentially activated, creating the rotational movement of the motor. The timing between the phases determines the direction of the motor's rotation, initiating the rotational movement of the magnetic field on the rotor.

Three-phase stator currents of the motor in this real-time HIL simulation were measured approximately 190A as shown in **Fig. 4.4**. To calculate power of motor from Ohm's law, RMS current value must be used for power calculation due to the sinusoidal form of the current. Also, motor supply voltage is 500V which is half of DC supply voltage of inverter. Then, input power of 3-phase AC motor is calculated as approximately 120kW from the Equation (4.1).

According to the data presented in **Fig. 4.4**, the motor's three-phase stator currents were measured to be around 190A. It is necessary to utilize the RMS current value for power calculation in order to compute the power of a motor using Ohm's law. This is because

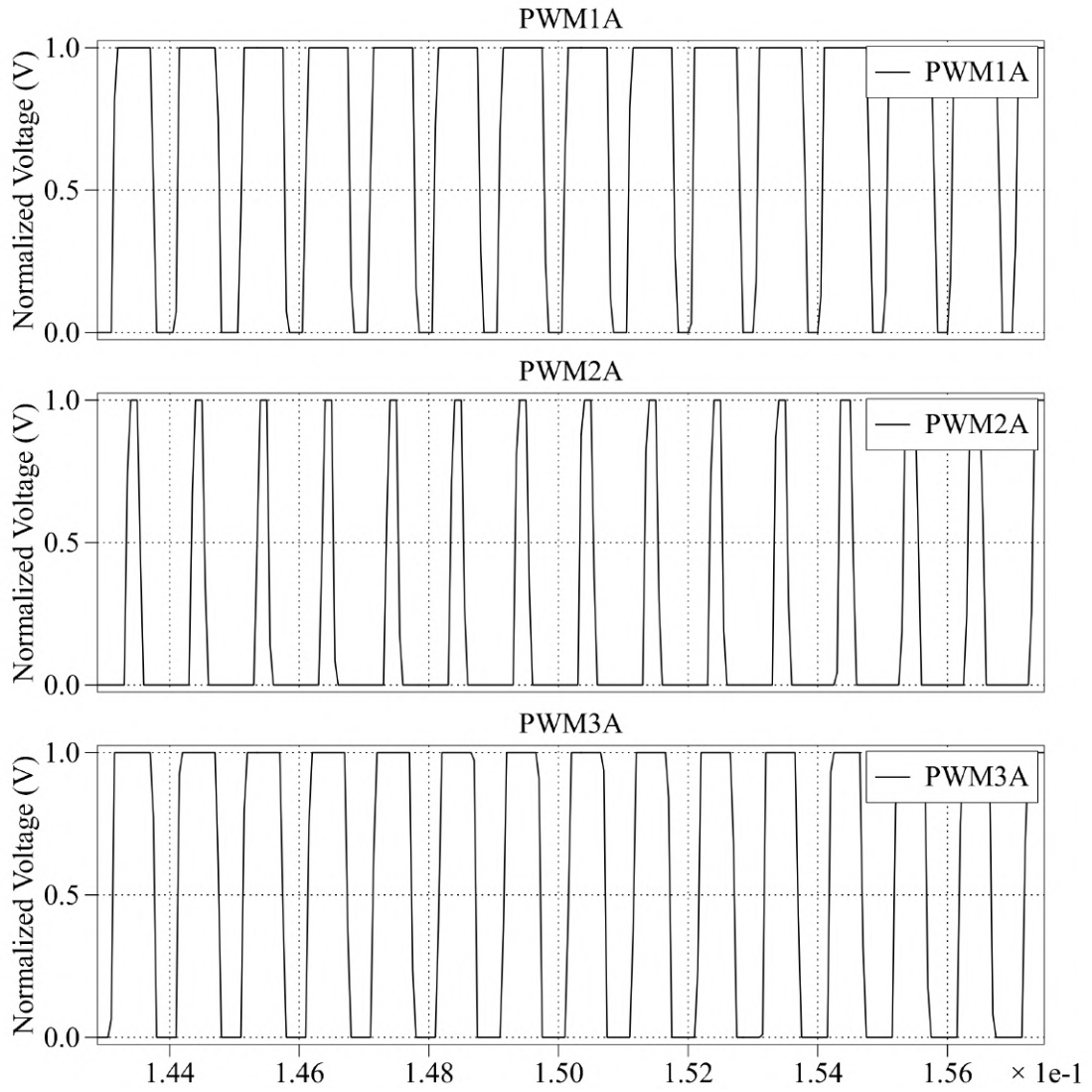


Figure 4.3: PWM signals.

the direction of the current is sinusoidal. Additionally, the voltage that is sent to the motor is 500V, which is equal to half of the DC supply voltage of the inverter. After that, the input power of a three-phase alternating current motor is determined to be roughly 120 kilowatts by using Equation (4.1).

$$P_{in} = \sqrt{3}V_{motor} \frac{I_{stator}}{\sqrt{2}} \quad (4.1)$$

Also, as can be seen from Equation 2.1, the summation of 3-phase voltages in **Fig. 4.4** is equal to 0.

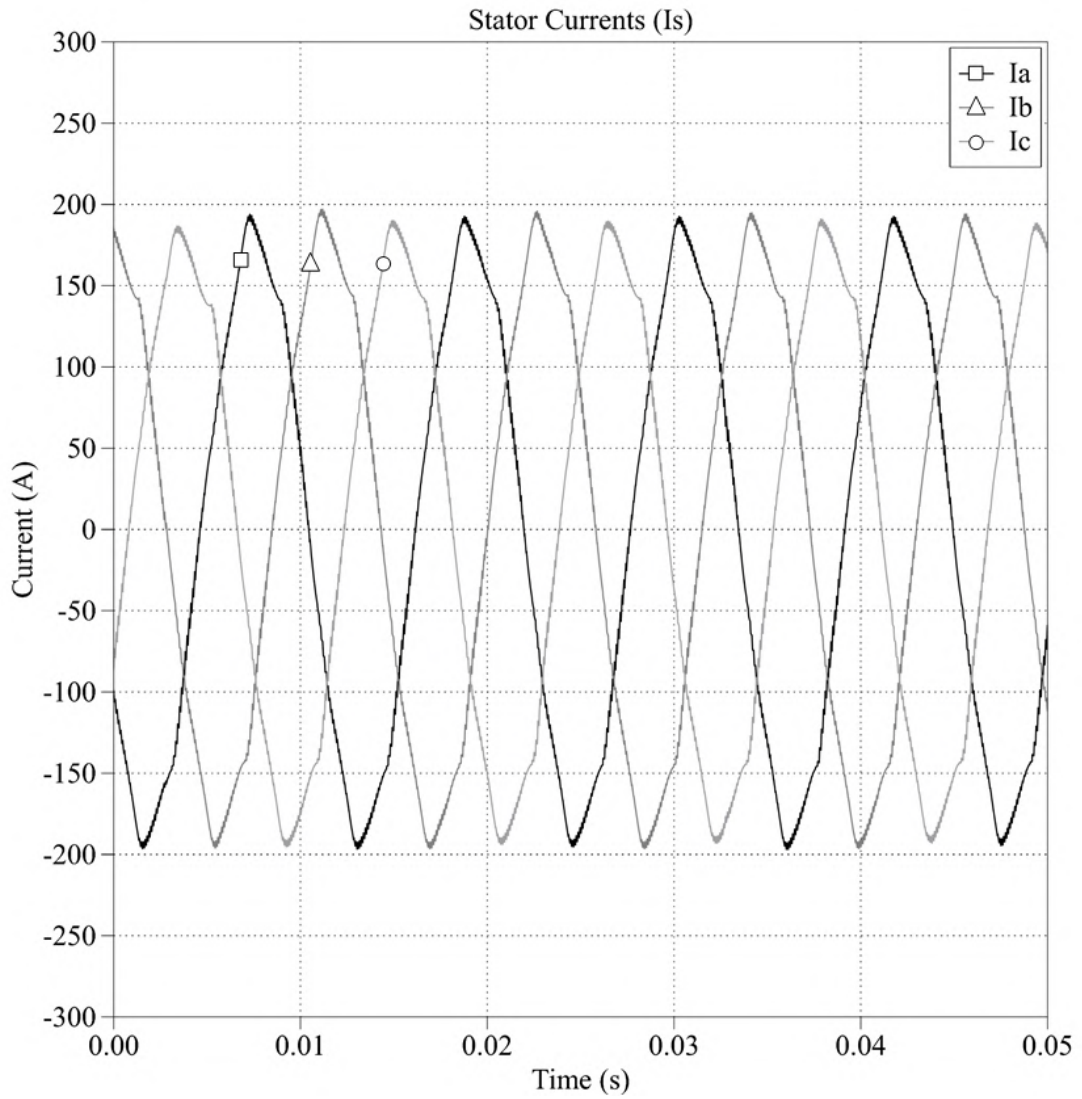


Figure 4.4: 3-phase stator currents.

The three-phase stator currents go through Clarke and Park transformation processes after being read from the analog-to-digital converter (ADC) blocks in the MCU. This is shown in the FOC diagram in **Fig. 2.4**. As a result of these transformations, I_d and I_q currents are calculated. The calculated I_d and I_q currents, along with the reference current values, are depicted in **Fig. 4.5**. Reference currents listed below are applied to the system from the controller and feedback signals from the motor are investigated in the controller.

- 60A stator currents in d-axis.
- 149A stator currents in q-axis.

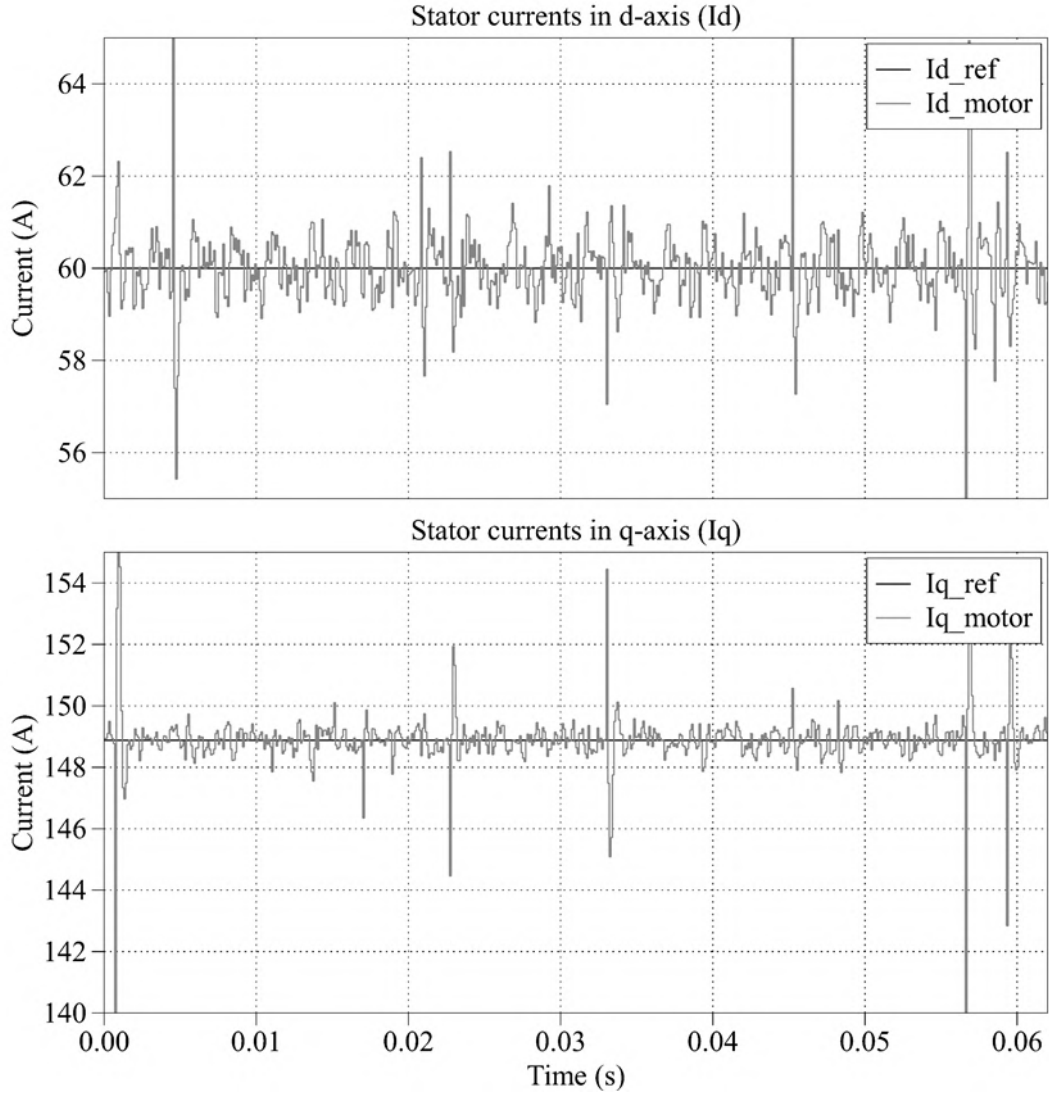


Figure 4.5: Reference and feedback two-axis stator currents.

As seen in **Fig. 4.5**, it is observed that the feedback signals align well with the reference currents. There is an approximate oscillation of 4% for I_d and 2% for I_q . This demonstrates the accuracy of the design and the system tested through the hardware-in-the-loop method.

In an alternating current (AC) induction motor, the electrical torque (T_e) is a vital parameter that serves as a representation of the motor's capacity to generate mechanical output. It has a direct connection to the interaction that takes place between the magnetic fields of the stator and the rotor. A reference torque of 400 Nm was applied from the controller in order to investigate the torque value that was read from the AC motor. At the beginning of the train's departure, particularly when it starts moving from a stop,

the torque that the motor needs to run dramatically increases. This is especially true when the train is moving. The surge can be attributable to the fact that the weight of the train and the resistance that was present during the initial acceleration were overcome. During the typical operational state of the train, particularly while traveling at low speeds and for light rail vehicles, a reference torque of 400 Nm is frequently sufficient. Because having a lower torque at low speeds and under light loads allows for less energy consumption and more efficient performance, this circumstance is essential for the efficiency and energy effectiveness of the motor for the reason that it is essential for the motor to have this scenario.

As observed in **Fig. 4.6**, the output torque of the asynchronous motor fluctuates between 420Nm and 380Nm. The peak-to-peak difference relative to the reference torque value is around 10%, which is considered an acceptable margin.

The rotor's position is a critical parameter in motor control systems. It indicates the angular orientation of the rotor with respect to the stator. Accurate knowledge of the rotor position allows for precise control of the stator currents, ensuring optimal torque production and efficient motor operation. Various sensor technologies, such as encoders or resolver feedback systems, are commonly employed to provide real-time rotor position information.

Rotational speed, referred also angular velocity, represents the rate at which the rotor is turning. It is a key factor in determining the motor's performance. By adjusting the frequency of the AC voltages applied to the motor through the VSI, one can control the rotational speed. In open-loop control, the speed can be estimated based on the applied voltage frequency, while closed-loop control utilizes feedback from sensors like encoders or tachometers for accurate speed control. Motor speed when there is no load was calculated as 2578 rpm from the Equation 4.2. Experimental results of the study are listed in **Table 4.2**.

$$N_s(rpm) = \frac{\omega_r \cdot 60 \cdot 2}{2\pi \cdot p} \quad (4.2)$$

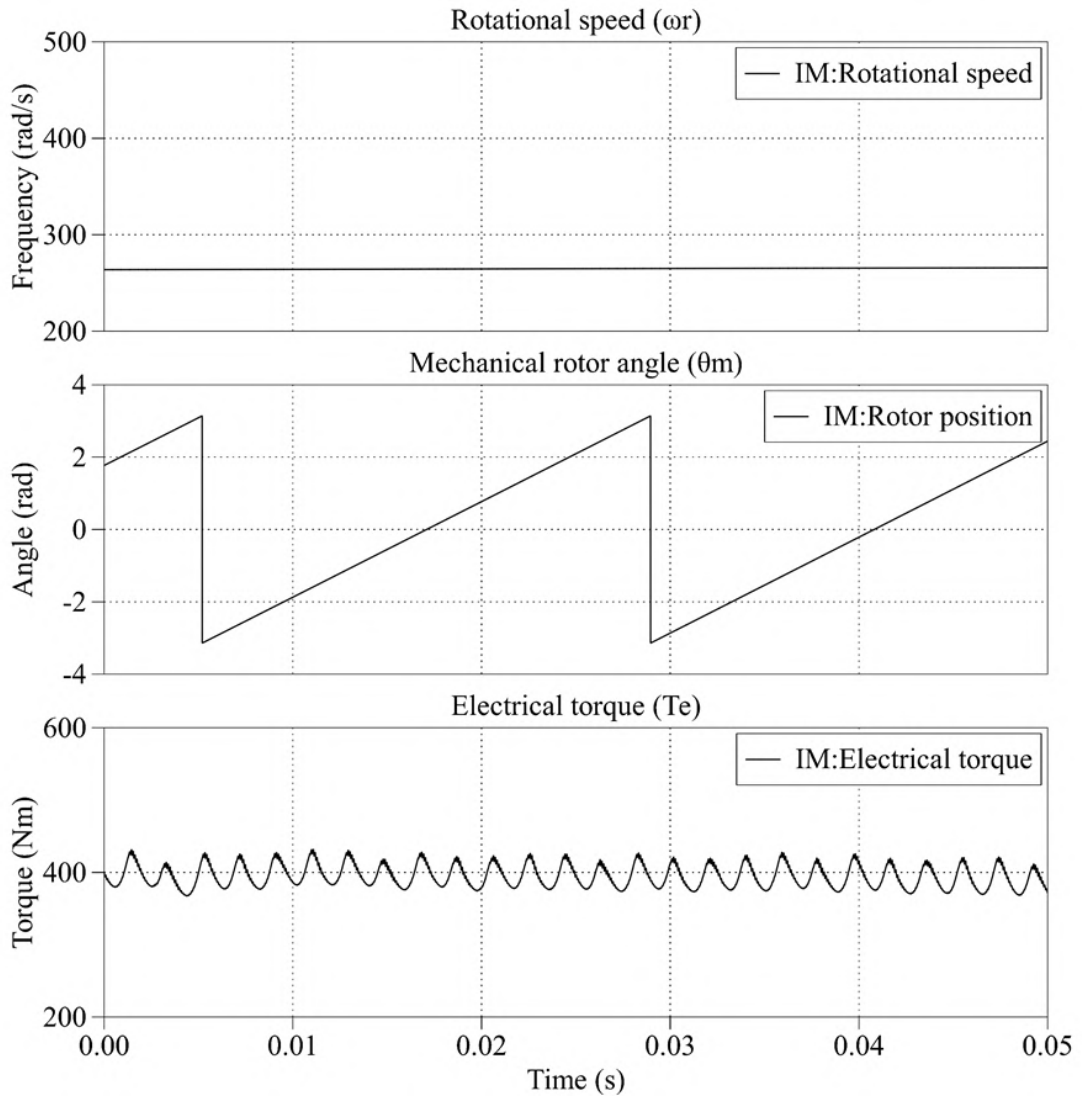


Figure 4.6: Motor outputs.

where,

- N_s is motor speed in RPM.
- ω_r is rotational speed.
- p defines number of poles.

Reference values of I_d and I_q are changed and same real-time simulation was conducted. New reference currents listed below are applied to the system from the controller and feedback signals from the motor are investigated in the controller.

- 40A stator currents in d-axis.
- 224A stator currents in q-axis.

Table 4.2: Experimental results

Parameters	Symbols	Reference	Deviation / Value
Direct Current	I_d	60A	2%
Quadrature Current	I_q	149A	4 %
Electrical Torque	T_e	400Nm	10 %
3-Phase Stator Currents	I_{abc}	—	$\pm 190A$
Rotor Position	Q_m	—	$\pm 3 \text{ rad}$
Rotational Speed	ω_r	—	270 rad/sec
Motor Input Power	P_{in}	—	120 kW
Motor speed	N_s	—	2578 rpm

New reference of I_d and I_q currents were applied to the system. New values of 3-phase stator currents are shown in **Fig. 4.7**, reference and feedback two-axis stator currents are shown in **Fig. 4.8**, and motor outputs are shown in **Fig. 4.9**. The magnetic field is regulated by the stator currents I_d and I_q in the implementation of field-oriented control (FOC). There is an enhancement of the magnetic field in the cross-axis when I_d is reduced and I_q is increased, especially with an increase in I_q . This intensified magnetic field may contribute to an overall rise in stator currents, leading to a general increase. As depicted in **Fig. 4.7**, stator currents exhibit an increase when compared to the previous study.

While there was an increase in the deviation of both I_d and I_q , there was no additional rise in the deviation of the motor-produced torque. This observation indicates the effective regulation of the torque value by both the PI controller and the field-oriented control (FOC) algorithm. FOC adeptly manages stator currents, optimizing them to meet specific torque demands. Consequently, the increased I_q contributes to enhanced torque performance, resulting in a higher motor speed. As illustrated in **Fig. 4.9**, the motor speed has indeed increased, accompanied by a slightly improved torque response. A new results of real-time simulation are listed at **Table 4.3**.

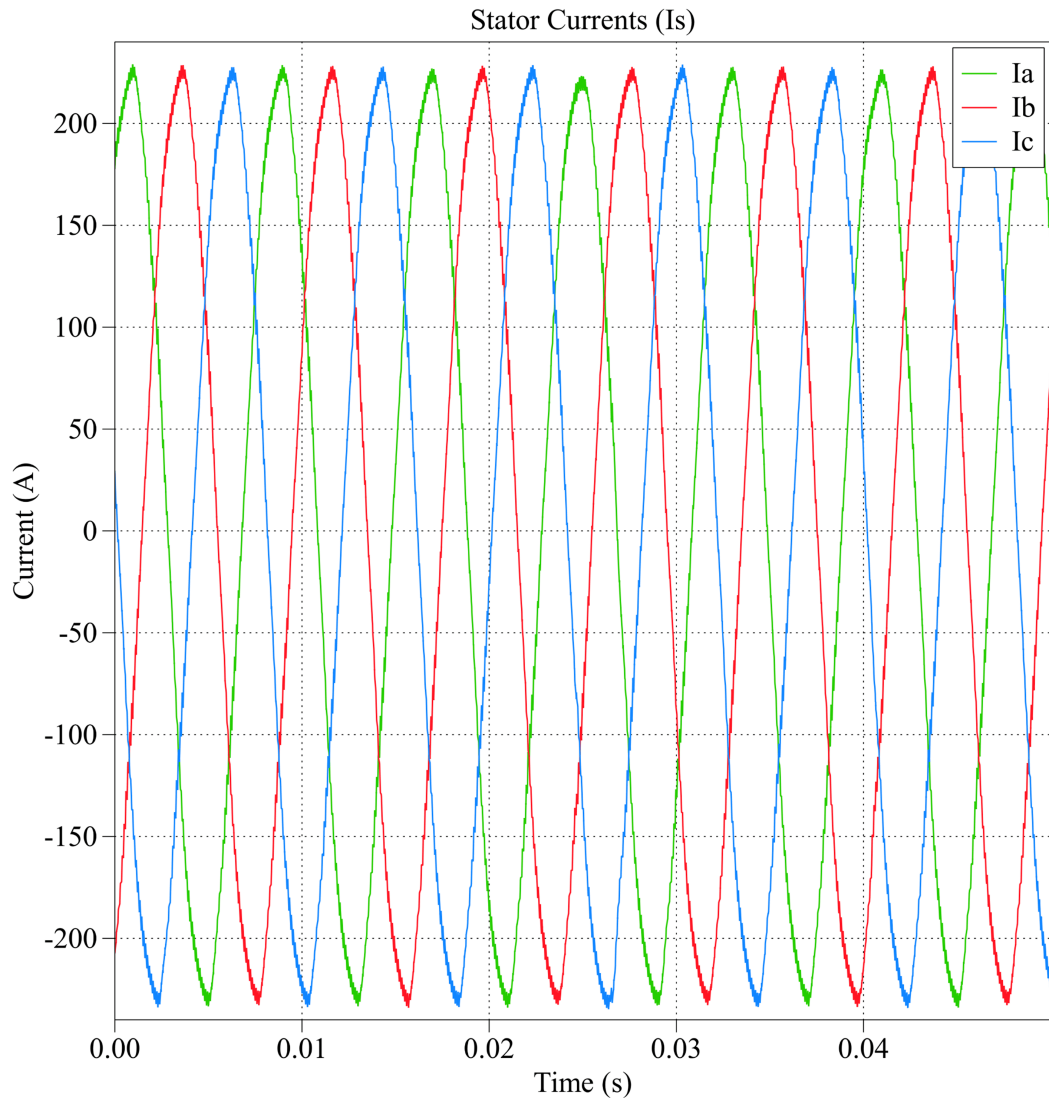


Figure 4.7: New 3-phase stator currents.

Table 4.3: New experimental results

Parameters	Symbols	Reference	Deviation / Value
Direct Current	I_d	40A	15%
Quadrature Current	I_q	224A	5 %
Electrical Torque	T_e	400Nm	10 %
3-Phase Stator Currents	I_{abc}	—	$\pm 230A$
Rotor Position	Q_m	—	$\pm 3 \text{ rad}$
Rotational Speed	ω_r	—	380 rad/sec
Motor Input Power	P_{in}	—	140 kW
Motor speed	N_s	—	3628 rpm

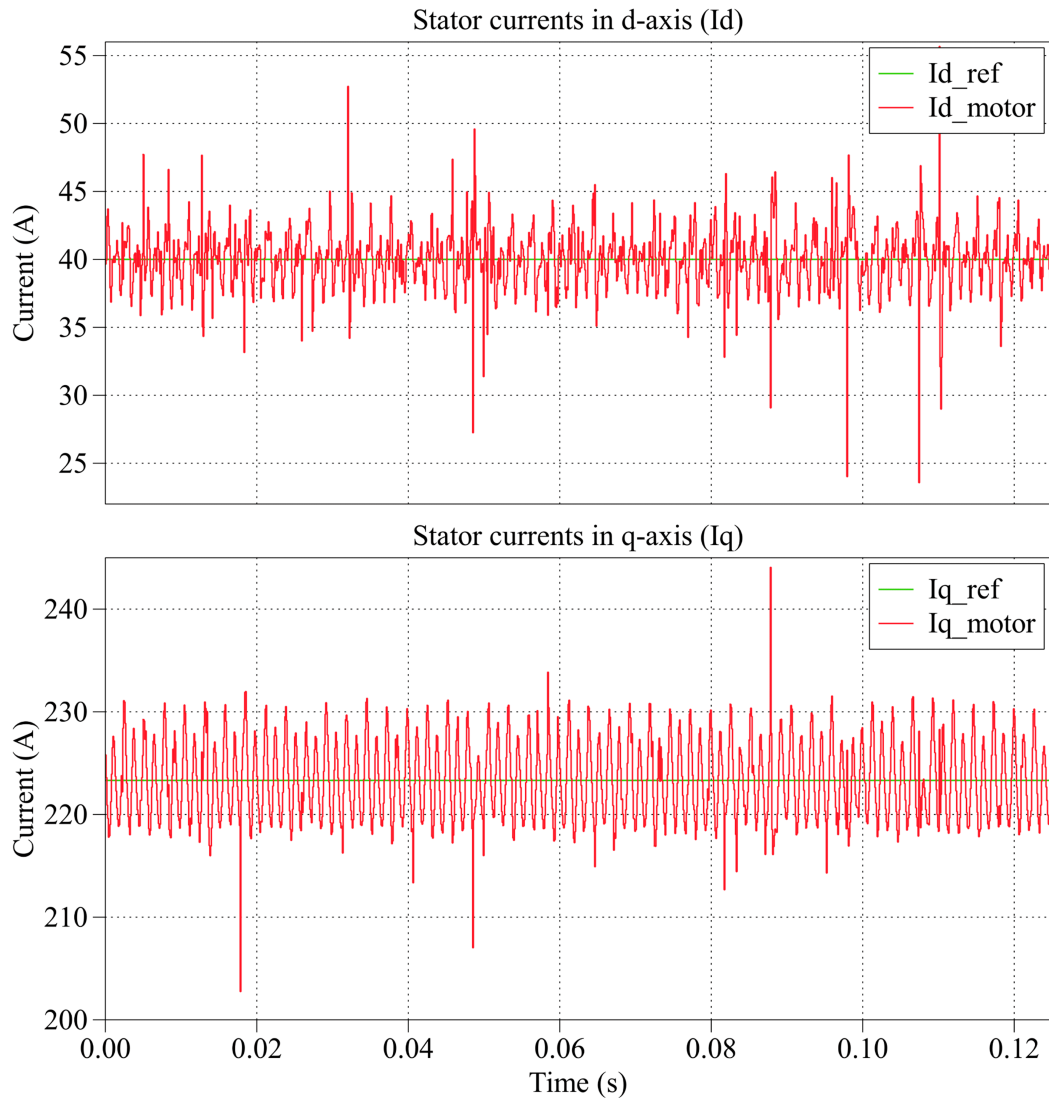


Figure 4.8: New reference and feedback two-axis stator currents.

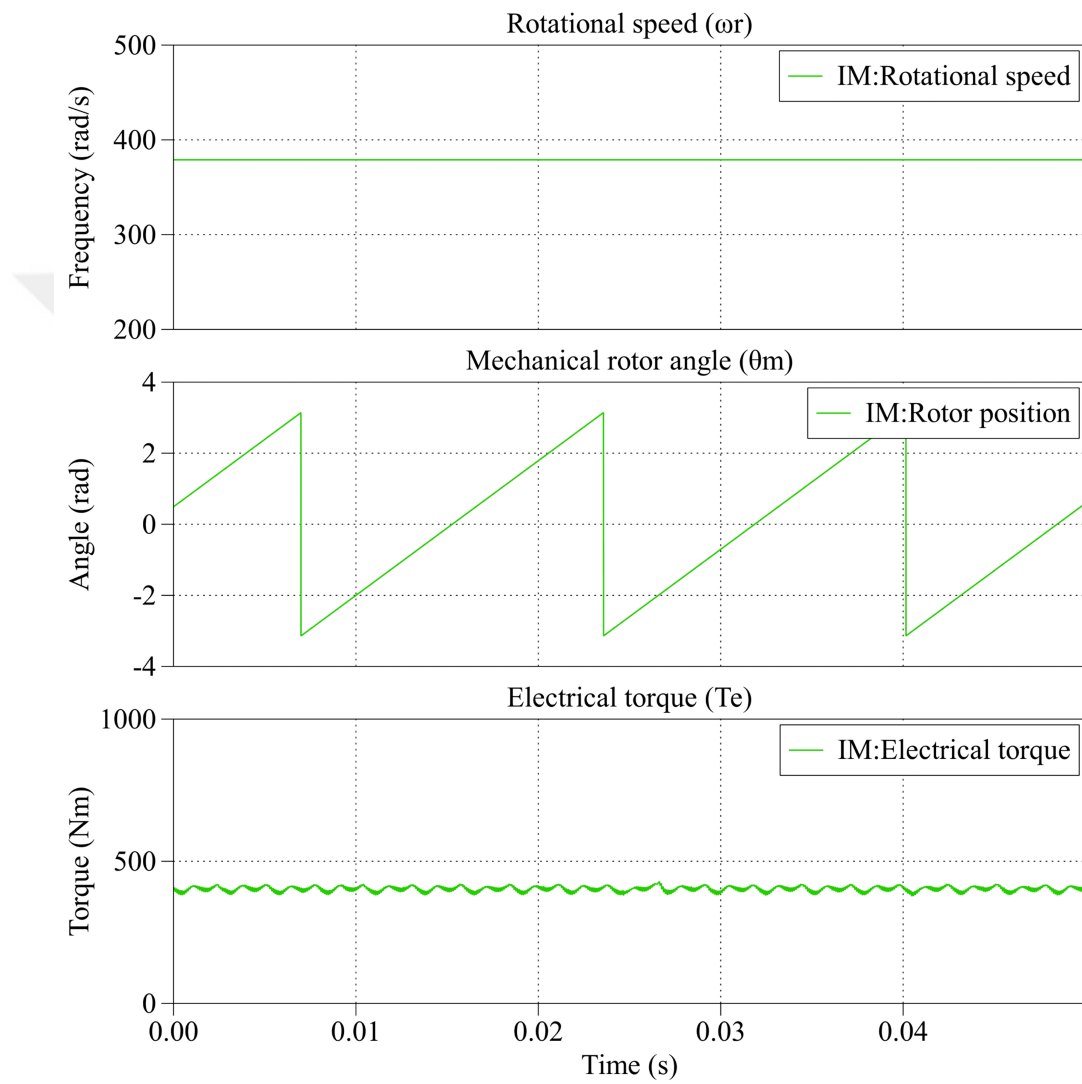


Figure 4.9: New motor outputs.

5. CONCLUSION AND FUTURE WORKS

In conclusion, this study delved into the critical phase of verifying and optimizing control strategies for railway traction motors, focusing on the implementation of an advanced field-oriented control (FOC) method within a hardware-in-the-loop (HIL) environment. Through an extensive investigation of various control systems, including vector and scalar control approaches, and considering both direct current (DC) and alternating current (AC) motor types, it was established that FOC, when coupled with an AC induction motor, emerged as the most suitable option for controlling railway traction motors.

The hardware-in-the-loop setup, employing the Plecs RT Box 3 simulator device and the F28379 development board, provided a robust testing environment. Real-time simulation and validation of the proposed FOC algorithm under diverse loads and dynamic conditions demonstrated efficient torque control with minimal deviation. The integration of the FOC algorithm into the microcontroller (MCU) and the traction motor model with a three-phase voltage source inverter (VSI) on the RT Box 3 simulator facilitated real-time and hardware-in-the-loop simulations, offering a more accurate representation of the actual operational conditions of the railway traction motor.

The achieved results indicate that the proposed FOC strategy, when applied to an AC induction motor with specific parameters such as a 1000V DC-link supply and a 1 kHz switching frequency, yields effective and precise torque control. This is particularly relevant for light railway vehicles, showcasing a peak-to-peak deviation of only 10%. A power rating of 120 kW and 400 Nm reference torque values indicate that this motor is suitable for light railway systems such as trams and metros. For high-speed trains or heavy-duty mainline locomotives requiring power in the megawatt range, more advanced design and testing systems need to be developed.

This study aims to evaluate the effectiveness of the traction control unit used in railway vehicles under real-world conditions. However, simulations and laboratory tests conducted do not necessarily imply that the application performs optimally in actual operational environments. Therefore, field tests are necessary to validate the findings of

the study. Field tests aim to assess the application's real-world performance by testing the train under full load and full speed conditions, thereby determining the application's limits and optimizing its performance accordingly. However, it is essential to carefully analyze the data collected during field tests and investigate the results to confirm whether the control strategy functions as intended. This ensures the reliability and efficiency of the application, making it suitable for safe and efficient use in the railway transportation industry.

Developing and expanding the field-oriented control (FOC) technique for railway traction motors is the goal of research that will be conducted in the future. Among these are the optimization of control parameters, the incorporation of new sensors, and the expansion of testing scenarios in order to gain an understanding of its application in a variety of industrial railway settings. For the purpose of evaluating the environmental and economic benefits of the FOC approach, energy efficiency analysis is also an extremely important component. Additionally, scalability and adaptability in a variety of railway structures should be taken into consideration in future studies.

As part of future work, a potential avenue for further enhancing and optimizing the application of the FOC method in railway motor control could involve a focus on chip technologies. This may include the integration of microcontrollers and digital signal processing (DSP) chips that have the potential to make motor control systems more compact, energy-efficient, and faster. Additionally, the incorporation of these chips could lead to the implementation of new measures to enhance system stability, reliability, and overall performance. This approach aims to ensure that motor control systems in railway transportation are aligned with future technological needs.

Researchers also could be directed towards power electronics components to further advance the field-oriented control method in railway motor control systems. Specifically, the integration of critical power electronics components such as inverters, power transistors, and capacitors with next-generation technologies could be explored. This integration holds the potential to provide higher efficiency, reduced energy losses, and more compact system designs. These studies aim to better align electric motor systems in railway transportation with future power and durability requirements.

REFERENCES

- [1] Pieper T., Obermaisser R., (2022), “Fault-injection for hardware- and software-in-the-loop testing of networked railway systems”, *Microprocessors and Microsystems*, 104456.
- [2] Bouscayrol A., (2008), “Different types of hardware-in-the-loop simulation for electric drives”, *IEEE International Symposium on Industrial Electronics*, 2146–2151.
- [3] Yong J. Y., Ramachandaramurthy V. K., Tan K. M., Mithulananthan N., (2015), “A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects”, *Renewable and Sustainable Energy Reviews*, 49, 365–385.
- [4] Pothireddy K. M. R., Vuddanti S., Salkuti S. R., (2022), “Impact of demand response on optimal sizing of distributed generation and customer tariff”, *Energies*.
- [5] Yildirim M., Polat M., Kürüm H., (2014), A survey on comparison of electric motor types and drives used for electric vehicles, in “2014 16th International Power Electronics and Motion Control Conference and Exposition”, 218–223.
- [6] Rahman K., Ehsani M., (1996), Performance analysis of electric motor drives for electric and hybrid electric vehicle applications, in “Power Electronics in Transportation”, 49–56.
- [7] Zeraouila M., Benbouzid M., Diallo D., (2005), Electric motor drive selection issues for hev propulsion systems: a comparative study, in “2005 IEEE Vehicle Power and Propulsion Conference”, 8 pp.–.
- [8] Faiz J., Sharifian M., Keyhani A., Proca A., (2003), “Sensorless direct torque control of induction motors used in electric vehicle”, *Energy Conversion, IEEE Transactions on*, 18, 1 – 10.
- [9] Yusof Y., Mat K., (2018), “Modelling, simulation and analysis of induction motor for electric vehicle application”, *International Journal of Engineering & Technology*.
- [10] Jisha L. K., Powly Thomas A. A., (2013), A comparative study on scalar and vector control of induction motor drives, in “2013 International conference on Circuits, Controls and Communications (CCUBE)”, 1–5.

- [11] H. Abu-Rub A. I., Guzinski J., (2012), “High Performance Control of AC Drives with MATLAB/Simulink Models”, John Wiley Sons, Inc.
- [12] Wolbank T., Moucka A., Machl J., (2002), A comparative study of field-oriented and direct-torque control of induction motors reference to shaft-sensorless control at low and zero-speed, in “Proceedings of the IEEE International Symposium on Intelligent Control”, 391–396.
- [13] Singh B., Singh B., Singh B., Chandra A., Al-Haddad K., (1997), Performance analysis of a low cost vector controlled induction motor drive: a philosophy for sensor reduction, in “1997 IEEE International Electric Machines and Drives Conference Record”, TB3/1.1–TB3/1.3.
- [14] Kitamura S., Kondo K., (2010), An enhanced torque control method of permanent magnet synchronous motor in the field weakening region, in “2010 International Conference on Electrical Machines and Systems”, 781–786.
- [15] Peroutka Z., Zeman K., Krus F., Kosta F., (2009), New generation of full low-floor trams: Control of wheel drives with permanent magnet synchronous motors, in “2009 IEEE Energy Conversion Congress and Exposition”, 1833–1840.
- [16] Benchaib A., Poullain S., Alacoque J.-C., Thomas J.-L., (2008), “High dynamics control under voltage/current and harmonic constraints: Sm-pmsm application for ac railways”, *Control Engineering Practice*, 16, 1308–1320.
- [17] Begh M., Herzog H.-G., (2018), Comparison of field oriented control and direct torque control.
- [18] Cuji W., Arcos-Aviles D., (2019), “Direct torque control and field oriented control for permanent magnet synchronous motor / control directo al par y control de campo orientado para un motor síncrono de imanes permanentes”, 24, 1–13.
- [19] del Toro Garcia X., Zigmund B., Terlizzi A. A., Pavlanin R., Salvatore L., (2011), “Comparison between foc and dtc strategies for permanent magnet synchronous motors”, *Advances in Electrical and Electronic Engineering*, 5, 76–81.
- [20] Wu X., Figueroa H., Monti A., (2004), Testing of digital controllers using real-time hardware in the loop simulation, 3622 – 3627 Vol.5.
- [21] Mihalič F., Truntič M., Hren A., (2022), “Hardware-in-the-loop simulations: A historical overview of engineering challenges”, *Electronics*.
- [22] P. Terwiesch T. K., Scheiben E., (1999), “Rail vehicle control system integration testing using digital hardware-in-the-loop simulation”, *IEEE Transactions on Control Systems Technology*, 7, 352–362.

- [23] J. N. Verhille A. Bouscayrol P. J. B., Hautier J. P., (2007), "Validation of anti-slip control for traction system using hardware-in-the-loop simulation", IEEE Vehicle Power and Propulsion Conference, 440–447.
- [24] Y. Hachicha D. Cypers M. T. S. B. P. L., Roux N., (2018), "Use of a hil railway traction simulator for low frequency network stability studies", IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference (ESARS-ITEC), 1–5.
- [25] Garramiola F., Poza J., Olmo J. d., Nieva T., (2019), "Hardware-in-the-loop performance analysis of a railway traction system under sensor faults", The Journal of Engineering, 2019(17), 3797–3801.
- [26] Higashikawa K., Urasaki S., Inoue M., Tomita M., Kiss T., (2016), "Hardware-in-the-loop simulation of superconducting devices for dc electric railway systems based on a real-time digital simulator", IEEE Transactions on Applied Superconductivity, 26(4), 1–4.
- [27] Chu L., Chao L., Ou Y., Lu W., (2012), "Hardware-in-the-loop simulation of traction control algorithm based on fuzzy pid", Energy Procedia, 16, 1685–1692. 2012 International Conference on Future Energy, Environment, and Materials.
- [28] Guo X., Tang Y., Wu M., Zhang Z., Yuan J., (2020), "Fpga-based-hardware-in-the-loop real time simulation implementation for high speed train electrical traction system", IET Electric Power Applications, 14(5), 850–858.
- [29] Böcker J., Sun M., Cao Z., Tong L., Zou H., Ranjan P., (2012), "High fidelity hybrid hardware-in-the-loop simulator with fpga and processor for ac railway traction".
- [30] Patel J. R., Vyas S., (2014), "Simulation and analysis of constant v/f induction motor drive", International Journal of Engineering and Technical Research (IJETR).
- [31] Mikhael H., Jalil H., Ibrahim I., (2016), "Speed control of induction motor using pi and v/f scalar vector controllers", International Journal of Computer Applications, 151, 36–43.
- [32] Riad T., Meziane S., Benalla H., (2007), "Direct torque control for induction motor using intelligent techniques", Journal of Theoretical and Applied Information Technology.
- [33] Kohlrusz G., Fodor D., (2011), "Comparison of scalar and vector control strategies of induction motors", Hungarian Journal of Industrial Chemistry Veszprém, 39(2), 265–270.

- [34] Blaschke F., (1971), "A new method for the structural decoupling of ac induction machines", In Conf. Rec. IFAC, 15, 1–15.
- [35] Popescu M., (2000), "Induction Motor Modeling For Vector Control Purposes", Helsinki University of Technology, Laboratory of Electromechanics.
- [36] T V. G. B., (2017), "Comparison between direct and indirect field oriented control of induction motor", International Journal of Engineering Trends and Technology (IJETT), 43, 364–369.
- [37] Ghoshal A., John V., (2010), "Anti-windup schemes for proportional integral and proportional resonant controller".
- [38] Yılmaz H. C., (2020), "Sürekli Mıknatıslı Senkron Motorun Alan Yönlendirmeli Kontrolü", Master's thesis, Kocaeli University.
- [39] Martinsson D., Lind M., (2006), "DSP Controller for Power Electronic Converter Applications", Master's thesis, Lund University.
- [40] Frasca E., (2022), "Design and Testing of Hardware in the Loop Test Bench for Permanent Magnet Synchronous Motors Controlled with Field Oriented Control Technique", Master's thesis, Politecnico di Torino University.
- [41] Kakodia S. K., Dynamina G., (2020), "A comparative study of dfoc and ifoc for im drive", IEEE International Conference on Measurement, Instrumentation, Control and Automation (ICMICA), 1–5.
- [42] Casadei D., Profumo F., Serra G., Tani A., (2002), "Foc and dtc: two viable schemes for induction motors torque control", IEEE Transactions on Power Electronics, 17(5), 779–787.
- [43] Gao J., Hu Y., (2010), "Direct self-control for bldc motor drives based on three-dimensional coordinate system", IEEE Transactions on Industrial Electronics, 57(8), 2836–2844.
- [44] Depenbrock M., (1988), "Direct self-control (dsc) of inverter-fed induction machine", IEEE Transactions on Power Electronics, 3(4), 420–429.
- [45] Steimel A., (2004), "Direct self-control and synchronous pulse techniques for high-power traction inverters in comparison", IEEE Transactions on Industrial Electronics, 51(4), 810–820.
- [46] Enache S., Vlad I., Enache M. A., (2022), "Aspects regarding the optimization

of cross geometry in traction asynchronous motors using the theory of nonlinear circuits”, *Energies*.

- [47] M. Aktaş K. Awaili M. E. A. A., (2020), “Direct torque control versus indirect field-oriented control of induction motors for electric vehicle applications”, *Engineering Science and Technology, an International Journal*.
- [48] Dewi H., Jufri F. H., Hudaya C., (2019), “Techno-economic analysis of slip ring motor replaced by standard squirrel cage induction motor with vsd”, *Journal of Physics: Conference Series*, 1402(3), 033107.
- [49] Chapman S. J., Stephen C., (2012), “Electric Machinery Fundamentals”, McGraw-Hill Science/Engineering/Math.
- [50] Emar W., Al-Omari Z., Rawashdeh T., (2023), “Slip-ring induction motor torque and current ripple minimization using bang-bang current control”, *Evergreen*, 10, 962–975.
- [51] Balashanmugham A., Maheswaran M., (2019), Permanent-magnet synchronous machine drives, in A. El-Shahat M. Ruba, eds, “Applied Electromechanical Devices and Machines for Electric Mobility Solutions”, IntechOpen, Rijeka, chapter 2.
- [52] Ahmed W., Adel M., Taha M., Saleh A., (2021), “Pso technique applied to sensorless field-oriented control pmsm drive with discretized rl-fractional integral”, *Alexandria Engineering Journal*, 60, 4029–4040.
- [53] Du G., Li N., Zhou Q., Gao W., Wang L., Pu T., (2022), “Multi-physics comparison of surface-mounted and interior permanent magnet synchronous motor for high-speed applications”, *Machines*.
- [54] Ogbuka C. N. C., Agu M., (2016), “Dynamic and steady state performance comparison of line-start permanent magnet synchronous motors with interior and surface rotor magnets”, *Archives of Electrical Engineering*, 65(1), 105–116.
- [55] Chen F., Ding H., Lee S., Feng W., Jahns T., Sarlioglu B., (2020), Current source inverter based large constant power speed ratio spm machine drive for traction applications, 216–221.
- [56] N. Tashakor Z. L., Goetz S. M., (2021), “A generic scheduling algorithm for low-frequency switching in modular multilevel converters with parallel functionality”, *IEEE Transactions on Power Electronics*, 36, 2852–2863.

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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