A Hybrid Intelligent-Based Speed Tracking Controller of Cement Rotary Kiln Motor Drive System
(Case Study: Mugher Cement Factory)

Banteamilak Tigabu Tessema

A Thesis Submitted to the Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power and Control Engineering (Control Engineering)

Office of Graduate Studies
Adama Science and Technology University

March, 2024

Adama, Ethiopia

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Declaration

Hereby, declare that this Master Thesis entitled "**A Hybrid Intelligent-Based Speed Tracking Controller of Cement Rotary Kiln Motor Drive System**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Banteamilak Tigabu Tessema	____________	25/04/2024
Name of Student	Signature	Date

Recommendation of Advisor

I, the major advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**A Hybrid Intelligent-Based Speed Tracking Controller of Cement Rotary Kiln Motor Drive System**" prepared under my guidance by Banteamilak Tigabu Tessema submitted in partial fulfillment of the requirement for the degree Masters of science in control engineering. Therefore, I recommended the submission of revised version of the thesis to the department for the following the applicable procedures.

Major Advisor	Signature	Date

Approval page of M.Sc.Thesis

I, the advisor of the thesis entitled "**A Hybrid Intelligent-Based Speed Tracking Controller of Cement Rotary Kiln Motor Drive System**" and developed by Banteamilak Tigabu Tessema here by certify that there recommendation and suggestion made by the board of examiners are appropriately incorporated into the final version of the thesis.

____________________	____________________	____________________
Name of Advisor	Signature	Date

We, the under signed, members of the Board of Examiners of the thesis by Banteamilak Tigabu Tessema have read and evaluated the thesis entitled "**A Hybrid Intelligent-Based Speed Tracking Controller of Cement Rotary Kiln Motor Drive System**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfilment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering (Control Engineering).

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Chairperson	Signature	Date
Internal examiner	Signature	Date
External examiner	Signature	Date

Final approval and acceptance of the thesis is contingent upon the Submission of its final copy to the Office of Postgraduate Studies (OPGS) through the department Graduate Council (DGC) and School Graduate Committee (SGC).

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Department Head	Signature	Date
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Office of postgraduate Studies, Dean	Signature	Date

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LIST OF ACRONYMS and ABBREVIATIONS

AC	Alternating Current
AI	Artificial Intelligence
AM	Asynchronous Motor
ANN	Artificial Neural Network
DC	Direct Current
DFOC	Direct Field Orientated Control
DRFOC	Direct Rotor Field Orientated Control
DTC	Direct Torque Control
FLC	Fuzzy Logic Controller
FOC	Field Orientated Control
IFOC	Indirect Field Orientated Control
IGBT	Insulated Gate Bipolar Transistor
MCF	Mugher Cement Factory
MRAC	Model Reference Adaptive Controller
MRAS	Model Reference Adaptive System
PI	Proportional Integral
PID	Proportional Integral Derivative
SMC	Sliding Mode Controller
SSLIM	Single Sided Linear Induction Motor
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter

ABSTRACT

The cement rotary kiln is the core equipment in the manufacturing of the cement industry, which is a large cylindrical furnace used for the production of clinker, it is a key ingredient in the cement production process. It has been driven by a high performance of an asynchronous motor and it plays a crucial role for efficient operation of the cement kiln. In this thesis, a case study has been taken from Mugher cement factory, the existing control technique of the kiln motor drive system has a conventional vector control or field orientated control technique using proportional, integral and proportional, integral and derivative controllers. In MCF the existing major problems in the factory such as challenging to handle the uncertain, nonlinear and complex dynamic of the system, leading to suboptimal control performance and in addition it has a speed sensor directly measures the motor speed using a physical sensor. Those all the above mentioned characteristics are degrade the performance of controllers. As a result many controllers fail to smoothly track the speed trajectory. Therefore, appropriate and real time speed controllers are required to attain the required level of control performance. In this thesis, the Model reference adaptive system control and artificial neural network control technique is used for the speed control of the kiln motor drive system. To overcome these challenges, the proposed control technique is designed and its performance evaluated against the model reference adaptive and artificial neural network controller individually. In this thesis, the simulation works have been carried out by using MATLAB/Simulink software setup (Ra2018). Hence, the results showed that the Model reference adaptive system control a tracking control of speed and torque is good, adaptability is good, response time is good, but disturbance handling capability is moderate and rise time is 0.170sec, settling time is 0.134sec and overshoot is 2.24%. On the other hand, artificial neural network controller outperforms speed and torque tracking control accuracy is excellent, response time is excellent, disturbance rejection capability is good, adaptability is excellent and rise time is 0.123sec, settling time is 0.016sec and overshoot is 1.64%. Finally, a hybrid Model reference adaptive system control and Artificial neural network control has a superior performance of an accurate speed tracking control, adaptability is excellent and response time is excellent and rise time is 0.106sec, settling time is 0.014sec and overshoot is 1.25%. In this study, the finding results have been proven that a combined control techniques are effectively regulated and improved that both the required speed control performance for kiln motor drive system.

Keywords: - *Asynchronous motor, Model reference adaptive system controller, Artificial neural network controller, A hybrid controller, Cement rotary kiln, MATLAB/SIMULINK.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

The cement rotary kiln is one of the major components in the cement production industry. This has a large cylindrical vessel used for the production of clinker. It is a key ingredient in cement production process. The kiln has been driven by an asynchronous motor drive system. To maintain the desired process operation of the cement kiln the speed and torque control of the motor drive system are very important. To precise control of the rotational speed ensures proper heat transfer and chemical reaction a within the kiln. Additionally, accurate torque control leads to smooth and efficient operation, preventing the kiln stoppage or excessive power consumption. The cement kiln process operation is a more complex and dynamic system, which can be influenced by various factors such as the characteristics of the raw material, process conditions, and load variations. Therefore effective control technique is essential to regulate the speed and torque, stable and reliable operation of the kiln (R. Nahavandi, 2022). The speed and torque control has a great role in the cement rotary kiln system. In this thesis, a case study was conducted at Mugher cement factory, the existing control technique of the kiln motor drive system using the conventional control techniques such as PI, PID control. However, this technique is unable to handle the nonlinearity and complex dynamic of the system, leading to suboptimal control performance. To improve the control performance of the motor drive system for kiln many machines control design has been developed (M. Vargas, 2023). In the advancement of control design the controller adaptations in the system has become mandatorily and the controllers such as Fuzz, PID, SMC, MRAC and ANN. Fuzzy logic control (FLC), known for control handling uncertainties and imprecise information, is suitable for systems with nonlinearities and vagueness. It relies on linguistic variables and fuzzy rules, offering a more intuitive and interpretable control system design. However FLC requires expert knowledge in rule design, which can introduce subjectivity and it may struggle to generalize well to unseen situations or significant changes in system dynamics. PID control is a widely used and simple control techniques that is easy to implement in is suitable for many applications and provides stability through well establish tuning methods. However, PID control is sensitive to model mismatch and parameter variations, it lacks adaptability to change conditions and uncertainties, requires frequent retuning. Sliding mode control (SMC) offers robustness and against uncertainties and disturbances, making it suitable for system with uncertain dynamics. SMC maintains control performance in the presence of parameter variations. However, SMC can introduce chattering, leading to increased wear on mechanical components and it typically requires an accurate model of the system dynamics, which can be challenging to obtain in practice. Model reference adaptive control technique is that offers adaptability and robustness by adjusting to changes in system dynamics compensating for uncertainties. It does not rely heavily on an accurate mathematical model, reducing the reliance on complex model assumptions. However, accurate parameter estimation is crucial for MRAC, which can be challenging in highly nonlinear or poorly observable systems(O. Stoicuta, 2021).On the other hand, Artificial neural network (ANN) provides nonlinear approximation capabilities, allowing for accurate modeling and control ANN can learn from historical data, adapt to change conditions and exhibit fault tolerance making it suitable for real world applications however, ANN requires a sufficient amount of training data and its implementation can be computationally demanding. A hybrid Model reference adaptive and artificial neural network control technique has been designed to control kiln motor drive system. This thesis is focused on the control design of an MRAC-ANN based control system for speed and torque tracking control of an asynchronous motor in cement rotary kiln. An MRAC component aims to estimate the motor parameters compensate for uncertainties and adapt to change operating conditions. The robustness, adaptability, disturbance rejection, nonlinear control and learning capability of the ANN controller and as well as this combined approach enables the system effectively handle parameter variation, uncertainty and nonlinear characteristics of an asynchronous motor. The ANN component leverages its capability to learn complex nonlinear relationships and enhance the control system performance by providing accurate motor speed and torque estimation (S. Khadar, 2021). The use of a hybrid MRAC-ANN offers several advantages in this context. Firstly it enables the control system to adapt to variations in the motor and kiln characteristics such as change in the load temperature and wear of mechanical components. Secondly, the integration of ANN allows for improved estimation accuracy by learning from the historical data and capturing non linearity in the motor response (Guillod, T., 2020).

1.2 Statement of the Problem

This thesis a case study has been taken from Mugher cement factory (MCF). The existing control technique of the kiln motor drive system using conventional vector control or field orientated control method based on proportional, integral and proportional, integral and derivative controllers. In MCF the existing major problems in the factory such as challenging to handle the uncertain, nonlinear and complex dynamic of the system, leading to suboptimal control performance and in addition the motor speed measuring using a physical sensor. Those all the above mentioned characteristics are degrade the performance of the controllers. As a result many controllers fail to smoothly track the speed trajectory. Therefore, appropriate and real time speed controllers are required to attain the required level of control performance. In this thesis, the Model reference adaptive control and artificial neural network control technique is used for the speed control of the kiln motor drive system. To overcome these challenges, the proposed control technique is designed and its performance evaluated against the model reference adaptive and artificial neural network controller individually. To face these major challenges the combination of Model reference adaptive control and artificial neural network control technique has been designed. A sensorless control using direct rotor field orientated control (DRFOC) algorithm of an asynchronous motor for cement rotary kiln system. The MRAC can estimate the rotor flux and rotor speed based on the measurements stator currents and voltages. The ANN controller can be complemented the MRAC by learning the nonlinear mapping between the input variables such as stator currents, voltages and rotor fluxes and the desired outputs are estimated rotor flux and motor speed. The ANN for sensorless control of motor drive system which will improve its estimation accuracy, adapt to varying operating conditions, handle uncertainties and disturbances that may affect the sensorless control performance. The ANN learns from training data and refine its internal parameters to enhance the estimation accuracy and robustness of the sensorless control algorithm. Therefore, a hybrid MRAC and ANN for sensorless control scheme of an asynchronous motor system has potential to accurately control speed of kiln motor drive system. Finally, evaluation of the simulation work will be carried out on MATLAB/SIMULINK.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this thesis work is to design a hybrid intelligent based speed tracking controller of cement rotary kiln motor drive system.

1.3.2 Specific Objectives

i. To model of an asynchronous motor for cement rotary kiln
ii. To design MRAS based controller for the kiln motor drive system.
iii. To design ANN controller for the kiln motor drive system.
iv. To design a hybrid MRAC-ANN based controller for kiln motor drive system.
v. To evaluate and analyze their speed tracking control performances through MATLAB simulation.

1.4 Significance of the Study

This proposed thesis study has many importance points for control of rotary kiln system. By developing a hybrid intelligent based controller using MRAC-ANN, the study aim to improve control performance specifically in cement rotary kiln motor drive. This can lead to enhanced control speed and torque reduced maintenance cost and improved product quality. The integration of MRAC and ANN control technique which is crucial for stable operation energy efficiency, product quality equipment protection of kiln motor drive.

1.3 Scope and Limitations of the Study

A hybrid intelligent based speed tracking controller of cement kiln motor drive system will be developed taking Mugher cement factory as a case study. Not all the cement plant related control will be controlled rather only the major ones focus of this thesis is specifically the cement kiln motor drive system not the overall cement production process control. However, the model reference adaptive control algorithm can estimate the speed and as well as to the rotor flux of motor drive system. It has the parameter adaptation mechanism which is one of the arts of model this study and other controller artificial neural network it is learning capability of historical data it is handle the nonlinear characteristics of cement rotary kiln motor system. Finally, the simulation has been carried out on the MATLAB/SIMULINK software environment. The hardware experimental validation is restricted due to the study limitation including time and resource constraints specifically, assumptions, and implementation challenges potential influence and some of external factors.

1.6 Organization of the Thesis

In this section the proposed work has been arranged as follows: Chapter one stated as introduction, beginning with a background of the study, which provide relevant information for the research. The problem statement is focuses on the specific issues being addressed, followed by the objective of the study, which outlines the intended goals. The significance and scope of the study are discussed, emphasizing how it aims to achieve a better control performance of cement rotary kiln motor drive system. Lastly, an overview of the thesis structure is presented, giving readers a clear roadmap of what to expect. Chapter two focuses on the literature review, where existing research papers on control techniques for cement rotary kiln motor drive systems are reviewed, special attention is given to model reference adaptive and artificial neural network control techniques. Additionally, the concept of a hybrid intelligent MRAC and ANN approach is explored, highlighting its potential benefits. Chapter three describes about methodology section, providing an overview of Mugher cement factory and the kiln motor drive system under technical investigation. The data collection procedures are described, ensuring that the study is based on reliable and relevant information. This chapter also covers the modeling of an asynchronous motor, load determination of critical component of the rotary kiln system. Chapter four presents the finding results and discussion. Based on the simulation results of Matlab then after, focusing on the performance evaluation and comparing of the controller each other. The finding results are compared with relevant research to gain insights into the effectiveness of the proposed methods. Hence, finally the conclusion and recommendations. The study contributions and key findings are summarized providing a concise overview of the achieved outcomes. Based on the analysis a conclusion is drawn, the implications of the research. The chapter concludes with recommendations for future research and the implication of hybrid intelligent control approaches in cement production systems, suggesting potential areas of further investigation. The thesis includes a reference section listing the cited sources and acknowledged them properly.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background of the Study

To ensure the relevance and importance of the present study, a comprehensive review of related literature was conducted, encompassing the modeling of cement kiln main drive, as well as the application of MRAC and ANN in speed and torque control system for cement kiln main drive. The literature review sought to explore previous studies and research conducted on different modeling techniques, speed and torque control methods applied to accurately control motor speed, specifically in the context of cement kiln motor drive. Various sources were reviewed, including books, research papers, journals, and online resources. In the literature review section, an overview of asynchronous motor can be provided (V. Teriaiev, 2022). This thesis aim to present the sit description of study, fundamental concept, working principle, and key characteristics of asynchronous motor which are commonly used in various industrial applications including the motor drive system of cement rotary kiln. The following are some of the previous related works have been mentioned below.

2.1.1 Related works

A.K Awasthi, R.T Ugale and A. kumar, (Waasthi, 2020). In this work, a novel sensorless artificial neural network (ANN) control for a single-sided linear induction motor (SSLIM). The controller eliminates the need of physical sensors by using data extracted from a direct torque control (DTC) scheme trained offline. A major drawback of DTC is the presence of current ripples but, ANN controller effectively suppresses it. The concept is validated through modeling of both the SSLIM and the ANN controller in a MATLAB/Simulink. The results showed that a superior speed tracking performance achieved by ANN controller compared to DTC.

R Nahavandi, M Asadi and A. Torkashvand, (N ahavandi, 2022). In this paper, introduced a novel control algorithm for field orientated control of an induction motor (IM). Which can be achieved with more reliable dynamics and steady state performance. This control strategy is an advancement in the FOC by incorporating a second order sliding mode (SOSM) approaches in the inner loop, which utilizes an artificial neural network (ANN) for rotor flux and motor speed estimation. The SOSM controller is designed based on an induction motor model encompassing a torque control loop (inner loop) and a speed tracking control (outer loop). Simulations results confirmed the capability of the control algorithm even there is in the presence of parameters uncertainty and load variations.

M.M Hassan, (Hassan, 2019). In this study, presented an efficient speed estimation scheme for field orientated control of three phase induction motor drive is presented. It utilizes a time series neural network to estimate the speed in sensorless field orientated control. The inputs to the neural network include d-q axis control voltage supplied by SVPWM inverter. Compared to the MRAS based speed estimation the proposed scheme reduced a computational complexity. The performance of the proposed scheme is demonstrated at low speed regions, specifically at zero and 10 rad/sec and the estimator performs satisfactorily across the specified motor speed range. The evaluation of the neural network based speed estimator was conducted using MATLAB/Simulink.

K.Bouhoune K.Yazid, M.S Bouchrit B. Nahid-Mobarakeh and M.Menna (Bouhoune, 2019). In this study, focus on electrical sensorless control of induction motors while much attention has been given to mechanical sensorless control. A fault of a single electrical sensor can lead to a malfunction in the entire control chain. To address this problem, the study proposed a new electrical sensorless control method for induction motors that offers compatible performance to field orientated control (FOC) but at a lower cost. The proposed control scheme is based on artificial neural networks (ANN). A neural block is designed to generate the required control signals for the induction motors based on minimal data provided by the motor at any operating points. The simplicity of the control scheme and its more cost effectiveness and an attractive alternative. The effectiveness of the proposed control method is verified under various operating conditions and compared to conventional FOC. The results that clearly demonstrated that merits of the proposed control including lower cost, simplicity of the control scheme, and most importantly its ability to handle technical failure at any one or both stator current sensors.

S.Mencous, M. Beyakhlef and E.B. Tazi, (Mencous, 2022). In this study, induction motors (IM) are recognized as highly promising candidates for electric propulsion in various applications including hostile environments. However, the analytical model of an IM is nonlinear, strongly coupled, and multivariable and complexity to control. Advanced control algorithms are required to effectively control the torque and flux of these machines in real-time. This paper provides an overview different modern techniques that have enhanced the performance of three conventional control methods such as Scalar control, field orientated control (FOC) and direct torque control (DTC) the following mentioned as a various aspects of performance improvement are considered including torque and flux ripple, switching, frequency, parameters sensitivity, dynamic response, current harmonic distortion, and algorithm complexity.

S. Hussain, H.Khan and M.A Baza, (Hussaain, 2018). In this work, introduced a direct torque control (DTC) for controlling torque and flux of an induction motor. Conventionally, torque and flux estimation in DTC requires measurements of current and voltage, existing control that speed measurements for generating reference torque and flux values for control actions. However, the use of sensors for these, measurements can be disadvantageous due to increased costs and decreased reliability. To address this challenges the study focused to implement of a neural network observer for torque, speed and flux estimation in direct torque controlled induction motor drive. The neural network based observer i-d designed to estimate these parameters without relying on sensor measurements. By utilizing the neural network the need for physical sensors is eliminated. The evaluation is demonstrating its potential for enhancing the performance and reducing the dependency on physical sensors in direct torque controlled induction motor drive.

A.B Sharma, S.Tiwari and B. singh (Sharam, 2020). In this paper, an intelligent of estimation of motor speed based on feed forward neural network using model reference adaptive system. The study proposes the use of a multilayered feed forward neural network technology to estimate the intensity of the rotor flux as part of a speed estimator. This proposed speed estimator replaces the conventional references model of the model reference adaptive system (MRAS). The performance of the speed estimator is evaluated under various operational conditions which particularly focus on low speed range situation. The artificial intelligence based speed estimator successfully estimates and control the speed of the induction motor and also it can demonstrating its effectiveness in enhancing energy efficacy and achieving reliable speed estimation in the absence of a velocity sensor.

M S. Sepeeh, S A. Zulkifli, S.Y. Sim, H J. Chiu and S A. Jumaat (Sepeeh, 2022). In this paper a novel sensorless control for induction motors using a flux estimator to represent the speed inputs for speed control. The study focuses on a small electric vehicle motor used to an EV motor scenario. The proposed method utilizes a hybrid controller combining flux estimation and speed control using artificial neural networks with improved field oriented control (ANN-IFOC). The objective of to change the actual speed sensor, thereby enhancing speed tracking and trajectory effects while reduce costs saving based on the flux speed estimation. The selection of the flux parameter is motivated by its sensitivity to changes in the load and making it suitable for application in electric vehicle EV motor. Although the speed signal is generated using ANN and IFOC and the flux parameters without a speed sensor separate speed controller is required.

2.1.2 Research Gap

Under this a summarized research gap, review of the literature was conducted. Many research papers were analyzed and their contribution was carefully examined. Through this reviews process a comparison was made among the various research papers, as much as possible try identify their similarities and differences. By identifying these comparisons and analyzing the research papers in detail a research gap was identified. Which are represents an area where further investigation and study are needed. The research gap will used as the foundation for a new insights and contributions will be made to fill this gap and advance the current state of knowledge in the field. The researchers have been studied the speed control of motor drive using ANN in the field of sensorless control strategy for induction motors, several research gap have been identified. Firstly, there is a lack of a sensorless control strategy specifically designed for single sided linear motor induction motors (SSLIM). The existing control methods fail to effectively suppress current ripples and achieve superior speed tracking performance in SSLIMs. Secondly, the issue of parameter uncertainty in induction motor control remains a challenge. Induction motors are subject to variations in their parameters due to factors such as temperature changes. Existing control strategy often struggle to handle such uncertainty, leading to suboptimal performance and to overcome this robust control strategy is needed that can effectively mitigate the effects of parameter uncertainty and ensure reliable motor operation. Furthermore many of the current sensorless control strategy for three phase induction motor drives suffer from computational complexity. This can limit their practical implementations especially in real- time control systems. Lastly, there is a demand for electrical sensorless control of induction motors that can provide performance similar to the widely adapted field orientated control (FOC) technique.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Components of an Asynchronous motor drive system

Under this chapter, mainly focused on the mathematical modeling of the components of an asynchronous motor drive system. It has consists six major components as follows: The required mathematical equations of motor should be clearly formulated. Firstly, the three phase AC power supply provides the rated electrical energy for the drive. The diode rectifier circuit is used to for converting AC power into DC power supply. The internal structure of diodes or SCR arranged in a specific task configuration. And the DC bus is an intermediate device which sored electrical power for the motor. The inverter is used for converting the DC power from the DC bus back into AC power with variable voltage and frequency magnitude (H. Mohan, 2018). It has consists of the power electronic switch insulated gate bipolar transistors (IGBTs) Control System. The control system is used for regulating and controlling the operation of the motor drive system (A. K. Sahu, 2023). It can be received feedback from sensor and generate appropriate control signal to adjust the motor speed monitoring the rotary kiln inside the plant temperature variations (P. Zhao, 2019).

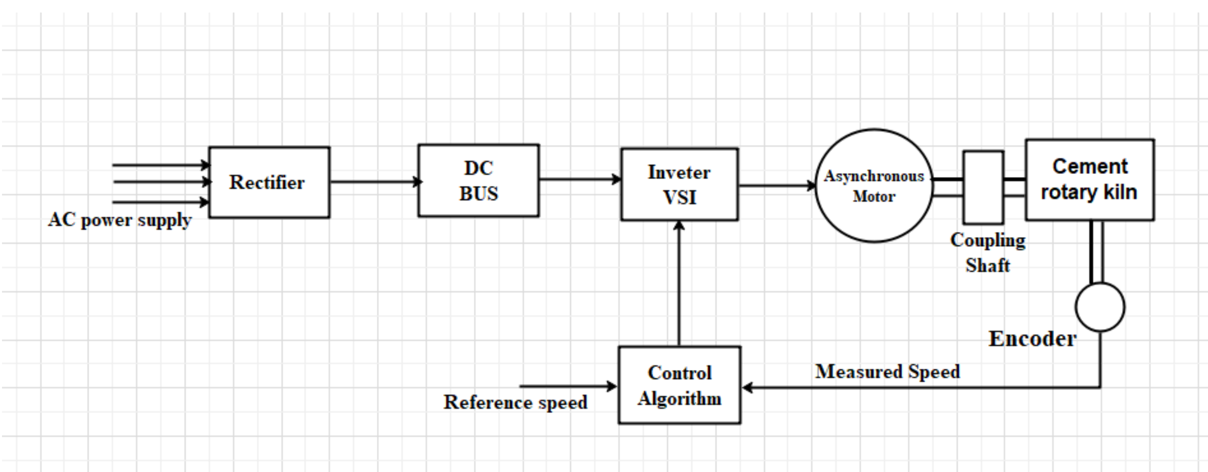

Figure 3.1 Block diagram of an asynchronous motor drive system for cement rotary kiln

3.1.2 Software tools

This research aims to design and various control techniques for an asynchronous motor used in the motor drive of a cement rotary kiln. The research will be involved modeling the motor's behavior in MATLAB/Simulink, design and simulation the controllers (MRAC, ANN and Hybrid MRAC-ANN)**.** The following are different the Research working Phases that have been mentioned below

1. Asynchronous Motor Modeling

❖ **MATLAB/Simulink**

✓ To model the mathematical of the asynchronous motor.

✓ Ensure the model captures key system dynamic behavior for realistic simulation results.

5. Documentation and Reporting

❖ **Edraw Max** is used to create clear and detailed block diagrams for

✓ The asynchronous motor drive system with its main components

✓ The MRAC-controlled for motor

✓ The ANN controlled for motor

✓ The Hybrid MRAC and ANN based speed and torque control for motor

❖ **Microsoft Word** is used to prepare comprehensive documentation that includes:

✓ A detailed the research description.

✓ Methodology and design procedures for each controller.

✓ Simulation results and analysis for each controller.

✓ Discussions and conclusions regarding the performance and effectiveness of each controller.

Resources of the software tools

❖ MATLAB/Simulink software

❖ Edraw Max software

❖ Microsoft Word software

3.2 Methods

3.2.1 Construction of a high performance asynchronous motor drive system

A high-performance asynchronous motor, also known as a high-performance induction motor, the construction of motor drive has several key components and design considerations. The construction includes the main stationary part of the motor laminated iron core and stator windings (S. Ozdemi, 2020). The core is used for low reluctance path for the magnetic flux and reduce energy losses due to eddy current. Typically, the stationary winding made of copper or aluminum are placed in slots on the stator core. The number of slots and winding configuration are determined based on the motor performance requirements. On the other hand the rotor part is the rotating part of the motor and constructed by laminated iron core. There are two common types of rotor construction such as the squirrel cage and wound rotor respectively. In the squirrel cage rotor conductor coil bars are placed in rotor slots and short circuited at the end by conducting end rings. This design allows for efficient torque production and easily in control. In a wound rotor the rotor winding is brought out through slip rings enabling external resistors. This type of rotor provides enhanced control capabilities at the expense of added complexity. Bearings are used to support and accelerate the rotation of the motor driving shaft speed. High-performance asynchronous motors typically incorporate high-quality roller bearings to ensure make a smooth operation and minimize friction losses. The motor enclosure is designed to provide protection to the internal components from environmental factors they are dust, moisture and temperature variations. Efficient cooling is crucial for high-performance motors to dissipate the heat generated during operation. Various cooling methods can be employed such as air cooling, liquid cooling or a combination of both of cooling system. Advanced cooling techniques, such as forced air circulation or liquid cooling jackets are often used to enhance motor performance and reliability. Additionally, high-performance asynchronous motors may incorporate advanced control and monitoring systems (N. -T. Nguyen, 2023). These systems can include sensors, motor control units communication interfaces, and condition monitoring capabilities.

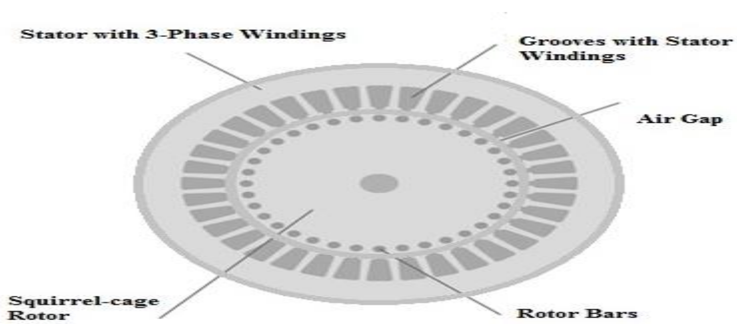

Figure 3.2 Construction of an asynchronous motor

Asynchronous motor, also known as an induction motor, offer several advantages that make them widely used in various applications. Some of the key advantages of asynchronous motor

- **Robustness:** it has robust construction and ability to withstand harsh operating conditions.
- **Cost effective:** it compared to other types of motors, it has a simple and rugged design.
- **High reliability:** it has a long operational life and require minimal maintenance.

Figure 3.3 Asynchronous motor

3.2.2 Operation of a high-performance an asynchronous motor drive system

The operational principle of a high-performance asynchronous motor, also known as a high-performance induction motor. The drive is working on the principle electromagnetic induction principle. When the three phase power is supplied to the stator winding and it develops revolving magnetic field around the stator winding gradually, this produced field is set up on the rotor part and cutoff coil the motor the field interaction between the stator and rotor components to produce rotation and generate mechanical power or torque. The motor operating based on the principle of a rotating field created by the stator winding. The rotating field develops currents in the rotor conductor coil by induction principle. The short circuited rotor bars cut across the rotating field resulting in the generation of rotor current (Forestieri, 2018). This developed torque used to drive and as well as to rotate motor drive. The speed of the rotor rotation is less than the speed of the rotating magnetic field, known as the slip. The slip is necessary for the motor to develop torque. The mechanical load on the motor increase and also the slip increase which is allowing the motor to maintain the required torque. The torque produced by the motor is proportional to the difference between the synchronous speed of the rotating field and the actual rotor speed is determined by the slip ratio. The motor performance characteristics such as efficiency torque control, and speed range are influenced by factors such as the design of the stator and rotor, winding configurations and control strategies employed. The Control techniques of vector control or field oriented control are often used for high performance asynchronous motors to achieve precise control of torque and speed. These advanced control method involve decoupling the torque and flux components of the motor and independently controlling them enabling high performance operation and efficient control over a wide range of operating conditions. Hence, the operational principle of a high performance asynchronous motor involves the interaction between the rotating magnetic field generated by the stator winding and the induced magnetic field in the rotor, resulting is to develop torque and the generation of mechanical power which can drive the desired load.

3.2.3 Mathematical modeling

Modeling a high-performance asynchronous motor involves developing mathematical models that accurately describe its electrical and mechanical characteristics. These models are used for analysis, simulation, and control design purposes.

- ✓ **Modeling of Electrical system** typically it includes the motor stator and rotor winding, resistances, inductance, and mutual inductance. The model can be based on a per phase equivalent circuit, where each phase is represented by resistor, inductor, and mutual inductance. The electrical model allows for the calculation of current, voltage, and power flows in the motor.
- ✓ **Magnetic circuit Model** the magnetic model represents the magnetic field distribution and magnetic saturation effects in the motor. It takes into account the magnetic properties of the stator and rotor materials, as well as the geometry of the motor. The magnetic model is crucial for accurately predicting the motor's torque production and magnetic losses.
- ✓ **Modeling of Mechanical system** it used to determine the total loads of the plant describes the mechanical system of the drive, including its inertia, damping, and load torque characteristics. It can be represented as a mechanical rotational system, where the motor shaft is coupled to a mechanical load. The mechanical model allows for the calculation of motor speed, torque, and mechanical power output.

- ✓ **Control Model** the control model represents the control system that governs the motor's operation. It consists the control techniques are field oriented control or other advanced control techniques, used to regulate the motor's torque and speed. The control model takes into account the motor's electrical and mechanical characteristics to achieve desired performance objectives. These models can be represented using mathematical equations, such as differential equations, transfer functions, or state-space representations. Various simulation and analysis tools, such as MATLAB/Simulink software, are commonly used to implement and analyze these models. Once the models are developed, they can be used for a variety of purposes, such as predicting motor performance under different operating conditions, designing and optimizing control algorithms, studying the effects of parameter variations and evaluating the motor's efficiency and dynamic response (B. V. S, 2022). It's important to note that the complexity of the models can vary based on the requirements of and the specific application. It can be used a simplified models for initial design and analysis, while more sophisticated models may be necessary for detailed performance evaluation and advanced control design.

Load determination of a cement rotary kiln

Determining the load of a cement rotary kiln involves measuring and analyzing various parameters. Here, are some methods commonly used for load determination for kiln.

- **Power consumption** monitoring the power consumption of the kiln motor can provide an indication of the load. As the load increase, the power consumption typically rises. By measuring the kiln motor power consumption ant it can be estimated the load level.
- **Kiln motor current** the current drawn by the kiln motor as often proportional to the load monitoring the motor current can give insights into the kiln load condition. As the load increase, the current drawn by the motor also tends to increase.
- **Kiln shell temperature** the temperature distribution along the kiln can offer valuable information about the load. Higher temperature in specific sections of the kiln shell may indicate areas of increased load. Temperature sensors can be installed at various locations to monitor the shell temperature and identify load variations.

- **Kiln drive torque** measuring the torque exerted by the kiln drive system can be used estimate the load. Torque sensors or load cells can be installed in the drive system to provide real-time data on the torque being applied.
- **Kiln vibration analysis** monitoring and analyzing the kiln vibration patters can help assess the load conditions. Increased vibration levels may indicate higher loads or potential issues with the kiln operation.
- **The feed rate and material flow** monitoring into the kiln can provide insights into the kiln load. By measuring the input material flow rate it can estimate the load being processed by the kiln.

3.2.3.1 Modeling of an asynchronous motor for cement rotary kiln

The 3 phase reference system

$$N_s = \frac{120f}{p} \tag{3.1}$$

$$[\, v_{sabc}]^T \;=\; [\, R_s]^T [\, i_{sabc}]^T \frac{d}{dt} [\, \varphi_{sabc}]^T \tag{3.2}$$

$$[\, v_{rabc}]^T \;= 0 = [\, R_r]^T [\, i_{rabc}]^T \frac{d}{dt} [\, \varphi_{rabc}]^T \tag{3.3}$$

Where,

v_{sabc} Voltage supply to three stator phase

v_{rabc} Voltage supply to three rotor phase

i_{sabc} Currents cross to three stator phase

φ_{sabc} Stator flux

R_s Motor stator resistance

R_r Motor rotor resistance

$$\begin{bmatrix} \varphi_{sa} \\ \varphi_{sb} \\ \varphi_{sc} \\ \varphi_{ra} \\ \varphi_{rb} \\ \varphi_{rc} \end{bmatrix} = \begin{bmatrix} i_s & m_s m_s m_1 m_3 \; m_2 \\ m_s & i_s \; m_s m_2 m_1 \, m_3 \\ m - s m_s & i_s \; m_3 m_2 \, m_1 \\ m_1 & m_2 m_3 \; i_r \; m_r \, m_r \\ m_3 & m_1 m_2 m_r \; i_r \; m_r \\ m_2 & m_3 m_1 m_r m_r \; i_r \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \\ i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} \tag{3.4}$$

Where,

i_s Stator current

i_r Rotor current

m_s Mutual inductance of stator

m_r Mutual inductance of rotor

m_{sr} Maximum mutual inductance between stator and rotor

$$m_1 = m_{sr} \cos(\theta) \tag{3.5}$$

$$m_2 = m_{sr} \cos\left(\theta - \frac{2\pi}{3}\right) \tag{3.6}$$

$$m_3 = m_{sr} \cos\left(\theta + \frac{2\pi}{3}\right) \tag{3.7}$$

Three phase abc system to stationary two phase alpha and beta transformation

The transformation from a three phase ABC system to a stationary two phase alpha-beta system is indeed used to control applications. This transformation allows for the decoupling of the motor torque and flux components enabling more effective control strategy of field orientated control. The a, b and c represents the number of phase quantities typically motor currents or voltages in the ABC reference frame alpha and beta are the two phase qualities in the alpha- beta reference frame (Sharma, 2020). Once the transformation is performed the resulting alpha and beta components can be used in control algorithm. In the FOC the alpha and beta components are used to decouple the control of torque and flux in the rotor.

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \xrightarrow{} C_{23} \quad \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} [X_{\alpha\beta}]^T \tag{3.8}$$

$$C_{23} \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} [x_{abc}]^T = C_{23} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \tag{3.9}$$

Two phase alpha beta system to three phase abc inverse transformation

Conversion process of the two phase alpha beta system back to a three phase ABC system and also the inverse transformation has been taken place that the alpha-beta. This conversion is useful in motor control applications where, control algorithms to be represented in the three phase domain for compatibility with standard three phase systems. ABC can be applied the transformation equations as follows:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} \overrightarrow{C_{32}} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \left[X_{\alpha\beta}\right]^T \tag{3.10}$$

$$C_{32}[X_{abc}] = C_{23} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \tag{3.11}$$

Park transformation and its inverse of matrix equations can be written as follows

$$p(\theta) = \mathrm{k} \begin{bmatrix} cos(\theta) & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ -sin(\theta) & -sin\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3.12}$$

$$p(\theta)^{-1} = p(\theta)^T = k \begin{bmatrix} cos(\theta) & -sin(\theta) & \frac{1}{\sqrt{2}} \\ cos\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ cos\left(\theta + \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix} \tag{3.13}$$

Model of an asynchronous motor based on the d-q reference frame

In motor control applications, it is common measure quantities of the currents, voltages and flux in the d and q reference frame. These quantities are essential for implementing control strategies FOC or vector control. The d and q reference frame is a rotating reference frame aligned with the rotor flux of the motor. The d-axis represents the direct axis which aligned with the rotor. On the other hand, d-axis represents the direct axis which is aligned with the rotor flux. The q axis represents the quadrature which is perpendicular to the rotor flux. By using the above equations such as 3.12 and 3.13 and also we can get the equations shown below:

$$v_{sd} \ = R_s i_{sd} + \frac{d\phi_{sd}}{dt} - \omega_s \varphi_{sq} \tag{3.14}$$

$$v_{sq} \ = R_s i_{sq} + \frac{d\phi_{sq}}{dt} - \omega_s \varphi_{sd} \tag{3.15}$$

$$v_{rd} = 0 = R_r i_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \varphi_{rd} \tag{3.16}$$

$$v_{rq} \ = 0 = R_r i_{rq} + \frac{d\phi_{rq}}{dt} - \omega_r \varphi_{rq} \tag{3.17}$$

$$\begin{bmatrix} \phi_{sdq} \\ \phi_{rdq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{sdq} \\ i_{rdq} \end{bmatrix} \tag{3.18}$$

The matrix system can be written as

$$\varphi_{sd} = L_s i_{sd} + L_m i_{rd} \tag{3.19}$$

$$\varphi_{sq} = L_s i_{sq} + L_m i_{rq} \tag{3.20}$$

$$\varphi_{rd} = L_m i_{sd} + L_r i_{rd} \tag{3.21}$$

$$\varphi_{rq} = L_m i_{sq} + L_r i_{rq} \tag{3.22}$$

The power supplied to stator and rotor windings of motor can be written as

$$p_e = \ [v_s]^T [I_s] + \ [v_r]^T . [I_r] \tag{3.23}$$

By applying the park transformation, the quantity d-q axis is expressed as follow

$$p_e = [v_{sd} v_{sq}] \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + [v_{rd} v_{rq}] \begin{bmatrix} i_{rd} \\ i_{rq} \end{bmatrix} = \frac{2}{3} \left[i_{sd} \frac{d\varphi_{sd}}{dt} + i_{sq} \frac{d\varphi_{sq}}{dt} + i_{rd} \frac{d\varphi_{rd}}{dt} + \ i_{rq} \frac{d\varphi_{rq}}{dt} \right] \tag{3.24}$$

$$+ \frac{2}{3} \left[\left(\varphi_{sd} i_{sq} \ - \varphi_{sq} i_{sd} \right) \omega_s \ + \left(\varphi_{rq} i_{rd} \ - \varphi_{rd} i_{sq} \right) \omega_r + \ \frac{2}{3} \mathrm{R_s} \left(\mathrm{i_{sd}^2} \ + \mathrm{i_{sq}^2} \right) + \mathrm{R_r} \left(\mathrm{i_{rd}^2} \ + \ \mathrm{i_{rq}^2} \right) \right]$$

By assuming the flux, we can find the equations as shown below

$$\Gamma_{em} = p \left(\varphi_{sd} \ i_{sq} - \varphi_{sq} \ i_{sd} \right) \tag{3.25}$$

$$\Gamma_{em} = p \left(\varphi_{rq} \ i_{rd} - \varphi_{rd} \ i_{rq} \right) \tag{3.26}$$

$$\Gamma_{em} = p L_m \left(\varphi_{sq} \ i_{rq} - \varphi_{sd} \ i_{rq} \right) \tag{3.27}$$

$$\Gamma_{em} = p\ \frac{L_m}{L_r}\left(\varphi_{rd}\ i_{sq} - \varphi_{rq}\ i_{sd}\right) \tag{3.28}$$

The reference coupled to the stator

The reference frame better to adapt with measured quantities it is characterized by

$\omega = \omega_r = 0$ and therefore, $\omega_r = -\omega_m$ where, ω is the arbitrary frame rate

$$v_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} \tag{3.29}$$

$$v_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} \tag{3.30}$$

$$v_{rd} = 0 = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rd} \tag{3.31}$$

$$v_{rd} = 0 = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} + \omega_r \varphi_{rq} \tag{3.32}$$

The reference coupled to the rotor

The d-q reference frame with the rotor $\omega = \omega_s = \omega_m = \omega_r = 0$ this reference frame is used simulation for dynamic state of machine where the speed is constant.

$$v_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} + \omega_s \varphi_{sd} \tag{3.33}$$

$$v_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sq} \tag{3.34}$$

$$v_{rd} = 0 = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} \tag{3.35}$$

$$v_{rq} = 0 = R_r i_{rq} + \frac{d\varphi_{rq}}{dt} \tag{3.36}$$

The reference coupled to the rotating magnetic field

Benefits of using a reference frame is constant quantities in the steady state it is control and regulate the motor drive $\omega = \omega_s$ the equations is written as follows

$$v_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sd} \tag{3.37}$$

$$v_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} - \omega_s \varphi_{sq} \tag{3.38}$$

$$v_{rd} = 0 = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rd} \quad (3.39)$$

$$v_{rq} = 0 = R_r i_{rq} + \frac{d\varphi_{rq}}{dt} - \omega_r \varphi_{rq} \quad (3.40)$$

Alpha beta reference frame modeling

Model equations are written as follows

$$v_{s\alpha} = R_s i_{s\alpha} + s\varphi_{s\alpha} \quad (3.41)$$

$$v_{s\beta} = R_s i_{s\beta} + s\varphi_{s\beta} \quad (3.42)$$

$$v_{r\alpha} = 0 = R_r i_{r\alpha} + s\varphi_{s\alpha} + \omega_{r\varphi r\beta} \quad (3.43)$$

$$v_{r\beta} = 0 = R_r i_{r\beta} + s\varphi_{r\beta} + \omega_{r\varphi r\alpha} \quad (3.44)$$

Stator and rotor flux equations

$$\varphi_{s\alpha} = L_s i_{s\alpha} + L_m i_{r\alpha} \quad (3.45)$$

$$\varphi_{s\beta} = L_s i_{s\beta} + L_m i_{r\beta} \quad (3.46)$$

$$\varphi_{r\alpha} = L_r i_{s\alpha} + L_m i_{s\alpha} \quad (3.47)$$

$$\varphi_{r\beta} = L_r i_{r\beta} + L_m i_{s\beta} \quad (3.48)$$

In this equation

$$\Gamma_{em} = \Gamma_r = f\Omega_m + \mathrm{J} \quad (3.49)$$

$$\Gamma_{em} = \frac{3}{2} p\left(\varphi_{s\alpha} i_{s\beta} - \varphi_{s\beta} i_{s\alpha}\right) \quad (3.50)$$

$$\frac{di_{s\alpha}}{dt} = \frac{1}{\sigma L_s}\left(R_s + \frac{1}{T_r}\frac{L_m^2}{L_r} \right) i_{s\alpha} + \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\frac{1}{T_r}\right)\varphi_{r\alpha} + \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\right)\omega_r \varphi_{r\beta} \quad (3.51)$$

$$\frac{di_{s\beta}}{dt} = \frac{1}{\sigma L_s}\left(R_s + \frac{1}{T_r}\frac{L_m^2}{L_r}\right) i_{s\beta} + \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\right)\omega_r \varphi_{r\alpha} + \frac{1}{\sigma L_s}\left(\frac{L_m}{L_r}\frac{1}{T_r}\right)\varphi_{r\beta} \quad (3.52)$$

$$\frac{d\varphi_{r\alpha}}{dt} = \frac{L_m}{T_r} i_{s\alpha} - \frac{1}{T_r}\varphi_{r\alpha} - \omega_r \varphi_{r\beta} \quad (3.53)$$

$$\frac{d\varphi_{r\beta}}{dt} = \frac{L_m}{T_r} i_{s\alpha} + \omega_r \varphi_{r\alpha} - \frac{1}{T_r}\varphi_{r\beta} \quad (3.54)$$

$\omega_m = p\Omega_m$; ω_r=[$\omega_s - \omega_m$]; $\alpha = 1 - \frac{L_m^2}{L_s L_r}$; $T_r = \frac{L_r}{R_r}$; $T_e = \frac{L_s}{R_s}$

State space representation of an asynchronous motor drive

An asynchronous motor state representation according to the chosen frame and identification of the model variables and determine the alpha and beta equations shown below:

$$x = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \varphi_{r\alpha} & \varphi_{r\beta} \end{bmatrix}^T \tag{3.55}$$

$$\dot{x}(t) = A(t)x(t) + \mathrm{B}(t)\,u(t) \tag{3.56}$$

$$\mathrm{A(t)} = \begin{bmatrix} -\frac{1}{\alpha L_s}\left(R_s + \frac{1}{T_r}\frac{L_m^2}{T_r}\right) & 0 & -\frac{1}{\alpha L_s}\left(\frac{L_m}{L_r}\frac{1}{T_r}\right) & \frac{1}{\alpha L_s}\left(\frac{L_m}{L_r}\right)\omega_r \\ 0 & -\frac{1}{\alpha L_s}\left(R_s + \frac{1}{T_r}\frac{L_m^2}{L_r}\right) & -\frac{1}{\alpha L_s}\left(\frac{L_m}{L_r}\right)\omega_r & \frac{1}{\alpha L_s}\left(\frac{L_m}{L_r}\frac{1}{T_r}\right) \\ \frac{L_m}{T_r} & 0 & \frac{-1}{T_r} & -\omega_r \\ 0 & \frac{L_m}{T_r} & \omega_r & \frac{-1}{T_r} \end{bmatrix} \tag{3.57}$$

$$B(t) = \begin{bmatrix} \frac{1}{L_{s\alpha}} & 0 \\ 0 & \frac{1}{L_{s\alpha}} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{3.58}$$

$$u(t) = \begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \end{bmatrix} \tag{3.59}$$

3.2.4 Methods of vector control

Motor control methods are the advanced control techniques that allow for precise torque and speed control. These methods manipulated the voltage and current commonly used vector control methods for induction motors.

3.2.4.1 Direct field oriented control (DFOC)

Direct Field Oriented Control is operates by decoupling the control of torque and flux components in the motor. It aims to achieve independent control of these two quantities similar to a separately excited DC motor (M. M. Hasan, 2019). By controlling the motor in a rotating reference frame aligned with the rotor flux, it provides efficient and accurate control. Here are the key principles and steps involved in implementing Direct Field Oriented Control for an induction motor:

- ✓ **Coordinate Transformation:** The stator current and voltage are transformed from the stationary reference frame (ABC three-phase system) to a rotating reference frame (d-q axis system) aligned with the rotor flux.
- ✓ **Flux Control:** The flux component of the motor is regulated by controlling the q-axis current. This control ensures that the motor operates at the desired flux level, providing efficient operation.
- ✓ **Torque Control:** The torque component of the motor is controlled by adjusting the d-axis current. The control system manipulates the d-axis current to achieve the desired torque output from the motor.
- ✓ **Flux and Torque Calculations:** Based on the desired torque and flux references, the control algorithm calculates the required voltage vectors that need to be applied to the motor. These voltage vectors are synthesized by the inverter.
- ✓ **Voltage Vector Selection:** The control algorithm selects the appropriate voltage vector from the inverter to achieve the desired torque and flux control. The chosen voltage vector is applied to the motor through pulse-width modulation (PWM) techniques.
- ✓ **Hysteresis Control:** DFOC is compare the actual and desired flux and torque values. The control system adjusts the voltage vectors to keep the motor's flux and torque within the desired limits.

The advantages of DFOC, which is mainly includes high dynamic performance, excellent torque and speed control accuracy, and robustness against parameter variations and load disturbances. It is widely used in high-performance applications area that require precise control electric vehicles, and industrial automation. DFOC is a complex control strategy that requires sophisticated algorithms and real-time computation capabilities (al, 2020). Finally, the equations of control are referenced to the phase motor drive currents to control the inverter operating conditions. The mathematical equations written as follows:

$$i_{qs}^{s} = \frac{2}{3} i_{as} - \frac{1}{3} i_{bs} - \frac{1}{3} i_{cs} \text{ A} \tag{3.60}$$

$$i_{ds}^{s} = \frac{1}{\sqrt{3}} (i_{cs} - i_{bs}) \, A \tag{3.61}$$

Because $\lambda^{s}_{mq}= \quad L_m\left(i^{s}_{qs} + i'^{s}_{qr}\right)$, components of flux linkages are λ'^{s}_{qr} and λ'^{s}_{dr}

$$\lambda'^{s}_{qr} = \frac{L'_r}{L_m}\lambda^{s}_{mq} \text{ -} L'_{lr}\, i^{s}{}_{qs} \tag{3.62}$$

$$\lambda'^{s}_{dr} = \frac{L'_r}{L_m}\lambda^{s}_{md} \text{ -} L'_{lr}\, i^{s}{}_{ds} \tag{3.63}$$

The calculated values of λ'^{s}_{qr} and λ'^{s}_{dr}

$$sin\left(\frac{\pi}{2} - \rho\right) = \cos\rho = \frac{\lambda'^{s}_{dr}}{\lambda'^{s}_{r}} \tag{3.64}$$

$$cos\left(\frac{\pi}{2} - \rho\right) = \sin\rho = \frac{\lambda'^{s}_{qr}}{\lambda'^{s}_{r}} \tag{3.65}$$

$$\lambda^{s*}_{qs} = i^{e*}{}_{qs}\cos\rho + i^{e}{}_{qs}\sin\rho \quad \text{A} \tag{3.66}$$

$$\lambda^{s*}_{ds} = i^{e*}{}_{qs}\sin\rho + i^{e}{}_{ds}\cos\rho \quad \text{A} \tag{3.67}$$

Hence, the Staionary reference frame has transformed to the three phase to control inverter operating conditions shown the equations below:

$$i^{*}_{as}= i^{*}_{qs} \text{ A} \tag{3.68}$$

$$i^{*}_{bs} = -\frac{1}{2}i^{*}_{qs}\text{-}\frac{\sqrt{3}}{2}i^{*}_{ds}\text{A} \tag{3.69}$$

$$i^{*}_{cs} = -\frac{1}{2}i^{*}_{qs}+ \text{ -}\frac{\sqrt{3}}{2}i^{*}_{ds}\text{A} \tag{3.70}$$

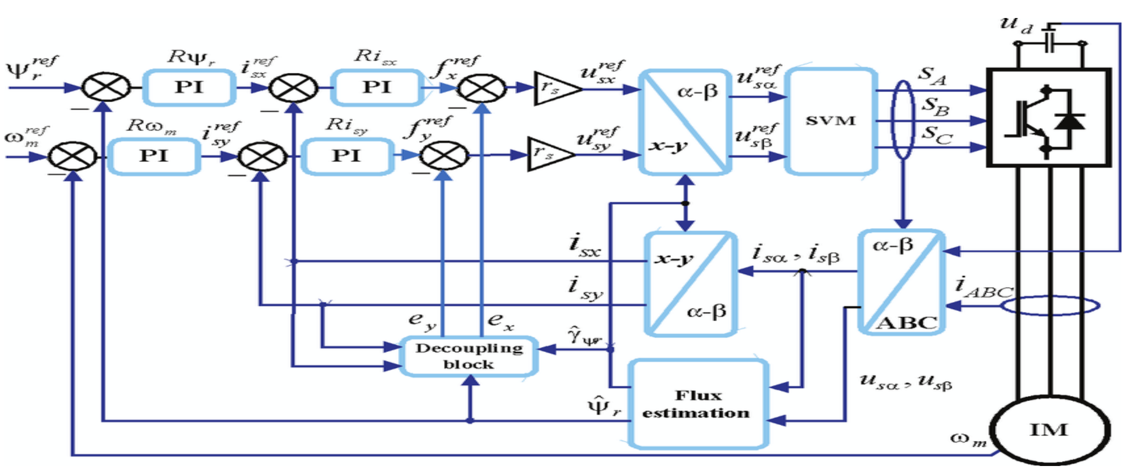

Figure 3.4 Direct field orientated control (DFOC) method (Wolkiewicz, 2015)

3.2.4.2 Indirect field orientated control

Indirect field orientated control (IFCO) also known as sensorless field orientated control (SFOC) is a technique used to control induction motors without using direct measurement of the rotor flux position or speed. It is an alternative to the traditional field orientated control (FOC) method which relies on accurate rotor position and speed information from sensors (B. Asad, 2018). Proper design and tuning of the flux estimation algorithm is crucial for the effective implementing of IFOC. Here are the key steps involved for implementing of indirect filed orientated control.

- **Stator Current and Voltage Measurements** the stator currents and voltages are measured using current and voltage sensors connected to the motor windings. These measurements provide information about the motor's operating conditions.
- **Current Control** a current control loop is implemented to regulate the stator currents ensuring they follow the desired reference values. The current control loop typically employs proportional-integral (PI) controllers to maintain accurate control of the current components.
- **Flux Orientation** the rotor flux position and speed are estimated or inferred indirectly from the stator current and voltage measurements. Various methods can be used for flux estimation such as model based observers adaptive algorithms or sliding-mode observers.
- **Current Transformation** the stator currents are transformed from the stationary reference frame (typically the ABC three-phase system) to a rotating reference frame (d-q axis system) aligned with the estimated or inferred rotor flux position. This transformation enables decoupled control of torque and flux components.
- **Torque and Flux Control** the torque and flux components in the rotating reference frame are controlled independently. The torque component is controlled by adjusting the d-axis current, while the flux component is controlled by adjusting the q-axis current. The control algorithm manipulates the current references to achieve the desired torque and flux control.
- **Voltage Synthesis** based on the desired torque and flux references and the estimated or inferred rotor flux position, the control algorithm calculates the required voltage vectors that need to be applied to the motor. These voltage vectors are synthesized by the inverter using techniques such as pulse-width modulation (PWM).

$$T^{*}{}_{em}= \frac{3}{2}\frac{\rho}{2}\frac{L_m}{L'_r}\lambda'^{e*}{}_{dr}i'^{e*}{}_{qs} \quad (3.71)$$

$$\omega_2^* = (\, \omega_e\text{-}\omega_r) = \frac{r'_r i'^{e*}{}_{qr}}{L_m i^{e*}{}_{ds}} \quad (3.72)$$

$$cos\rho = cos(\, \theta_r + \theta_2\,) = cos\theta_r\, cos\theta_2\text{-}sin\theta_r sin\theta_2 \quad (3.73)$$

$$sin\rho = sin(\theta_r + \theta_2) = sin\theta_r\, cos\theta_2\ \text{-}cos\theta_r\, sin\theta_2 \quad (3.74)$$

Where; ρ Angle of orientation; θ_r Rotor angle and θ_2 Slip speed angle

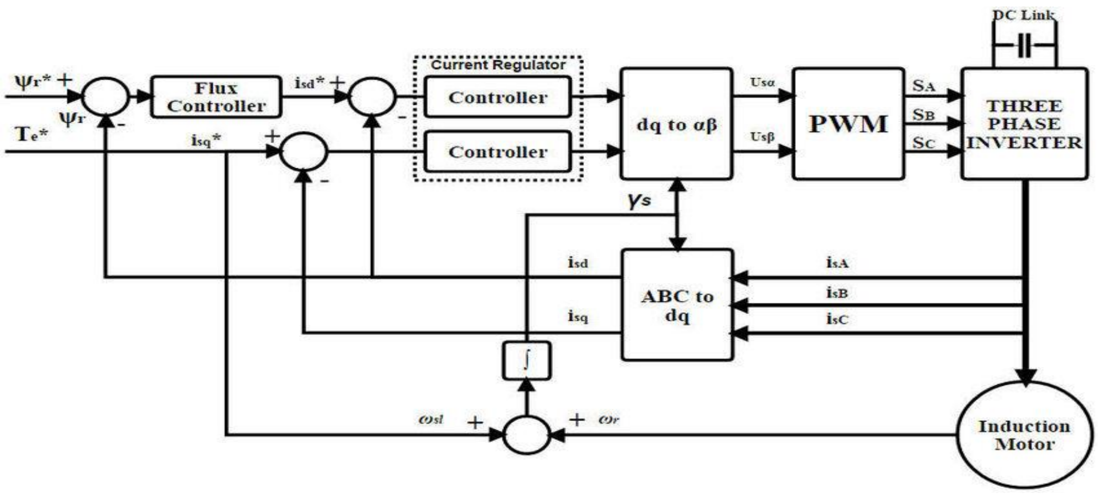

Figure 3.5 Indirect field orientated control scheme (2018, Angga)

3.2.5 Controller design

The controller design is focused to design the control techniques such as model reference control is used to measure stator currents and voltages and estimate the speed. In this approaches the MRAC is used to the outer control loop through a reference adaptive control strategy. The MRAC is compared the measured values with a reference model that represent the desired motor drive control (Z. Zhang et al, 2020). The difference between the measured values and reference model output is generated the error signal. This error signal is used to the control motor. The MRAC is working on continually adapting the control parameters based on the error signal (J, 2015). The ANN controller is used to control the inner speed control loop of the motor drive system. The ANN controller takes the speed error and its rate of change as inputs based on these input, generate the control signals to control and regulate the inner speed control loop. The ANN controller can handle the complex relationship between the speed and the required control signals. This allows the ANN controller accuracy track the desired motor speed. A hybrid proposed technique is the combination of MRAC-ANN controller the MRAC is utilizes to outer control loop based on the stator currents and voltages measurements and the ANN the inner speed control loop using the speed error signal and its rate of change input (G. Agrawal, 2022). This combined approach is used to accurately control of the sensorless speed and torque estimation for motor drive system.

3.2.5.1 MRAC controller design

The controller design has been done for MRAC based on speed and torque control of an asynchronous motor drive system; firstly the mathematical model has been formulated that accurately represents the motor drive system dynamics behavior. By considering the stator currents and voltages, the reference model is selected to represent the designed system. Based on the MRAC controller the error signal is defined by comparing the output the reference with the stator currents and voltages. Then the control law is designed to adjust the control parameters the MRAC system based on the error signal.

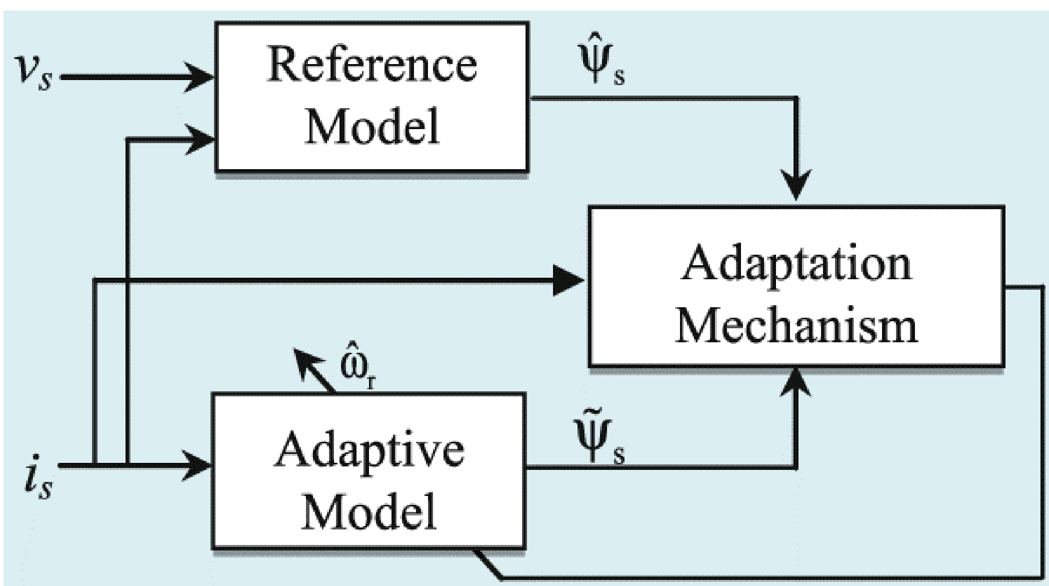

Figure 3.6 Model reference adaptive system based on stator parameters (Ouanjli, 2023)

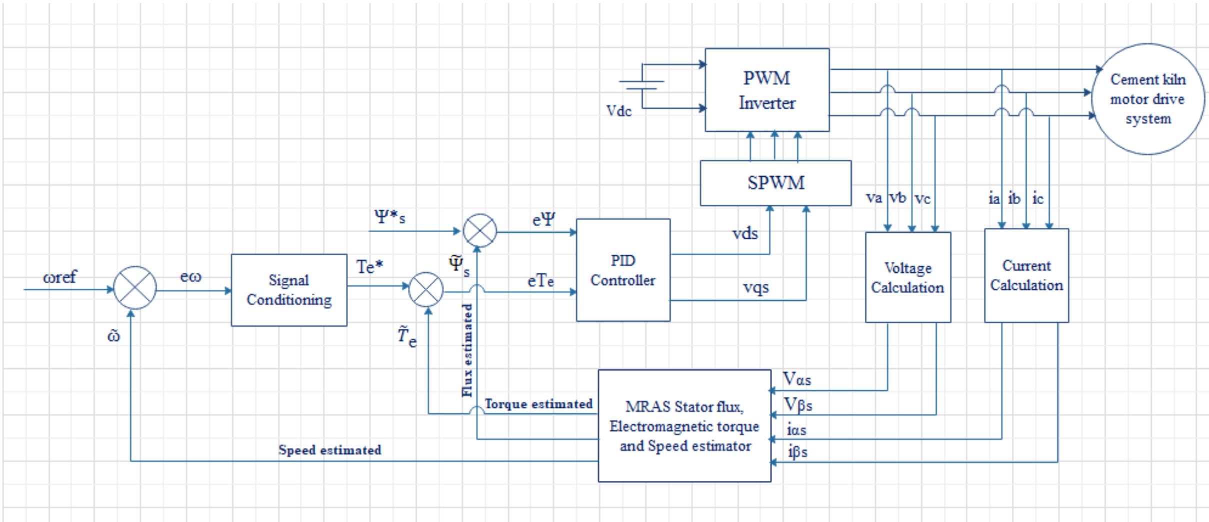

Figure 3.7 Block diagram of MRAS controlled for kiln motor drive system

The step by step explanation of the above block diagram of MRAS controlled for kiln motor drive system

- ✓ **DC Voltage Supply** the DC voltage supplied as an input to a PWM (Pulse Width Modulation) inverter.
- ✓ **PWM Inverter** the PWM inverter converts the DC voltage into a variable voltage and frequency AC output. The output of the PWM inverter is then fed into the kiln motor drive system. The output of the PWM inverter generates three-phase voltages, namely va, vb, and vc. These voltages used as input to the voltage calculation block.
- ✓ **Voltage Calculation Block** the voltage calculation block processes the three-phase voltages and generates two components, vαs and vβs. These components represent the stator voltage in the α-β reference frame and are passed as inputs to the MRAS controller.
- ✓ **Current Calculation Block** simultaneously, the PWM output or motor inputs, namely ia, ib, and ic, are fed into the current calculation block. This block computes two components, iαs, and iβs, which represent the stator current in the α-β reference frame. These components are also input to the MRAS controller.
- ✓ **MRAS Controller** the MRAS controller utilizes the estimated stator voltage (vαs and vβs) and the estimated stator current (iαs and iβs) to estimate the speed, stator flux, and electromagnetic torque of the motor.

- ✓ **Error Detector** the reference speed and the estimated speed obtained from the MRAS output are compared in the error detector block. The output of the error detector is the speed error (error speed), which is then passed to the signal conditioning block.
- ✓ **Signal Conditioning Block** the signal conditioning block takes the speed error as input and performs any necessary conditioning and generate ref torque on the signal. This block replaced the previous PID controller.
- ✓ **Error Detector** the reference torque from output of the signal conditioning block and the estimated torque (obtained from the MRAS output) are compared in the error detector block, resulting in the torque error (error torque) and on the other hand, ref stator flux and the estimated stator flux (obtained from the MRAS output) are compared in the error detector block, resulting in the flux error.
- ✓ **PID Controller** the torque error and flux error are fed directly to PID controller. This PID controller computes the control signal required to adjust and optimize the system. The PID controller uses these inputs to generate the control signals vds and vqs
- ✓ **SPWM Block** from the PID control signals output vds and vqs are passed to the Space Vector Pulse Width Modulation (SPWM) block. The SPWM block generates the appropriate switching signals that control the PWM inverter.
- ✓ **PWM Inverter** (Again): The switching signals (va, vb, vc) obtained from the SPWM block are fed back to the PWM inverter, completing the control loop.

Therefore, the modified block diagram replaces the original PID controller with a signal conditioning block to preprocess the speed error signal. Additionally, the ANN controller is replaced with a PID controller to compute the control signal for torque and flux adjustment. The modified configuration still incorporates the MRAS control technique for estimating motor parameters and utilizes the PWM inverter to control the motor based on the generated switching signals

Estimated rotor speed of an asynchronous motor

$$\dot{\psi}_{dr} = \frac{L_r}{L_m}\left[V_{ds} - R_s i_{ds} - \sigma L_s \frac{d}{dt} i_{ds}\right] \tag{3.75}$$

$$\dot{\psi}_{qr} = \frac{L_r}{L_m}\left[V_{qs} - R_s i_{qs} - \sigma L_s \frac{d}{dt} i_{qs}\right] \tag{3.76}$$

$$i_{ds} = \frac{1}{L_m}\left\lfloor \psi_{dr} + \omega_r T_r \psi_{qr} + T_r \dot{\psi}_{dr} \right\rfloor \tag{3.77}$$

$$i_{qs} = \frac{1}{L_m}\left\lfloor \psi_{qr} + \omega_r T_r \psi_{dr} + T_r \dot{\psi}_{qr} \right\rfloor \tag{3.78}$$

$$i_{ds}\text{-}\hat{\imath}_{ds} = \frac{T_r}{L_m}\psi_{qr}(\omega_r - \widehat{\omega}_r) \tag{3.79}$$

$$i_{qs}\text{-}\hat{\imath}_{qs} = \frac{T_r}{L_m}\psi_{dr}(\omega_r - \widehat{\omega}_r) \tag{3.80}$$

$$(i_{ds} - \hat{\imath}_{ds})\psi_{qr} \text{ -}\left(i_{qs} - i_{ds}\right)\psi_{dr} = \frac{T_r}{L_m}(\omega_r - \widehat{\omega}_r)\left(\omega_{qr}^2 + \omega_{qr}^2\right) \tag{3.81}$$

From the equation (3.55) the rotor speed error is obtained as follow

$$e_{\omega r} = \omega_r - \widehat{\omega}_r = \mathrm{c}\left\lfloor(i_{ds} - \hat{\imath}_{ds})\psi_{qr} \ - \left(i_{qs} - i_{ds}\right)\psi_{dr}\right\rfloor \tag{3.82}$$

The model reference control method

The motor dynamic model and the reference model are described as below, respectively

$$\dot{x}(t) = A_p x(t) + B_p u(t) + D_p w(t) \tag{3.83}$$

$$\dot{x}(t) = A_m \hat{x}(t) + B_m r(t) \tag{3.84}$$

$$\left\|A_p - A_m\right\| \leq \eta \tag{3.85}$$

Control law design

Based on the equitation (3.85) and (3.86) the dynamic error between the motor drive system and the reference model has been proposed in this thesis.

$$\dot{e}_t \ = \ \dot{x} \ - \dot{\hat{x}} \tag{3.86}$$

$$= A_{m\, e(t)} + \left(A_p - A_m\right)\mathrm{x}(t) + A_p u(t) + D_p w(t) - B_m r(t) \tag{3.87}$$

$$S_t = C_e(t) \text{ -}\int_0^1 \left(CA_m - CB_p G\right)\mathrm{e}(\tau)d\tau \tag{3.88}$$

$$\left(A_m + B_p \ \ G\right)\zeta + \zeta\left(A_m + B_p G\right)^T + D_p w D_p^T = 0 \tag{3.89}$$

$$G = \frac{-1}{2B_p^{-1}}(A_m\zeta + \zeta A_m^T +) + D_p w {D_p^T}^{-1} + \left(B_p^{-1} H B_p\right)\zeta^{-1} + \left(1 - B_p^{-1}\right)\mathrm{Z} \tag{3.90}$$

$$u(t) = G_e(t) - (CB_p)[k\|C\| . \|x(t)\| + \|C\|. \|B_m\|. \|r(t)\| + \alpha]\mathrm{sgn}(S(t)) \quad (3.91)$$

$$J\ddot{\theta} + B\dot{\theta} = K_T i + T_L \quad (3.91)$$

$$\ddot{x} = \begin{bmatrix} 0 & 1 \\ 1 & \frac{-B}{J} \end{bmatrix} x + \begin{bmatrix} 0.5 \\ \frac{K_T}{J} \end{bmatrix} u_t + \begin{bmatrix} 0 \\ \frac{-1}{J} \end{bmatrix} \omega \quad (3.92)$$

$$y = |1 \quad 0| x$$

The related to equation (3.89) state coefficient matrix A_p , B_p, D_p are obtained as follow

$$A_p = \begin{bmatrix} 0 & 1 \\ 1 & \frac{-B}{J} \end{bmatrix} B_p = \begin{bmatrix} 0.5 \\ \frac{K_T}{J} \end{bmatrix} D_p = \begin{bmatrix} 0 \\ \frac{-1}{J} \end{bmatrix} \quad (3.93)$$

Coefficient matrix the A_m and the B_m on the reference model are set as, respectively

$$A_m = \begin{bmatrix} 0 & 1 \\ 2\delta & \delta \end{bmatrix} B_m = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (3.94)$$

Where, δ is simulation coefficient to set into equation (3.94) it can establish in actual control ANN adaptive algorithm is used to calculate A_P, B_P.

Matrix C =[2 0] $CD_p = 0$

Hence, $y = |1 \quad 0|x$ is obtained lastly.

3.2.5.2 ANN controller design

In this section a mathematical model artificial neural network speed estimator method of an asynchronous motor in the stationery reference frame under mmf has sinusoidal wave distribution is expressed as

$$\begin{bmatrix} v_{sd} \\ v_{sq} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pl_s & 0 & pm & 0 \\ 0 & r_s + pl_s & 0 & pm \\ pm & \omega m & r_r + pl_r & \omega l_r \\ -\omega m & pm & -\omega l_r & r_r + pl_r \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (3.95)$$

Where, i_{rd}, i_{rq} d and q axis rotor current elements, ω is the speed M, L_s and L_r are the stator and rotor mutual inductance and p is differential operator $\frac{d}{dt}$ drive the estimated stator current consistent with DFOC technique in which the stator flux is controlled variable, the stator flux equations that depend on stator and rotor currents are

$$\psi_{sd} = L_s i_{sd} + M i_{rd} \tag{3.96}$$

$$\psi_{sq} = L_s i_{sq} + M i_{rq} \tag{3.97}$$

We can substitute equations (3.96) and (3.97) into equation (3.95) the mathematically determine the estimated stator current which is stated as

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \frac{R_s^*}{\sigma L_s} & -\omega \frac{R_r}{\sigma L_s L_r} & \frac{\omega}{\sigma L_s} \\ \omega & \frac{R_s^*}{\sigma L_s} - \frac{\omega}{\sigma L_s} & \frac{R_r}{\sigma L_s L_r} \end{bmatrix} \begin{bmatrix} \hat{i}_{sd} \\ \hat{i}_{sq} \\ \hat{\psi}_{sd} \\ \hat{\psi}_{sq} \end{bmatrix} + \frac{1}{\sigma L_s} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} \tag{3.98}$$

Where, $R_s^* = R_s + L_s R_r / L_r \sigma = 1 - M^2 / L_s L_r$

$$\begin{bmatrix} \hat{\imath}_{sd}(k) \\ \hat{\imath}_{sq}(k) \end{bmatrix} = \frac{(1 - TR_s^*)}{\sigma L_s} \begin{bmatrix} \hat{\imath}_{sd}(k-1) \\ \hat{\imath}_{sq}(k-1) \end{bmatrix} + \frac{T\omega}{\sigma L_s L_r} \mathrm{J} \begin{bmatrix} \hat{x}_{sd}(k-1) \\ \hat{x}_{sq}(k-1) \end{bmatrix} \tag{3.99}$$

$$+ \frac{TR_r}{\sigma L_s L_r} \begin{bmatrix} \hat{\psi}_{sd}(k-1) \\ \hat{\psi}_{sq}(k-1) \end{bmatrix} + \frac{T}{\sigma L_s} \begin{bmatrix} v_{sd}(k-1) \\ v_{sq}(k-1) \end{bmatrix}$$

Estimated stator current can be written based on equation (3.99) as follow

$$\vec{i}_s(k) = w1\, x1 + w2 x2 + w3 x3 + x4 w4$$

Where, $w1 = 1 - \frac{(1 - TR_s^*)}{\sigma L_s}$, $w2 = \frac{T\omega}{\sigma L_s}$, $w3 = \frac{T_{Rr}}{\sigma L_s Lr}$, $w4 = \frac{T}{\sigma L_s}$

$$x1 = \begin{bmatrix} \hat{\imath}_{sd}(k-1) \\ i_{sq}(k-1) \end{bmatrix}, x2 = j \begin{bmatrix} \hat{x}_{sd}(k-1) \\ \hat{x}_{sq}(k-1) \end{bmatrix}, x3 = \begin{bmatrix} \hat{v}_{sd}(k-1) \\ \hat{v}_{sq}(k-1) \end{bmatrix} \tag{3.100}$$

$$x4 = \begin{bmatrix} \hat{\psi}_{sd}(k-1) \\ \hat{\psi}_{sq}(k-1) \end{bmatrix} \mathrm{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \vec{i}_s(k) = \begin{bmatrix} \hat{\imath}_{sd}(k) \\ i_{sq}(k) \end{bmatrix}$$

$$\hat{x}_{sd} = \sigma L_s \hat{\imath}_{sd}(k) - \hat{\psi}_{sd}(k), \quad \hat{x}_{sd}(k) = \sigma L_s \hat{\imath}_{sq}(k) - \hat{\psi}_{sq}$$

The learning rule is more selective and appropriate than other learning methods because, it is very simple and accurate. Therefore, a weight, W2 speed will be tuned online as well as updated by learning rule to minimize the sum of squared errors between the measured and estimated stator current. The sum of squared errors at sampling K is defined as

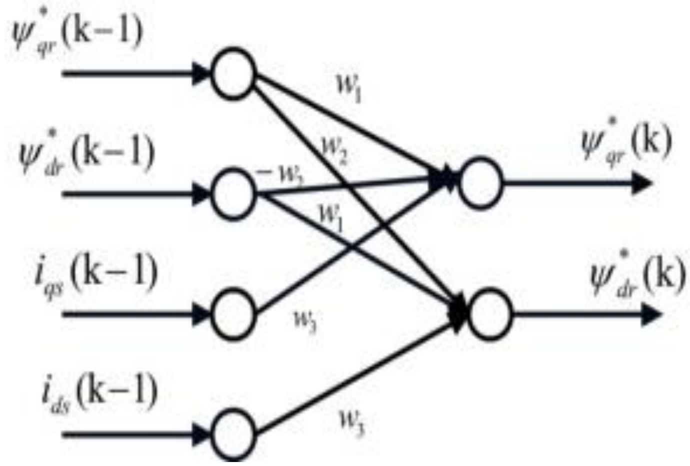

Figure 3.8 Neural network structure with weight estimation

$$E = \frac{1}{2} \vec{e}^{\,T}(k)\, \vec{e}(k) \tag{3.101}$$

To reduce the sum of squared error of the learning rule is used to set w2 as follows

$$\Delta W2 = -\mu \frac{\partial E}{\partial W2} = -\mu \left(\frac{\partial E}{\partial \vec{i}_s(k)} \frac{\partial \vec{i}_s(k)}{\partial W2} \right) \tag{3.102}$$

The updated weight can be written as

$$W2(k) = W2(k-1) + \Delta W2 \tag{3.103}$$

Using equation (3.102) and w2 into equation (3.103) and rearranging it. Estimated rotor speed can be written as where μ positive value of learning rate $\mu = \mu\sigma L_s$/T As shown on figure 3.8 the w2 parameter can be adjusted online and the estimated speed which is strongly dependent on the stator current. ANN controller the learning rate is slow rate and the large learning rate value brings good stability. Hence, the learning rate should be properly selected.

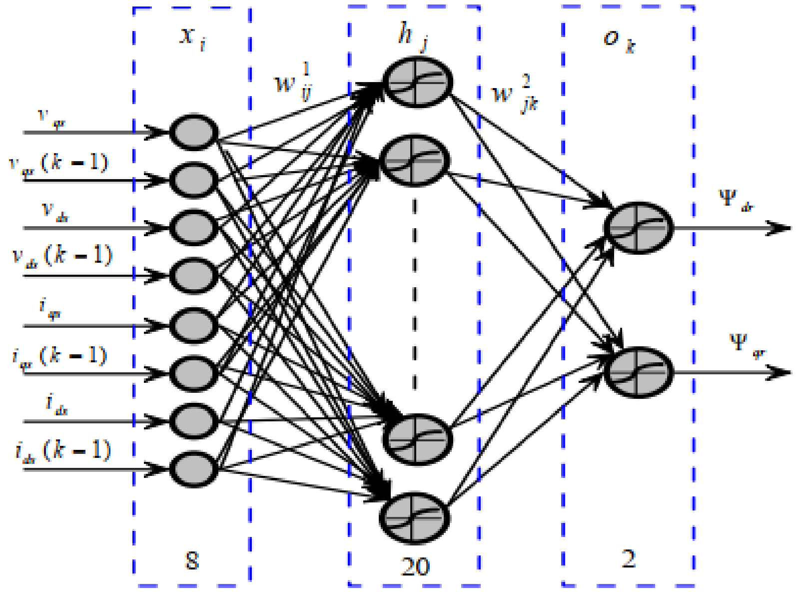

Figure: 3.9 Structure of multilayer ANN

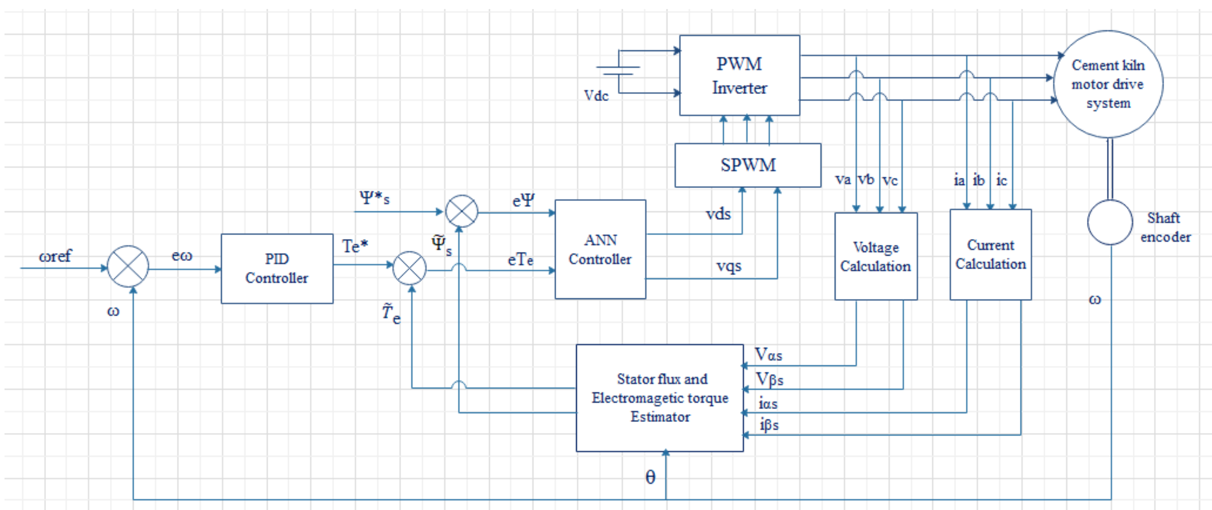

Figure 3.10 Block diagram of ANN controlled for kiln motor drive system

As observed on the above block diagram, step by step explanation elements of the block of ANN (Artificial Neural Network) control technique for the kiln motor drive system:

- ✓ **DC Voltage Supply** the system is powered by a DC voltage supply.
- ✓ **PWM Inverter** the DC voltage is fed into a PWM inverter, which converts it into a variable voltage and frequency AC output.

- ✓ **Kiln Motor Drive System** the output of the PWM inverter is connected to the kiln motor drive system, which drives the kiln motor.
- ✓ **Voltage Calculation Block** the three-phase voltages (va, vb, and vc) from the PWM inverter are processed in the voltage calculation block to generate two components, vαs and vβs. These components represent the stator voltage in the α-β reference frame.
- ✓ **Current Calculation Block** the motor currents (ia, ib, and ic) are processed in the current calculation block to compute two components, iαs and iβs, representing the stator current in the α-β reference frame.
- ✓ **Estimator** the estimator utilizes the estimated stator voltage (vαs and vβs) and the estimated stator current (iαs and iβs) to estimate the stator flux and electromagnetic torque of the motor.
- ✓ **Error Detector** the reference speed and the measured speed from the motor speed sensor are compared in the error detector block to obtain the speed error (error speed).
- ✓ **PID Controller** the speed error is input to the PID controller, which generates a reference torque (ref torque) based on the control strategy. The reference torque and the estimated torque from the estimator are compared in the error detector block, resulting in the torque error (error torque).
- ✓ **Error Flux Calculation** the reference stator flux and the estimated stator flux from the estimator are compared, resulting in the flux error (error flux).
- ✓ **ANN Controller** the error torque and error flux are inputs to the ANN controller. The ANN controller uses these inputs to generate the control signals vds and vqs.
- ✓ **SPWM Block** the control signals vds and vqs are passed to the Space Vector Pulse Width Modulation (SPWM) block, which generates appropriate switching signals (va, vb, and vc) to control the PWM inverter.
- ✓ **PWM Inverter** the switching signals (va, vb, and vc) obtained from the SPWM block are fed back to the PWM inverter, completing the control loop.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Simulink Model of an Asynchronous Motor Drive System for Cement Kiln

In this chapter, the MATLAB simulation results have been carefully analyzed and studied by applying and computing the proposed system such as MRAC, ANN and Hybrid MRAC-ANN their controller performance have been evaluated individually and combined form. The simulation has been carried out using MATLAB/Simulink software. As mentioned above, the kiln has been using a high performance an asynchronous motor in this thesis a case study has been taken from Mugher cement factory, all the required simulation work have been completed successfully. The Evaluation of the finding results of control performance and as well as the proposed system controller evaluated under various speed and torque operating conditions. Finally, it has been analyzed and compared the simulation results in terms of speed tracking accuracy, error tracking capability after the load torque is applied, speed regulation, stability, disturbance rejection and handling capability system responsiveness and adaptability. As shown below in figure 4.11 the proposed system block diagram for MRAC and ANN controller of kiln motor drive system. As shown from figure 4.1 General structural block diagram MRAC-ANN based controlled of an asynchronous motor for cement rotary kiln. It has been used to model of motor drive and mathematical model motor drive system has clearly formulated. Simulink model has been consists the following main components such as motor drive system model, voltage source inverter model, current controller, transformation model, controller model, voltage model, and current model.

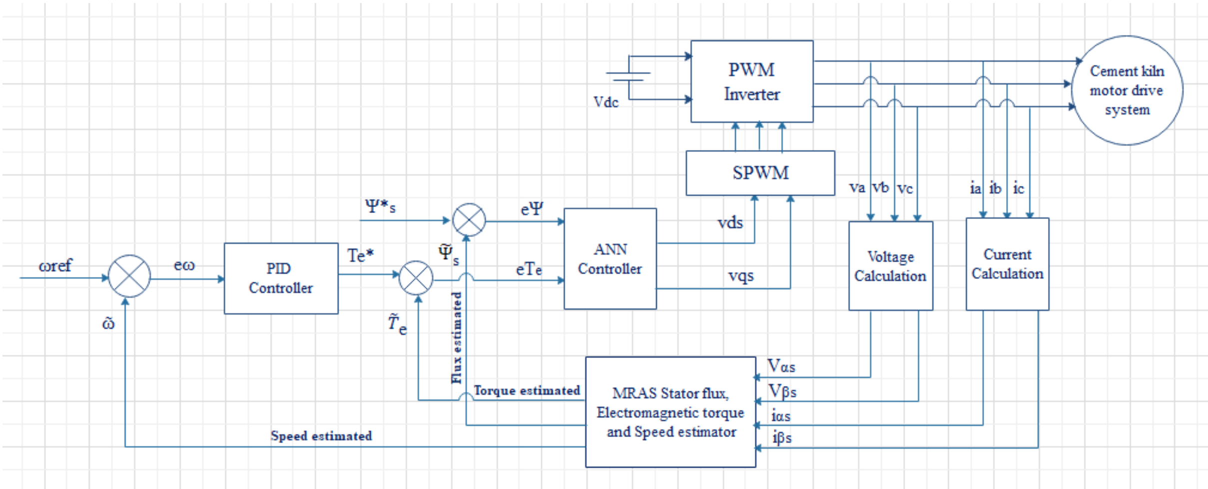

Figure 4.11 General structure of MRAS-ANN controlled kiln motor dive system

As observed on the above the block diagram the hybrid controllers consisting of ANN (Artificial Neural Network) and MRAS (Model Reference Adaptive System) are utilized to enhance the performance and control capabilities of the Kiln motor drive system. A hybrid control technique can be explained as follows:

- ✓ **DC Voltage Supply** the input to the system is a DC voltage, which is supplied to a PWM (Pulse Width Modulation) inverter.
- ✓ **PWM Inverter** the PWM inverter converts the DC voltage into a variable voltage and frequency AC output. The output of the PWM inverter is fed to the kiln motor drive system. The output of the PWM inverter produces three-phase voltages, namely va, vb, and vc. These voltages are considered as inputs to the voltage calculation block.
- ✓ **Voltage Calculation Block** the voltage calculation block processes the three-phase voltages and generates two components, vαs and vβs. These components represent the stator voltage in the α-β reference frame and serve as inputs to the MRAS controller.
- ✓ **Current Calculation Block** simultaneously, the output PWM or motor inputs, namely ia, ib, and ic, are passed through the current calculation block. This block computes two components, iαs, and iβs, which represent the stator current in the α-β reference frame. These components are also input to the MRAS controller.
- ✓ **MRAS Controller** the MRAS controller utilizes the estimated stator voltage (vαs and vβs) and the estimated stator current (iαs and iβs) to estimate the speed, stator flux, and electromagnetic torque of the motor.

- ✓ **Error Detector** the reference speed and the estimated speed obtained from the MRAS output are compared in the error detector block. The output of the error detector is the speed error (error speed), which is then passed to the PID (Proportional-Integral-Derivative) controller.
- ✓ **PID Controller** the PID controller takes the speed error as input and generates a reference torque (ref torque) based on the control strategy. The reference torque and the estimated torque (obtained from the MRAS output) are compared in the error detector block, resulting in the torque error (error torque) on the other hand, the reference flux is compared to the estimated flux (obtained from the MRAS output). The resulting is error flux represented.
- ✓ **ANN Controller** the error torque and the error flux (obtained by comparing the reference stator flux and the estimated stator flux from the MRAS output) are fed as inputs to the ANN controller. The ANN controller uses these inputs to generate the control signals vds and vqs.
- ✓ **SPWM Block** the control signals vds and vqs are passed to the Space Vector Pulse Width Modulation (SPWM) block. The SPWM block generates the appropriate switching signals that control the PWM inverter.
- ✓ **PWM Inverter** the switching signals (va, vb, vc) obtained from the SPWM block are fed back to the PWM inverter, completing the control loop.
- ✓ Therefore, the hybrid controller combines the MRAS technique, which estimates motor parameters, with the ANN technique, which generates control signals based on the error values. This combination enables adaptive control and enhances the overall performance of the kiln motor drive system.

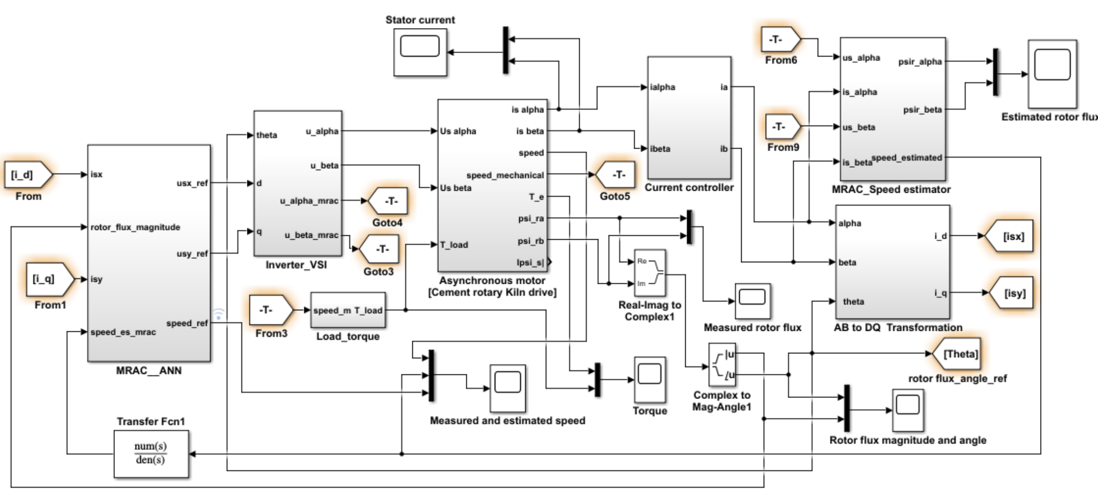

Figure: 4.12 General structure of Simulink model for kiln motor drive system

As shown on figure 4.12 Simulink model for an asynchronous motor speed and torque control which is incorporated direct rotor field orientated control DRFOC, Model reference adaptive and Artificial neural network control is a comprehensive representation of control system that enables simulation and analysis of motor performance.

- ❖ DRFOC is a one control techniques algorithm used to decouple torque and flux this controlled parameters are used to control motor drive. As seen from the simulation results its Simulink model of DRFOC is implement the control algorithm that can accurately control the rotor flux.
- ❖ MRAC is an adaptive control mechanism that used to adjust control parameters based on the difference between the desired and the actual system outputs.
- ❖ ANN is used as a modeling and control purpose. It approximate the nonlinear dynamics of motor system and compensate for uncertainties. The ANN can be trained offline or online to improve the accuracy of generated control signal.

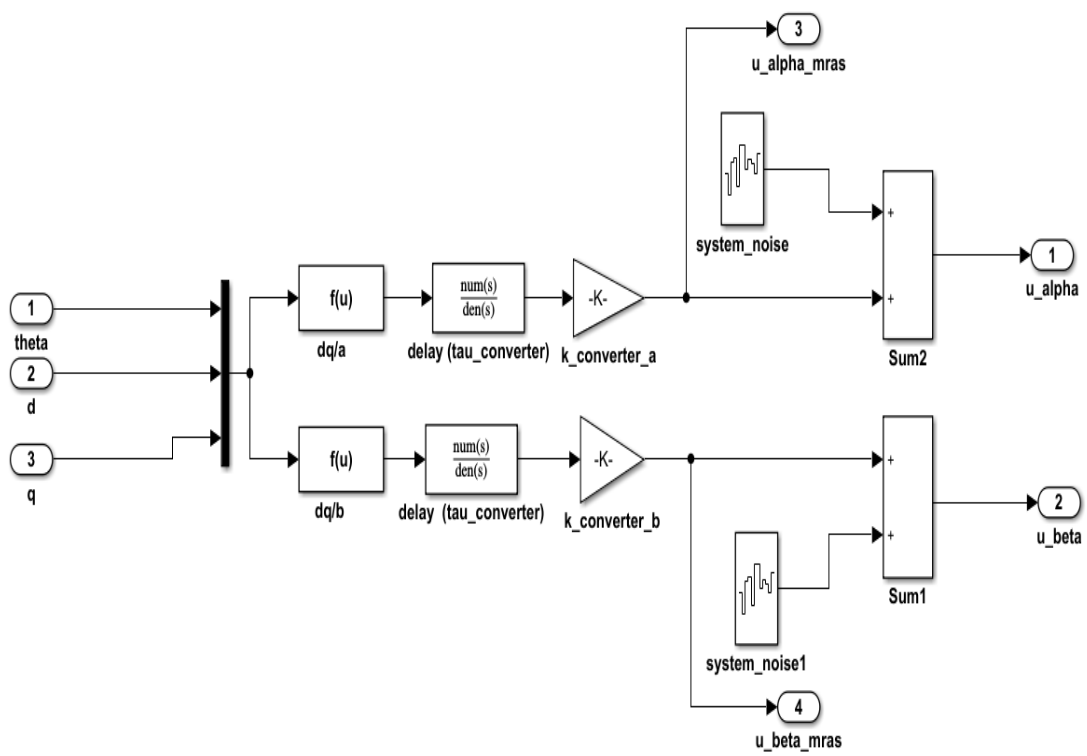

Figure 4.13 Voltage source inverter (VSI) Simulink model

As based on the Simulink model the voltage source inverter as shown figure 4.13 inputs for VSI are Theta, d and q and the expected outputs are u_alpha, u_beta, u_alpha_mrac and u_beta_mrac, this enables to facilitate the simulation and analysis. The model is incorporated as inputs of (theta, d and q) therefore, theta is representing the rotor position and the d-q references are assigned values respectively. This inputs are transformed into the alpha-beta reference frame using a coordinate transformation method. The values alpha_ref and beta_ref are used as inputs for the control algorithm system. It implements the desired control strategy such as space vector modulation (SVM) to generate the appropriate control signal for the power electronics within the VSI. Space Vector Modulation (SVM) to generate the appropriate control signals for the power electronic devices within the VSI. These devices typically represented by VSI system simulating IGBTs respond control signals and produced the desired VSI output.

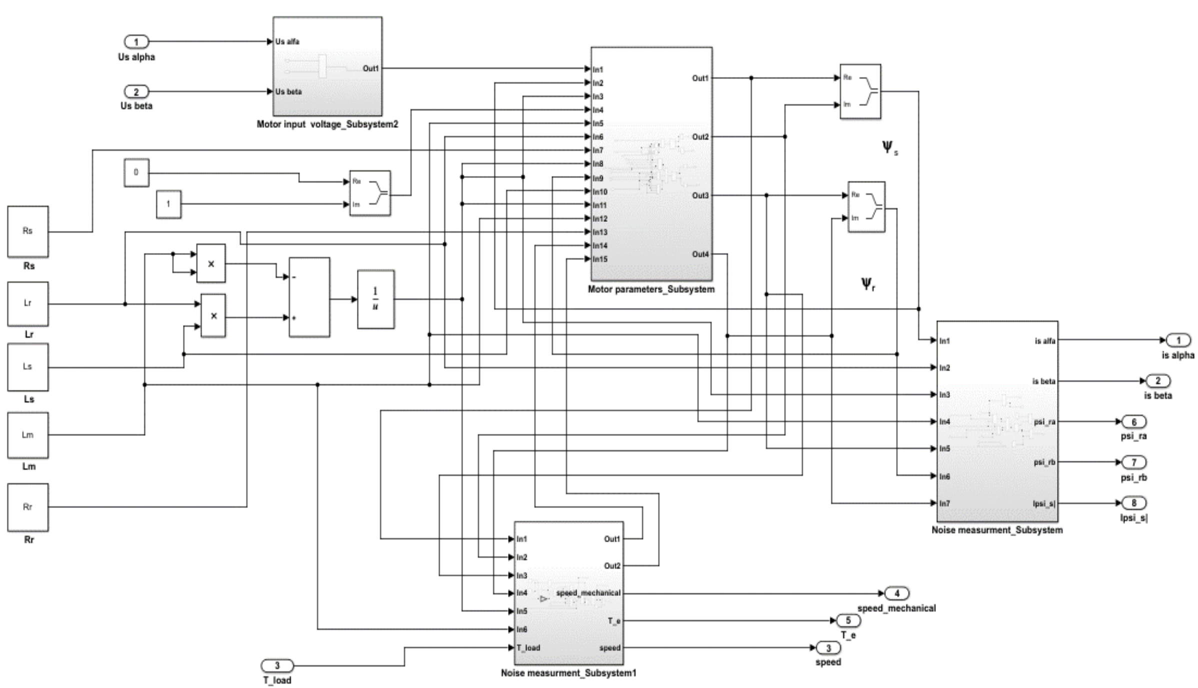

Figure: 4.14 Simulink model for an asynchronous kiln motor drive system

The Simulink model of a motor drive is allows to simulate the motor under different operating conditions and load scenarios. It can analyze the motor's performance evaluate the effectiveness of the control algorithm and update the system parameters to achieve desired speed, torque and efficiency of the control performance.

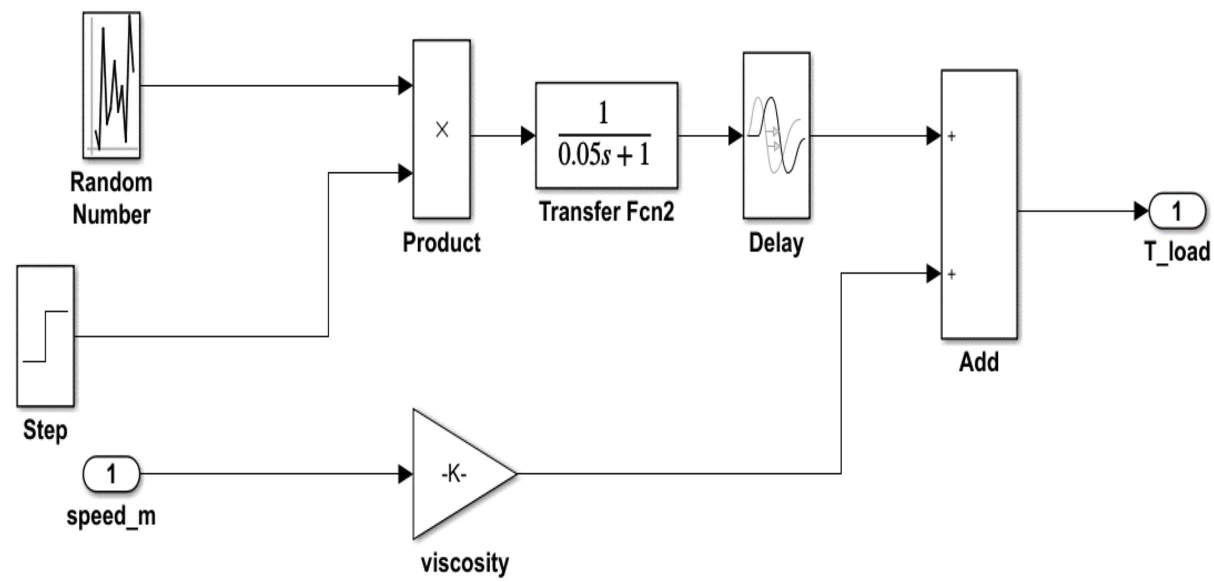

Figure 4.15 Simulink model of load to torque for an asynchronous motor drive

In the Simulink model, the load torque can be applied to the motor either as a constant value or as a time-varying signal. The load torque affects the motor's response and performance, and by analyzing the motor's response under different load torque conditions, it can easily evaluate its ability to handle different loads and assess the effectiveness of the control algorithm.

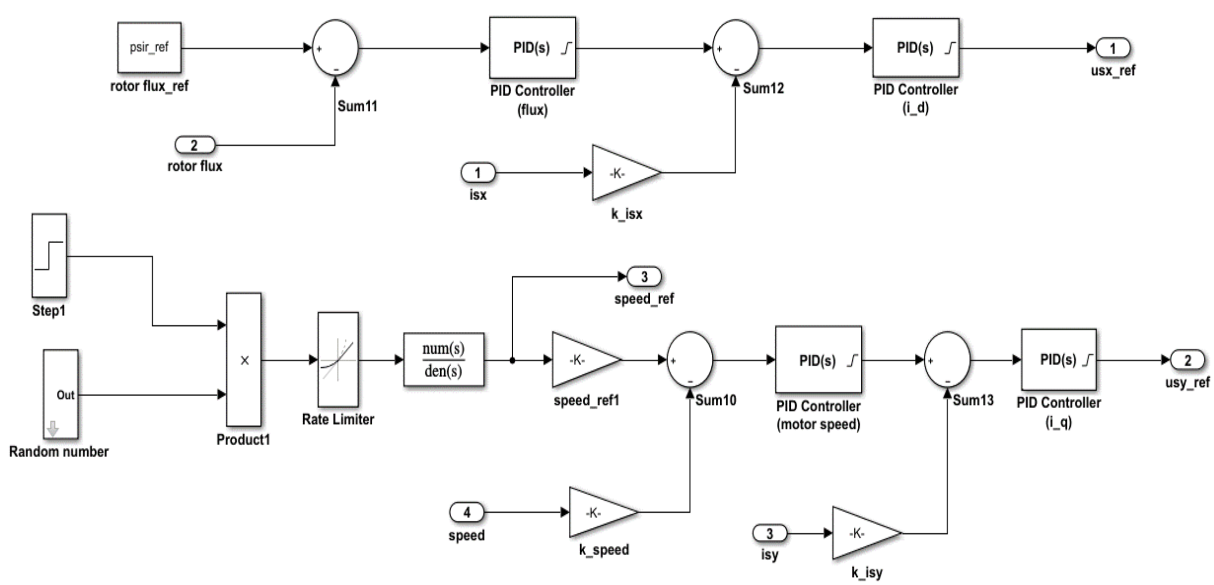

Figure 4.16 Speed and rotor flux based DRFOC-PID controller for kiln motor drive system

In the Simulink model, the simulation of the kiln motor drive system under different operating conditions, evaluate the performance of the DRFOC control strategy, and optimize the PID controller parameters to achieve the desired speed and rotor flux response.

The current measurement model

This block is designed to convert the alpha and beta components of the stator current into the measured current components ia and ib this is achieved by using a combination of transfer function and delays in Simulink. The alpha input is fed into a transfer function with a time delay of tau_measurment_i, representing the conversion to the output ia. Similarly, the beta input is fed into another transfer function with the same delay to obtain the out ib. the delays accounts for any time delay in the measurement process. By simulating this measurement process, including the time delays, the block provides the desired current measurement outputs. It's important to determine the appropriate transfer function parameters and sets the values of tau_measurment_i based on the specific system dynamics and measurement requirements.

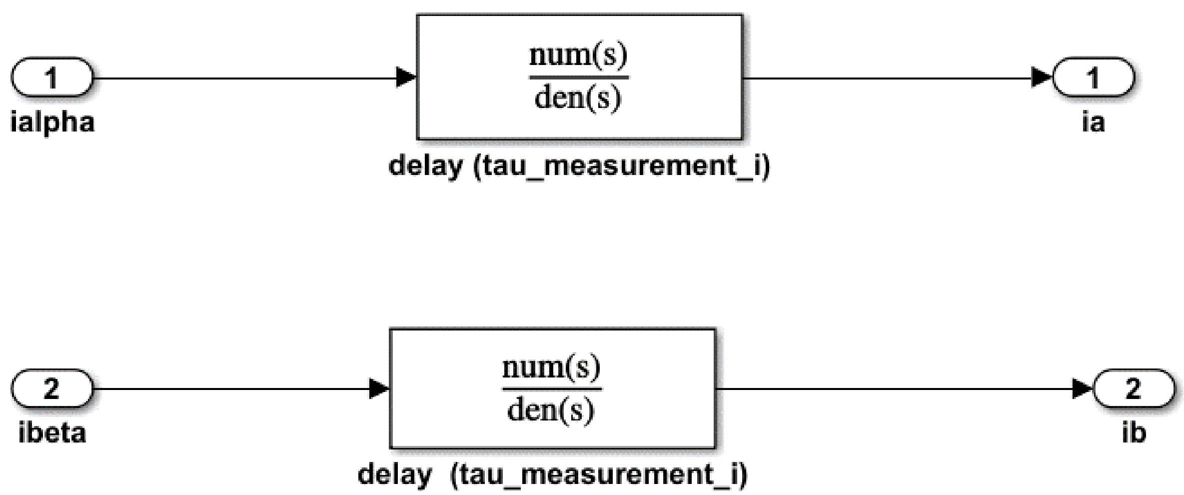

Figure 4.17 Current controller subsystem Simulink model

AB to DQ park transformation

In this transformation, the reference angle theta represents the angular position of the rotating DQ reference frame with respect to the stationary AB reference frame. The reference angle is an important parameter to facilitate the transformation process. It makes for the decoupling of the flux-producing and torque producing components in the DQ reference frame. By adjusting the reference angle to ensure the effectiveness of the conversion process. The value of the reference angle theta is typically determined based on the rotor flux position or the desired motor operating conditions. It can be derived from sensor feedback, such as rotor position sensors or estimated using sensorless control techniques. During the AB to DQ transformation, the alpha beta components along with the reference angle theta are used to calculate the d-axis and q-axis components (id and iq) in the DQ reference frame. These d-axis and q-axis components then become inputs for control algorithm, using for independent control of flux and torque.

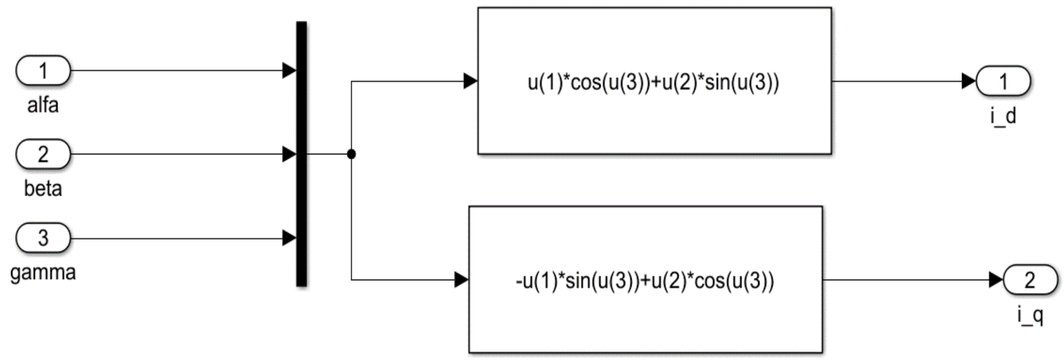

Figure: 4.18 Park Transformation Simulink model

In this section of the Simulink model the park transformation takes the alpha, beta and theta signals as inputs and performs the coordinate transformation based on the rotor position. The outputs of are the transformed signals id and qi that representing the d-axis and q-axis components as a new reference frame. By simulating the model and it can be observed that input signals in the alpha-beta reference frame are transformed into d-q reference frame and allowing for analysis and control in the rotating reference frame. This transformation is commonly used in motor control applications such as inverter control for motor.

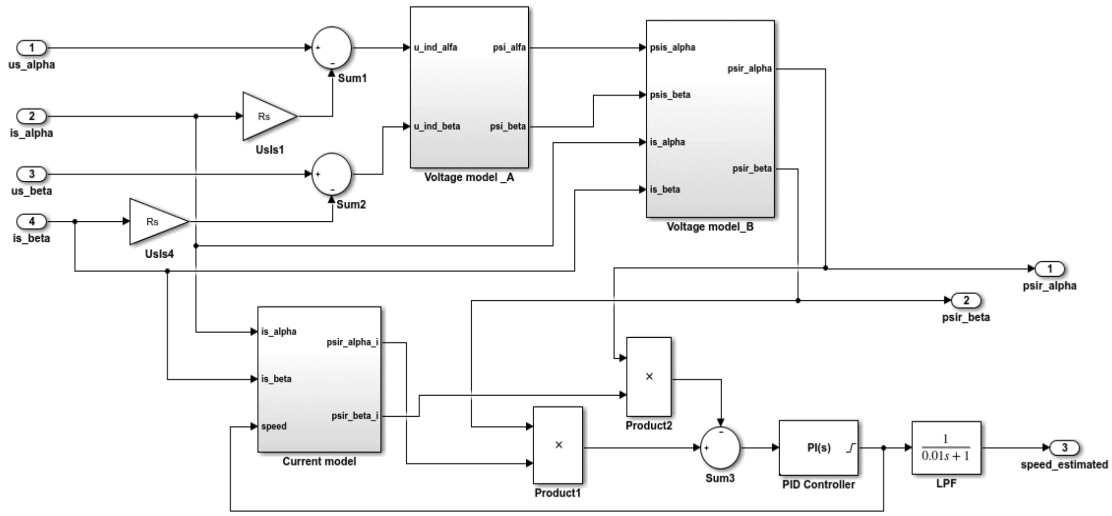

Figure 4.19 Simulink model of MRAC for an asynchronous motor drive system

As shown on figure 4.19 Simulink model, the MRAC algorithm continuously adjusts the control parameters based on the error between the desired and estimated values of the speed and the rotor flux. This adaptive control helps to enhance the performance and robustness of the motor system. Make sure configure the specific motor parameters, estimation algorithms and MRAC algorithm parameters according to the motor system requirements. Additionally ensure that the power electronics components are properly designed to interface with the power supply and generate the appropriate control signals.

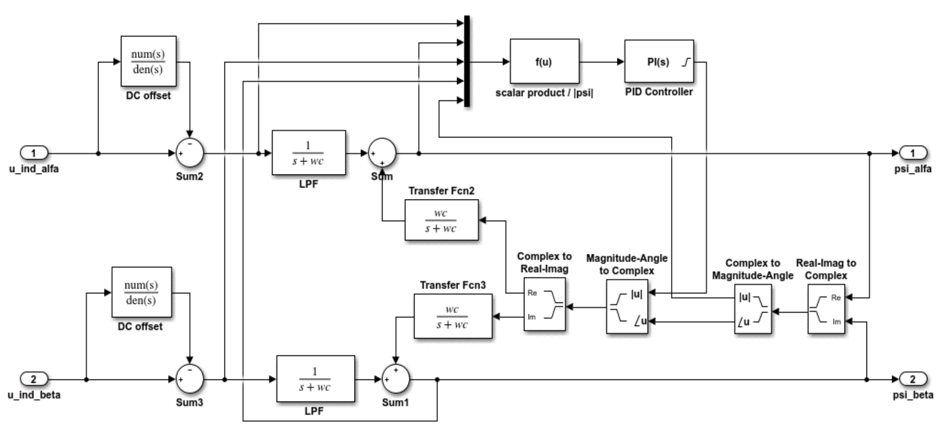

Figure (a) voltage equation model

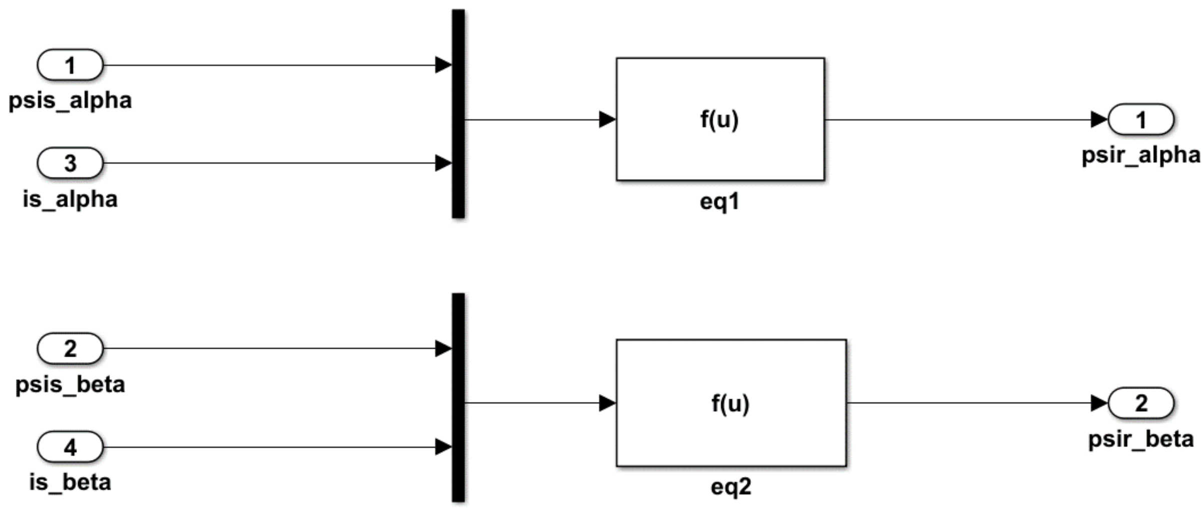

Figure (b) voltage equation model

Figure 4.20 MRAC sub-blocks voltage equations (a) and (b) Simulink model for kiln motor

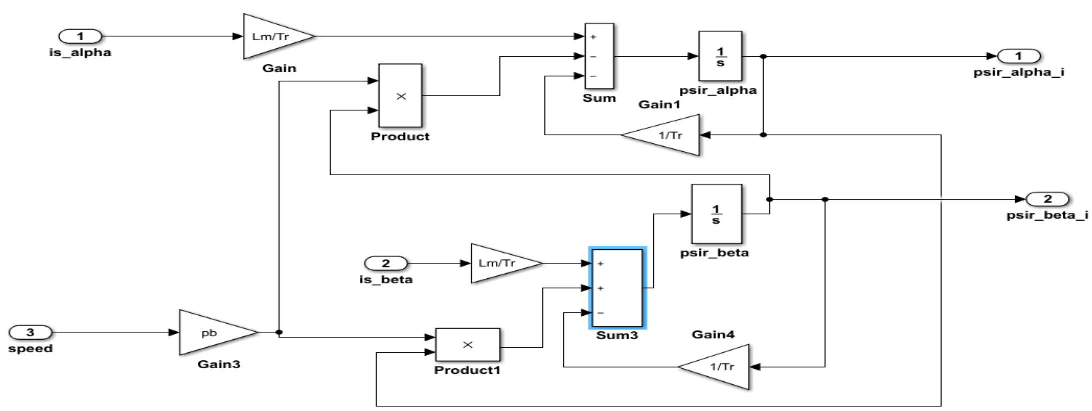

Figure 4.21 Simulink model MRAC sub-bock current controller for kiln motor drive system

In this Simulink model the MRAC algorithm has adaptive mechanism, therefore, adjust the control parameters based on the error between the desired and estimated current and voltage responses. This adaptive control helps to enhance the performance accuracy and robustness of the motor system. To ensure that the current and voltage models accurately represent the electrical behavior of the motor and that the MRAC algorithm is appropriately design to adapt the control parameters based on the error signals. Additionally, configure the specific motor parameters model equations and MRAC algorithms parameters according to the designed motor system requirements.

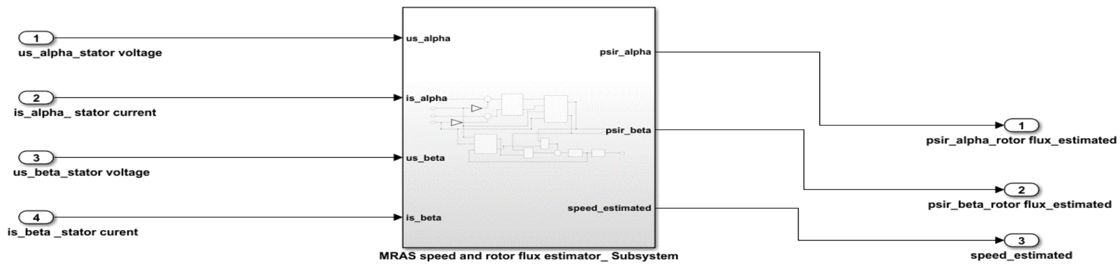

Figure 4.22 MRAC based speed and rotor flux estimator Simulink model subsystem

As shown subsystem Simulink block diagram on figure 4.22 that representing the input and output parameters configuration of the MRAC algorithm. For more clarity the algorithm takes inputs from VSI inverter such as stator current and voltage such as is_alpha, is_beta, us_alpha and us beta and the outputs are estimated rotor speed and flux.

4.2. The proposed system Simulation results and discussions

In this section, the simulation results have been evaluated based on the controller performance measures and MRAC based speed and torque control of an asynchronous motor for cement kiln motor drive system and also the other controller is ANN control the speed and torque of an asynchronous motor and finally the combination of MRAC and ANN control has been designed.

4.2.1 Model reference adaptive controller (MRAC) for kiln motor drive system

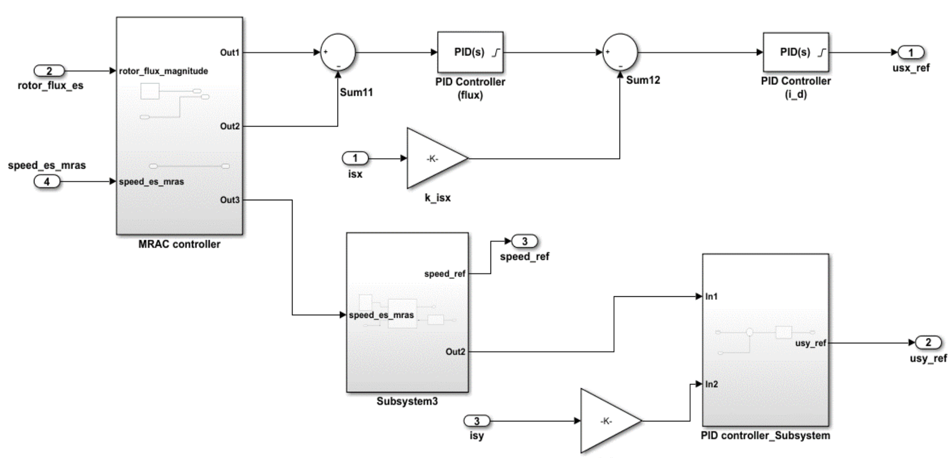

Figure 4.23 Simulink model of MRAC controlled for an asynchronous motor drive system

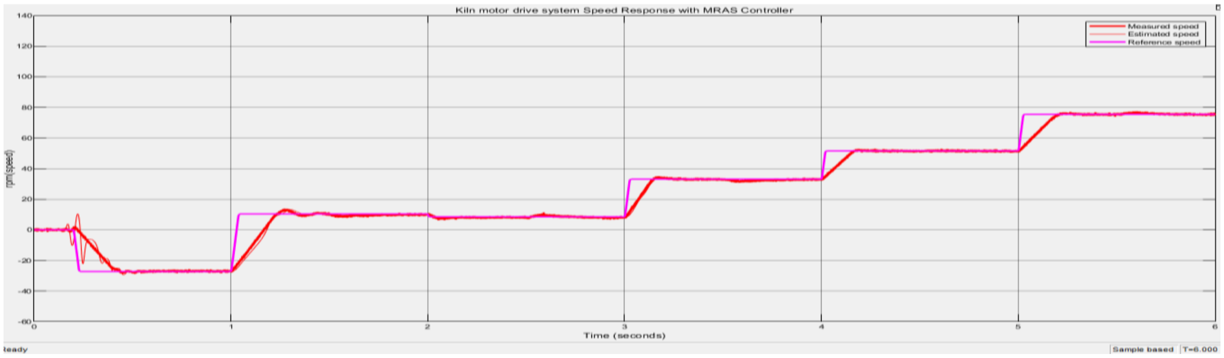

Figure 4.24 Measured and Reference speed response with MRAS controller for kiln motor

As observed from simulation results, the actual speed regulation performance MRAC controller as shown on figure 4.24 it has achieved a good result. The speed response of a rise time is 0.170 second and 2.24% overshot. After a load torque 10 Nm is applied as a disturbance input to a motor drive at 1 second, the simulated output signal format has been changed to some extent, it has not the same signal format compared to the previously desired output so, and it is clearly showed that the MRAC has a struggle to handle the disturbance and nonlinearity of the motor. Finally, by comparing of both the measured and estimated speed response motor drive, the evaluation has been showed that the MRAC algorithm is effectively estimating the motor speed. And also I observed their signal levels in terms of speed that the estimated speed closely followed the measured speed, and definitely, it has been indicated that the MRAC is performing well for tracking the desired speed and adapting to changes in the motor's dynamics. Therefore, it has been leveled as a good speed tracking control performance was achieved.

Figure 4.25 Electromagnetic torque and load torque response with MRAS for kiln motor

As observed from the simulation results on figure 2.25 the electromagnetic torque response with the MRAC, the simulation has been properly examined. It has achieved a good torque tracking control ability and maintain the desired torque response therefore, it is effectively control performance and speed regulation.

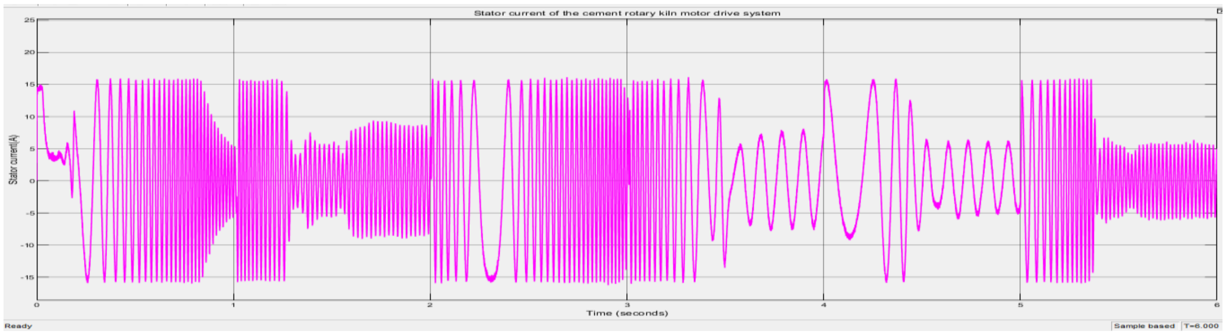

Figure 4.26 Stator current of the motor drive system for cement kiln

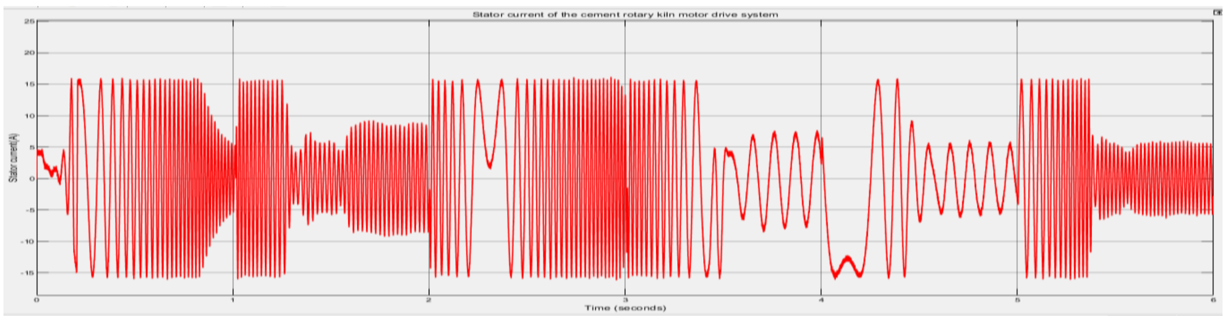

Figure 4.27 Stator current of the motor drive system for cement kiln

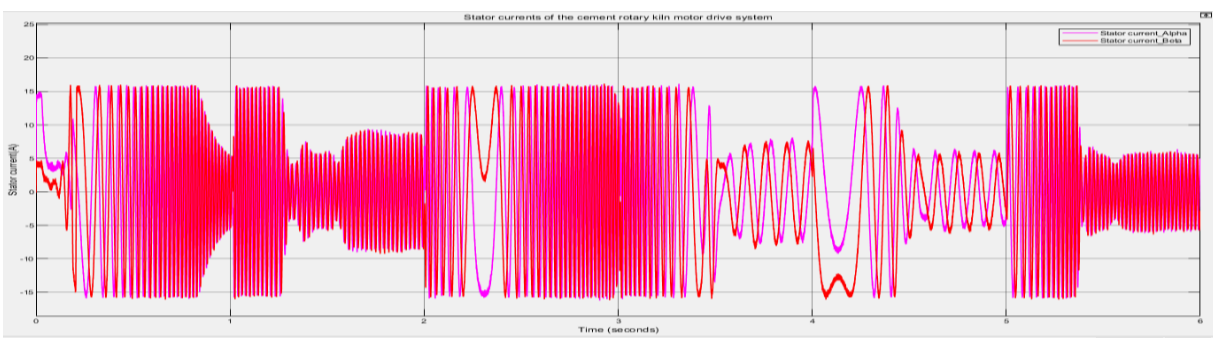

Figure 4.28 Stator currents of the motor drive system for cement kiln

As seen from the simulation results, the stator currents of the alpha and beta of the asynchronous motor as shown from figure 4.26, figure 4.27 and figure 2.28 based on the displayed outputs current signals the motor rated current rise during the starting time of the motor drive because at staring operation, the high current inrush in the motor winding and it has decreased gradually, and it is very reduced at no load conditions when a load torque is applied to the motor, the load current is rapidly increased to the rated current.

Based on the figure 2.25 the torque generated by the motor with response to the applied load torque. Hence, from the simulation results observation when the load torque is increased to drive the motor and also the motor load current is increased at the same proportional level.

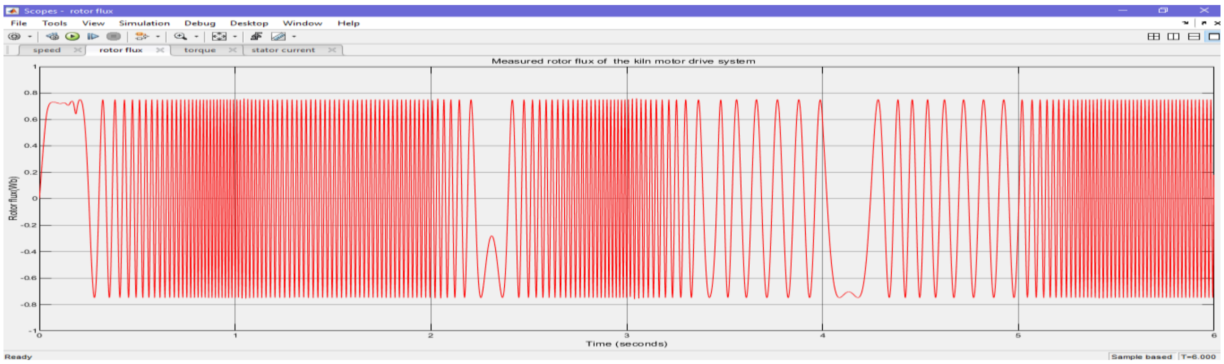

Figure 4.29 Estimated rotor flux of an asynchronous motor drive system for kiln

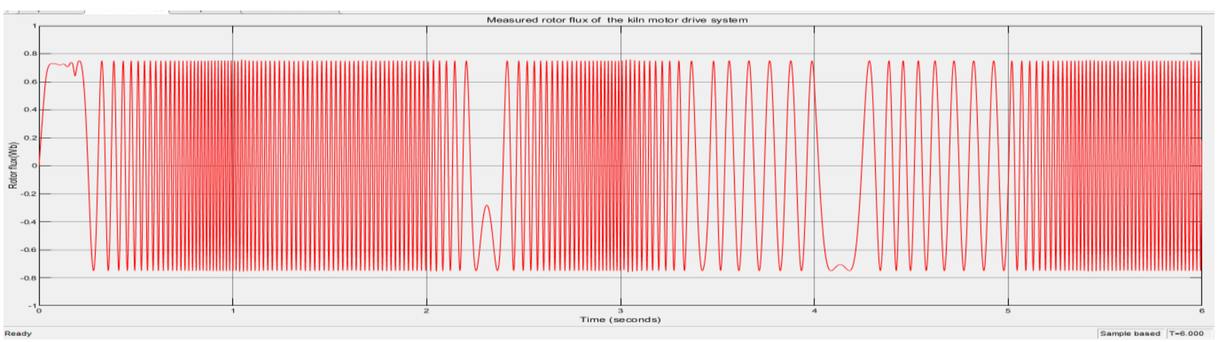

Figure 4.30 Measured rotor flux of an asynchronous motor drive system for kiln

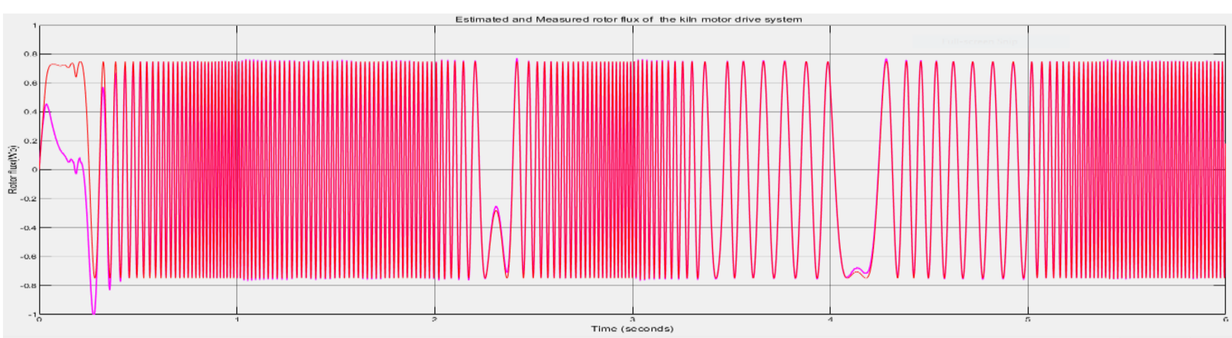

Figure 4.31 Estimated and measured rotor flux of an asynchronous for cement kiln

From the simulation result on figure 4.29, figure 4.30 and figure 4.31 described as estimated, measured estimated and measured rotor flux response respectively. The rotor flux here, as examined the estimated and measured rotor flux response of motor drive based on motor magnetic field it includes, flux magnitude dynamic response at different operating condition. The control performance has been evaluated that the accuracy of the flux estimation on load variations it is very stable with the reference rotor flux of 0.85wb.

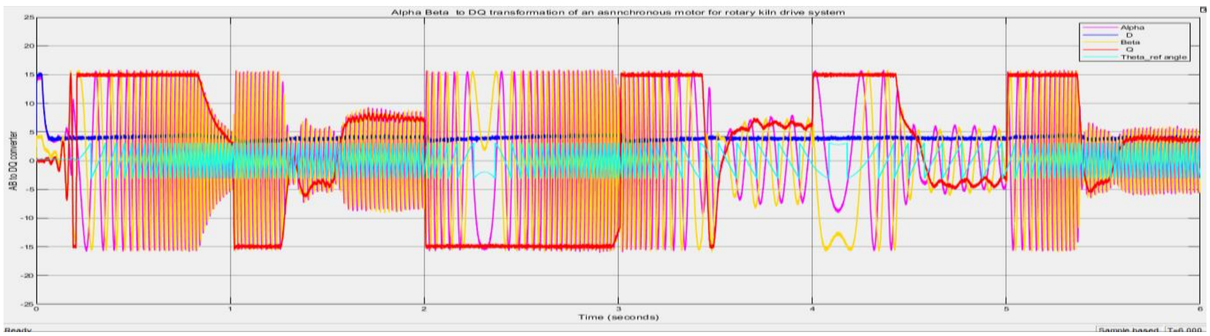

Figure 4.32 AB to DQ Transformation

From the simulation results on figure 4.32 as shown the MRAC based control of alpha and beta inputs with the reference frame theta and the corresponding outputs d and q. The alpha and beta inputs, which typically represent the coordinates in the stationary reference frame. The error between the actual motor response d and q outputs and the desired reference model is calculated.

4.2.2 ANN controller for cement rotary kiln motor drive system

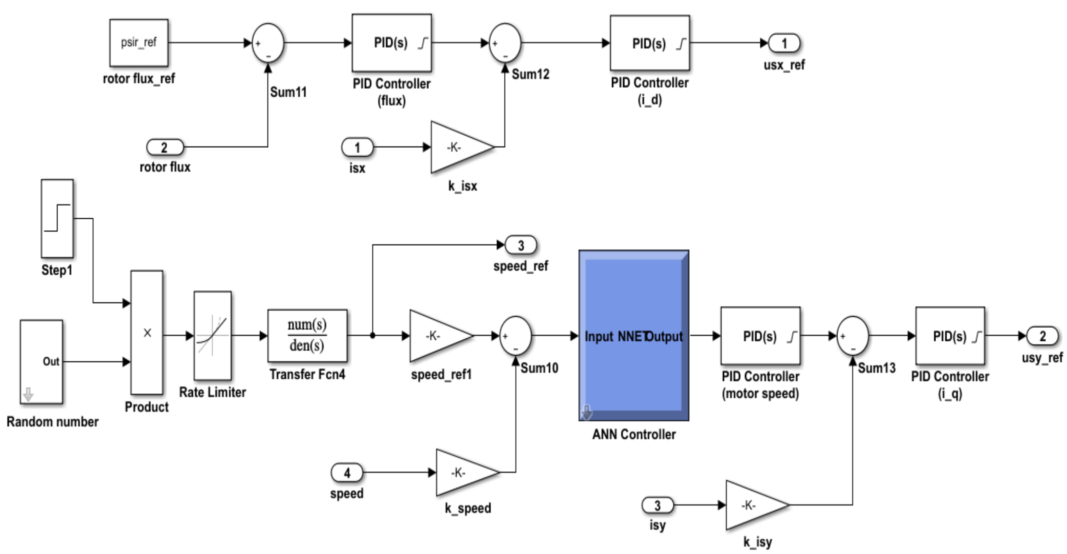

Figure 4.33 ANN controller based speed and torque control for cement kiln motor dive system

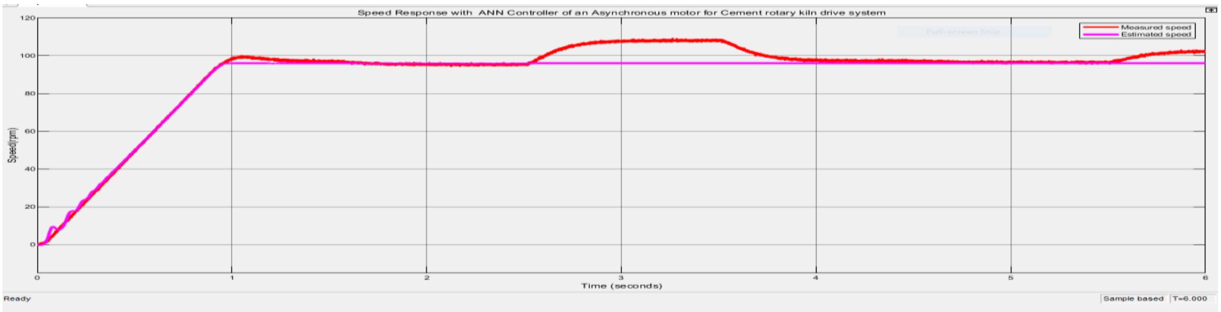

Figure 4.34 Measured and Estimated speed response with ANN controller for kiln motor drive

Based on the simulation results on figure 4.34 the speed regulation performance of the kiln motor drive system utilizing an artificial neural network (ANN) controller has been achieved a good result. As evaluated simulation findings result, indicating that motor quickly reached the desired speed which is corresponding to changes in the reference signal. This fast response time is indicated of the ANN controller ability to effectively control the motor speed. Secondly, the speed response displayed at a minimal overshoot of 1.64%. The low overshoot is indicated that ANN controller maintains stability and accurately mange excessive oscillation in the motor speed regulation. Moreover, when a load torque of 10 Nm was introduced as a disturbance to the motor drive at 1 second, the simulated output signal format remained unchanged compared to the previous output. This observation demonstrated that robust disturbance handling capability of the ANN controller, as it was able to maintain the desired speed despite the introduced disturbance. The comparison between the measured and estimated speed response of motor the ANN algorithm effectively estimated the motor speed. The estimated speed closely followed the measure speed, indicating the ANN controller accuracy the tracking the desired speed and adapting to changes the motor dynamics. Hence the performance of ANN controller such as fast response time, low overshot effective disturbance handling capability, nonlinear, uncertainty and contribute to its ability to accurately regulate the motor speed.

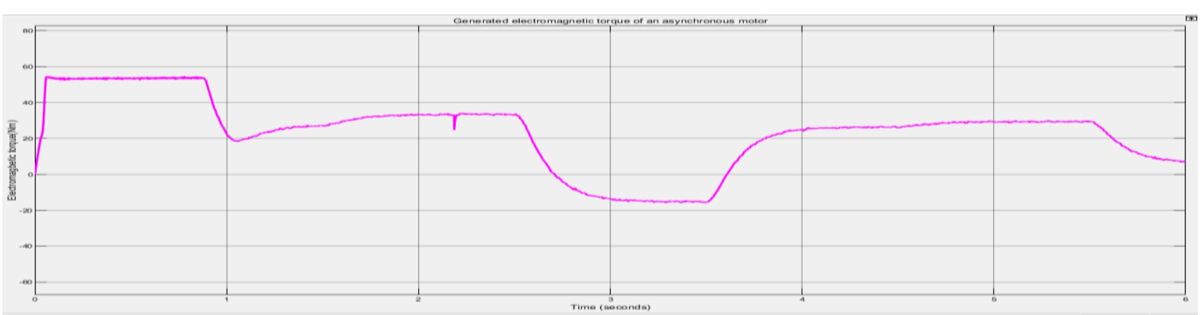

Figure 4.35 Electromagnetic torque response with ANN controller for motor drive system

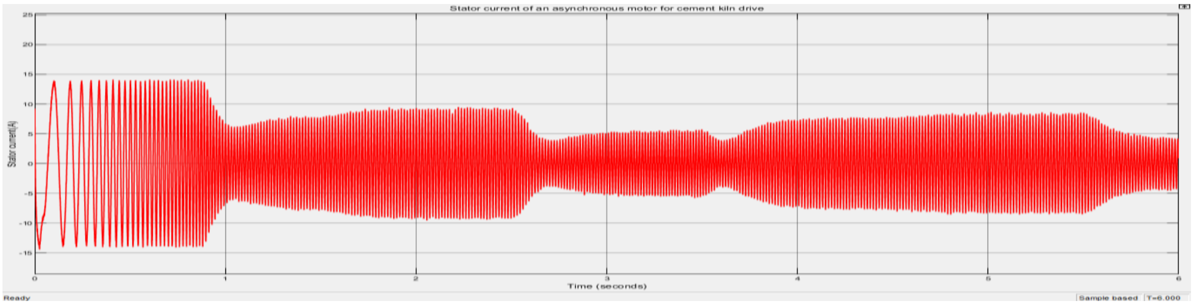

Figure 4.36 Stator current of an asynchronous motor drive system

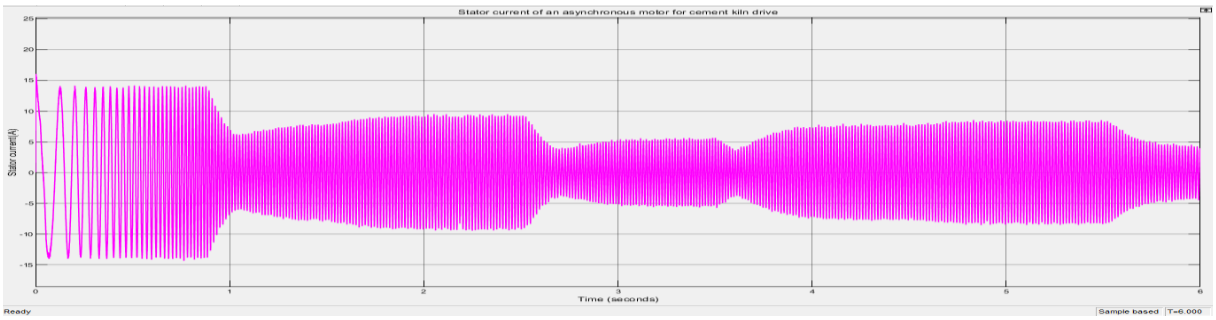

Figure 4.37 Stator current of an asynchronous motor drive

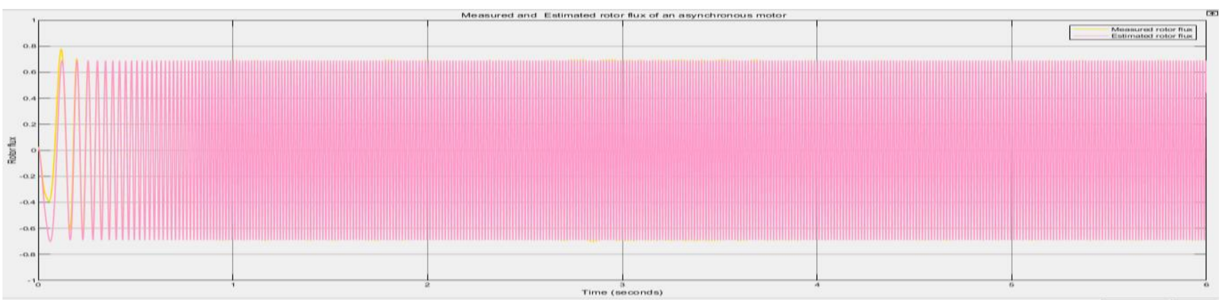

Figure 4.38 Measured and Estimated rotor flux of an asynchronous motor drive system

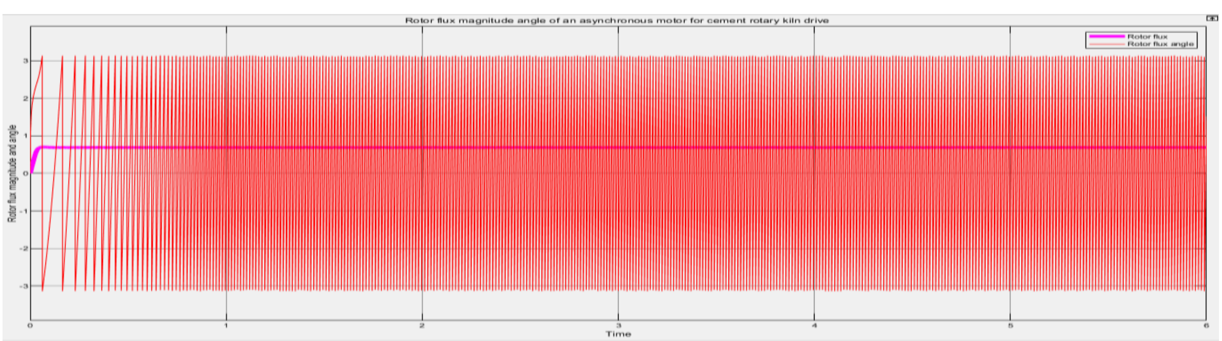

Figure 4.39 Rotor flux magnitude and angle of an asynchronous motor drive system

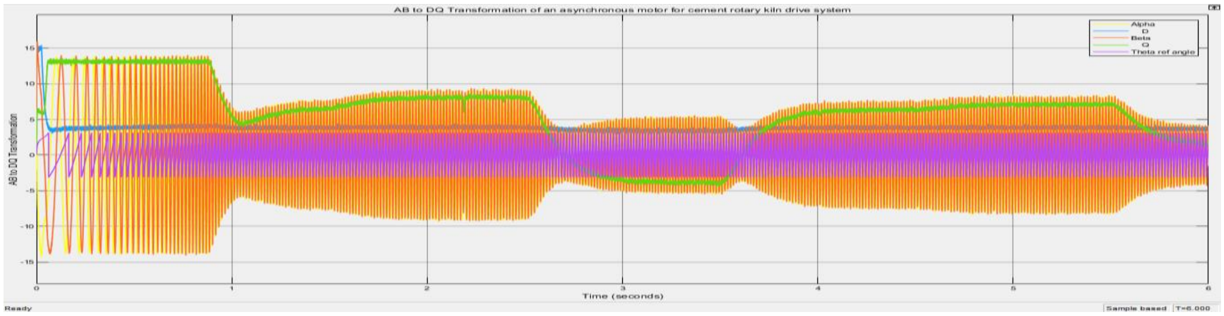

Figure 4.40 AB to DQ Transformation of an asynchronous motor drive system

As observed from the simulation result on figure 4.40 ANN controller algorithm with the learning capabilities of artificial neural network. Update online or offline control parameters based on the error between the actual motor responses and the reference model, while the ANN component learns the mapping between the inputs (Alpha, beta and theta) and the outputs (d and q) to control the performance of motor.

4.2.3 MRAC-ANN based controller of the cement rotary kiln motor drive system

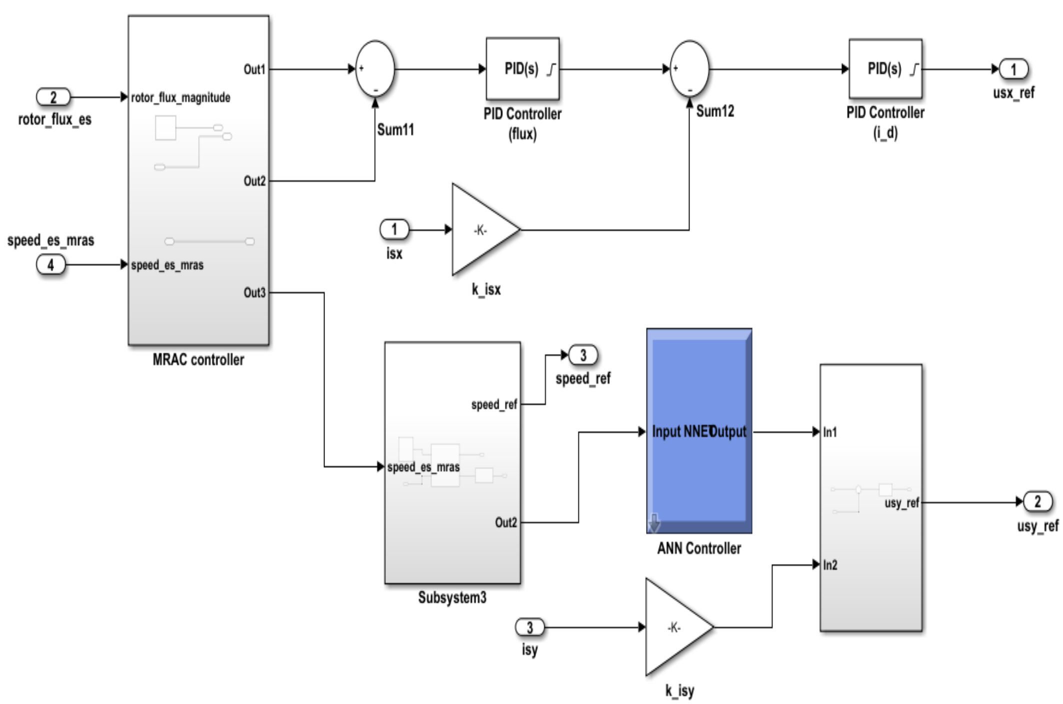

Figure 4.41 Simulink model MRAC-ANN controller of the kiln motor drive system

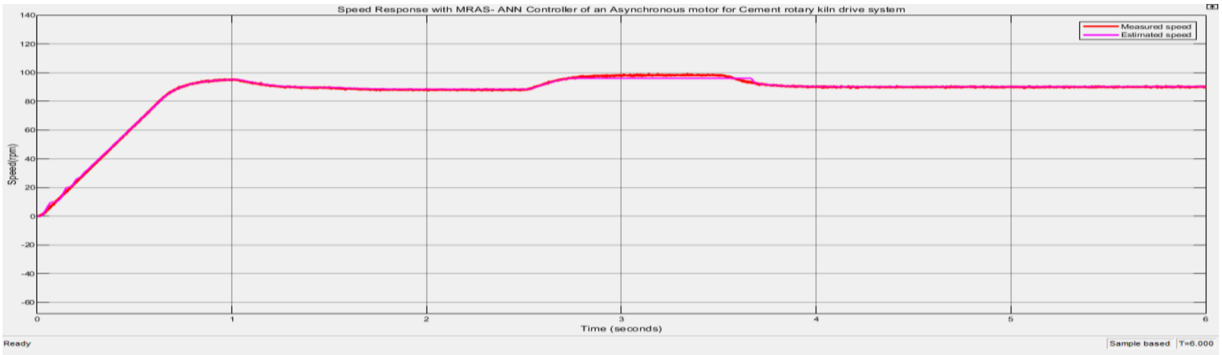

Figure 4.42 Measured and estimated speed response with MRAC-ANN controller for motor

As seen from simulation results on figure 4.42 the required evaluation has been done and the speed regulation performance of the kiln motor drive system utilizing a hybrid MRAC-ANN controller result is excellent. Speed response of motor with a rise time is 0.106 seconds, which is indicating that motor quickly reached the desired speed following changes in the reference signal. This response time is indicated of the MRAC-ANN controller ability to effectively control the motor speed. The speed response displayed a minimal overshoot is 0.014%. The low overshoot indicated that the MRAC-ANN controller maintains stability and prevents excessive oscillation in the motor speed regulation. Moreover, when a load torque of 10 Nm was introduced as a disturbance input to the motor drive at 1 second, the simulated output signal format remain unchanged compared to the previous output. This observation demonstrated that MRA-ANN controller has excellent disturbance rejection capability. Hence, the performance of MRAC-ANN controller such as fast response time, low overshot effective disturbance rejection capabilities contribute to its ability to accurately regulate the motor speed.

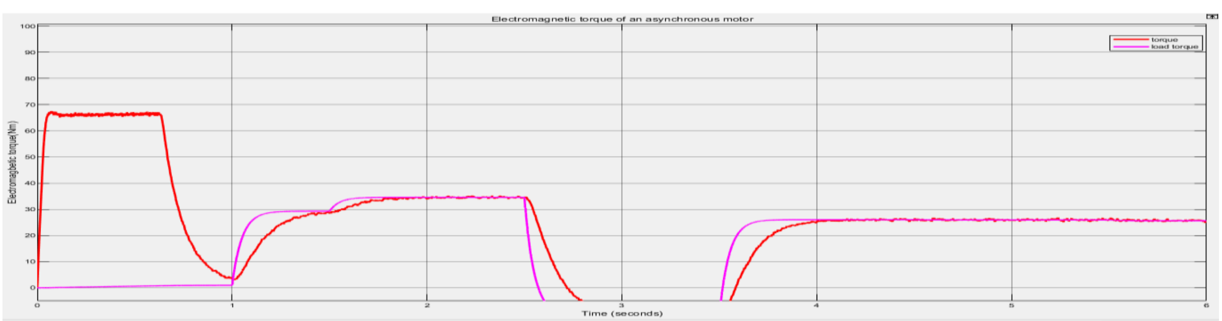

Figure 4.43 Electromagnetic torque response for kiln motor drive system

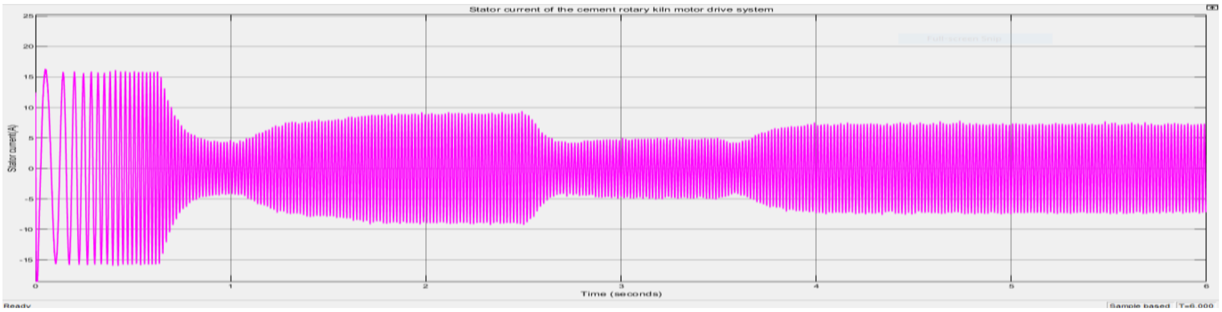

Figure 4.44 Stator current of an asynchronous motor drive for cement kiln

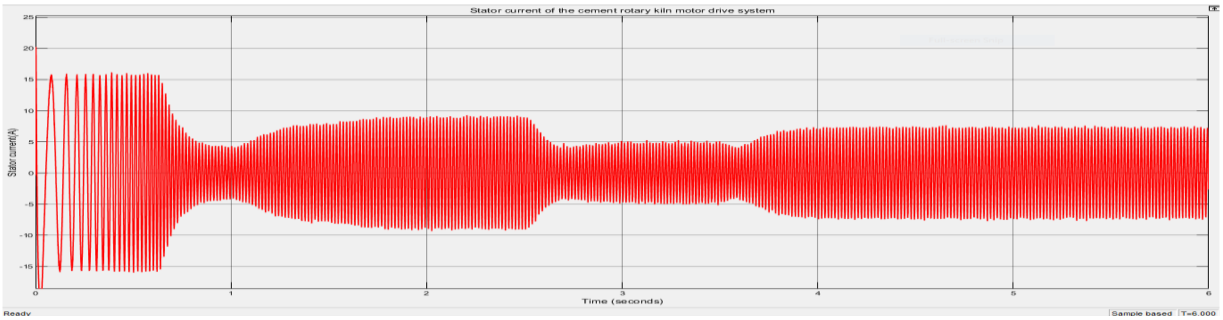

Figure 4.45 Stator current of an asynchronous motor drive system for cement kiln

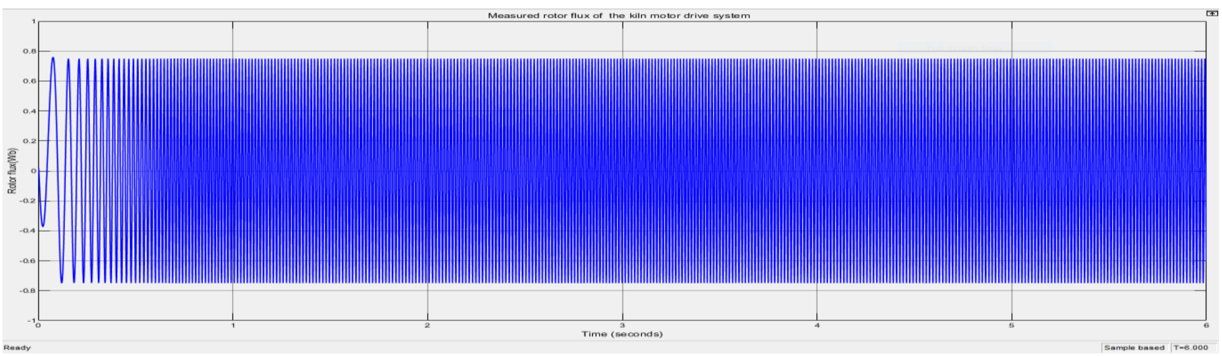

Figure 4.46 Measured rotor flux of an asynchronous motor drive system for kiln

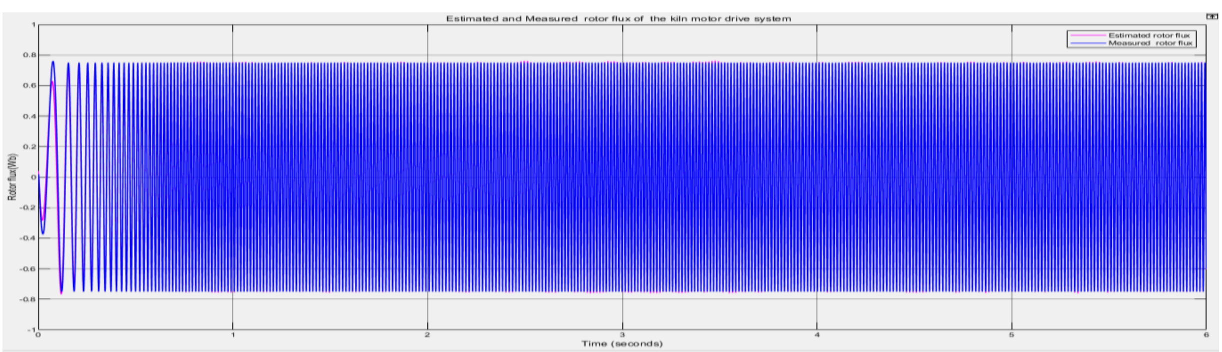

Figure 4.47 Measured and Estimated rotor flux of an asynchronous motor drive system for kiln

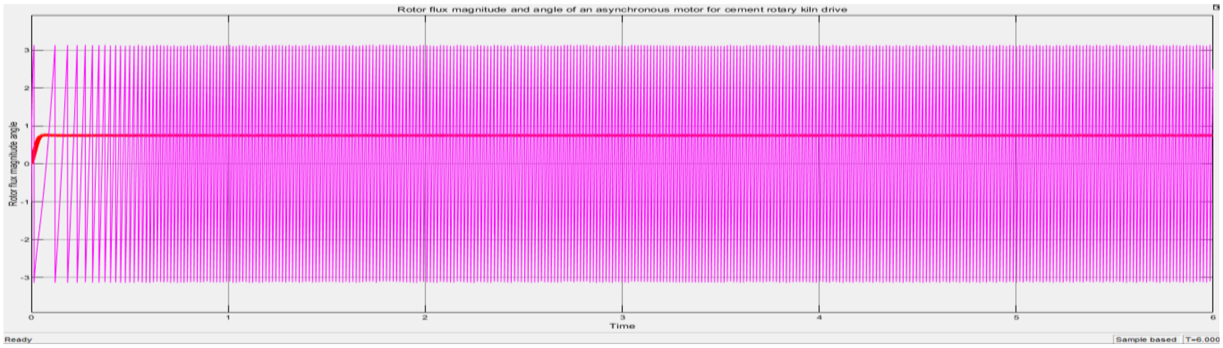

Figure 4.48 Rotor flux magnitude and angle of an asynchronous motor for kiln

As seen the simulation result from above figure 4.46 figure, 4.47 and figure 4.48 are described as measured rotor flux, measured and estimated and rotor flux magnitude angle respectively. Between the actual rotor flux response and the desired reference model is calculated. This error is used to update the control parameters of the MRAC components, ensuring improved tracking and regulation of the rotor flux. The ANN component received the inputs (d and q) and adjusts its internal weights and biases to optimize the mapping between the inputs and outputs of rotor flux.

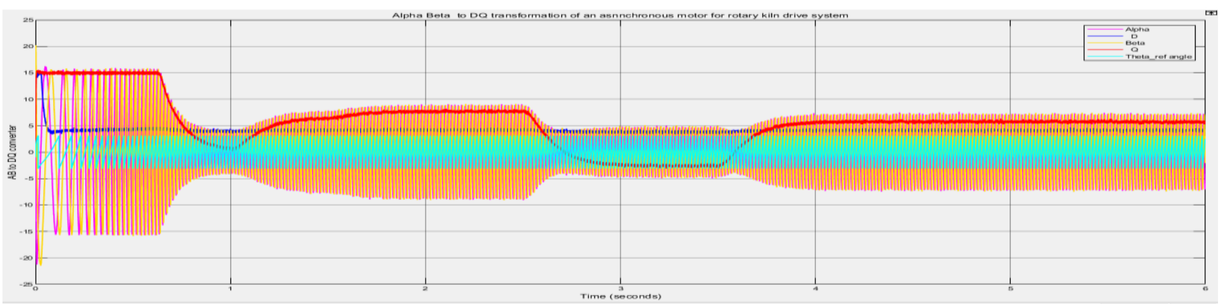

Figure 4.49 AB to DQ Transformation of an asynchronous motor drive system for kiln

As seen simulation result on figure 4.49 MRAC-ANN controller combined the adaptive capabilities of the MRAC algorithm with the learning capabilities of artificial neural network. MRAC is adjusts its control parameters based on the error between the actual motor responses and the reference model, while the ANN component learns the mapping between the inputs (Alpha, beta and theta) and the outputs (d and q) to control the performance of motor The following table summary as shown below the performance measures and comparison for MRAS, ANN and MRAC-ANN controllers based speed control of an asynchronous motor for cement rotary kiln.

Table 4.2 Lists of Summarized performance measures and comparison of controllers based on their simulation results

Performance measures	MRAC controller	ANN controller	MRAC-ANN controller
Rise time	0.170 sec	0.123sec	0.106sec
Settling time	0.134 sec	0.016sec	0.014 sec
Overshoot	2.24%	1.64%	1.25%
Control performance	Good	Excellent	Excellent
Speed and torque tracking accuracy	Good	Excellent	Excellent
Adaptability to System Changes	Good	Excellent	Excellent
Response time	Good	Excellent	Excellent
Disturbance rejection ability	Moderate	Good	Good
Disturbance handling after load torque applied	Moderate	Good	Good
Robustness of parameter variations	Good	Good	Good

The table 4.1 compares the performance measures of three controllers MRAC, ANN, and MRAC-ANN for speed and torque control for cement rotary kiln motor drive

- ✓ Rise time the MRAC-ANN controller achieves the fastest response with a value of 0.106 seconds following by ANN controller with 0.123 seconds and MRAS controller with 0.170 seconds
- ✓ Settling time both the ANN and MRAS-ANN controller exhibits significantly lower values compared to the MRAC controller. The MRAC -ANN controller has the lowest settling time of 0.014 seconds, followed by the ANN controller with 0.016 seconds and the MRAC controller with 0.134 seconds.
- ✓ Overshoot the MRAC-ANN controller again outperforms the other two controller with the lowest value of 1.25%. The ANN controller has an overshoot of 1.6% and the MRAC controller has the highest overshoot of 2.24%.

Both showed controllers performance are rated as excellent with ANN controller and also excellent performance while the MRAC-ANN controllers.

The MRAC-ANN controller also excels in adaptability to system changes, response time disturbance rejection ability, disturbance handling after load torque is applied and robustness to parameter variations. It achieves excellent ratings in these categories while the MRAC and ANN controller shows varying levels of performance ranging from moderate to excellent. In summary, the MRAC-ANN controller generally outperforms the MRAC and ANN controller in most performance measures, demonstrating faster response times, shorter settling time, lower overshoot and excellent control performance. It also shows superior adaptability to system changes response time, disturbance rejection ability, disturbance handling after load torque is applied and robustness to parameter variations. On the other hand, the MRAC and ANN controller performs adequately with the MRAC controller generally exhibiting lower performance compared to the ANN controller.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

In this thesis study, the findings of simulation results have been evaluated, therefore, the speed control technique of an asynchronous motor drive system for cement rotary kiln has been presented and as well as the simulation work of the proposed system have been evaluated successfully. To improve the performance of the designed controller for kiln motor drive system that MRAC and ANN each controller has been simulated individually. To get the best performance measures, applied the combination of both controllers of the MRAC and ANN control technique have been simulated. The simulation has been done on the MATLAB/Simulink software. The simulation results have been clearly showed that the results of MRAC is a tracking control performance of speed is good, adaptability is good, response time is good, but it is moderate on disturbance handling capability and rise time is 0.170sec, setting time is 0.134sec and overshoot is 2.24%. On the other hand, artificial neural network controller (ANN) outperforms speed tracking control accuracy is excellent, response time is 0.123sec, setting time is 0.016sec and overshoot is 1.64%. Finally, a hybrid MRAC-ANN controller has a superior performance of an accurate speed tracking control, adaptability is excellent and response time is excellent, rise time is 0.106sec, settling time is 0.014sec and overshoot is 1.25% and it consistently meets the desired control objectives. Therefore, MRAC-ANN controller can effectively regulate the speed of the asynchronous motor for cement rotary kiln, which is leading to stable and reliable operation of the kiln. This hybrid controller has high speed tracking control accuracy, adaptability to system changes and response time. The controller can accurately followed desired speed and torque reference adapt to variations in the motor drive system parameters and respond quickly to change in operating conditions. These are crucial for maintaining optimal performance and ensuring the motor drive system reliable operation for cement rotary kiln. The MRAC-ANN controller exhibits good disturbance rejection ability and disturbance handling after load torque is applied. Hence, the controller can effectively eliminate that the impact of disturbances such as sudden load changes or external disturbances on the motor speed drive system.

RECOMMENDATION

As evaluated based on the findings results of simulation work, it is very effective to implement the MRAC-ANN controller of an asynchronous motor system for cement kiln rotary kiln. A hybrid MRAC-ANN controller can offer several advantages including better speed tracking and improved disturbance rejection, minimized sensitivity to parameter variation and enhanced adaptability to change under different load conditions. Therefore, by combining the strength of model reference adaptive system and artificial neural network can provide a reliable and more efficient control performance for kiln motor drive system. To improve the speed tracking control performance of a kiln motor drive system or an asynchronous motor, it is better and recommended to consider implementing SMC-ANN (Sliding mode control with artificial neural network) controller. SMC-ANN controller which can be combined the robustness of sliding mode control with learning capabilities of artificial neural network, offering improved control performance and adaptability. Sliding mode control with artificial neural network can provide enhanced speed control by effectively handling nonlinearities, uncertainties and disturbances in the kiln motor drive system.

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APPENDICES

Appendix A

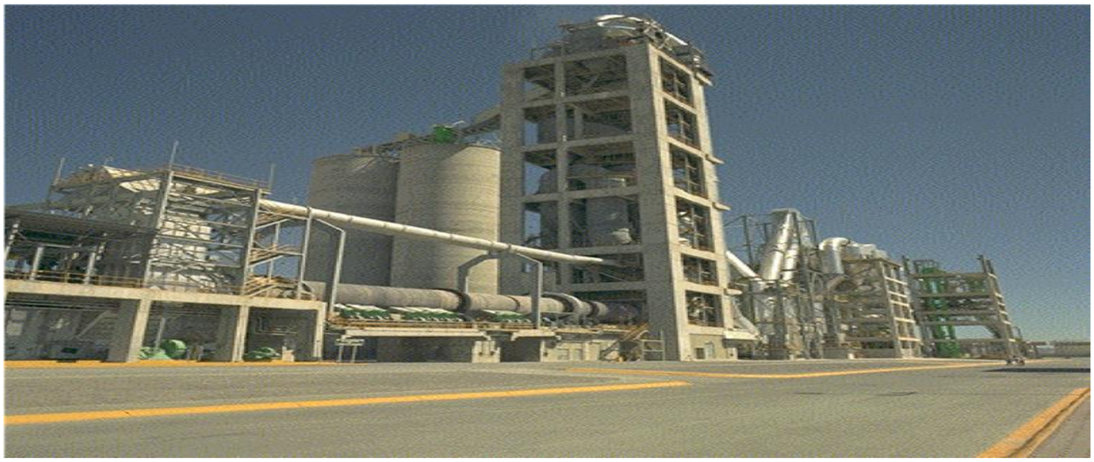

Figure A.1 Mugher cement factory (3rd line plant)

Table 4. 2 Asynchronous motor parameters for cement rotary kiln

S.№	Description of parameters	Symbol	Values
01	Rated Voltage	V	400 V
02	Rated power	W	50 Kw
03	Rated Speed	N	995 rpm
04	Rated Frequency	f	50 Hz
05	Power Factor	PF	0.80
06	Stator Resistance	Rs	1.84 Ω
07	Rotor Resistance	Rr	1.48 Ω
09	Stator inductance	Ls	0.2011 H
10	Rotor inductance	Lr	0.1969 H
11	Mutual Inductance	Lm	0.1928 H
12	Moment of Inertia	J	0.5kg·m^2
13	Number of Poles	p	4
14	Torque constant(kt)	T	30.63 Nm

Appendix B

MATLAB Simulation code of an asynchronous motor drive system for cement rotary kiln for MRAC and ANN controllers

```
the_mdl = 'MRAC_ANN_Speed_Torque_Controller_Thesis_Banteamlak.slx';
open(the_mdl);
rng(shuffle);
k_measurment_i = 1/15;
tau_measurment_i = le-4; % delay
tau_measurment_omega =1/100;
tau_meaurment_omega = 0.005; % delay
k_convertyer = 300;
tau_converter = 1.5e-4;% delay
out_sat =1; % saturation level
psir_ref = 0.788; % rotor flux_ref
J_moment of inertia = 0.5;
% Asyncchronous motor drive system parameters for cement rotary kiln
Stator inductance (Ls)  = 0.2011;
Rotor resistance  (Ls)  = 0.1969;
Mutual inductance (Lm) = 0.1928;
sigma = 1-Lm.Lm/Lr/Ls;
Stator resistance (Rs)  = 1.84;
Rotor resistance (Rr)   = 1.48;
Pb= 4;
c_viscosity = 1e-2;
Tr =Lr/Rr;
Ts = le-4;
Imax = 15; % to determine the nois signal
Omegamax = 80; % to determine the noise signal
Umax = k_converter; % to determine the noise signal
```

```
Upper_speed = 120;

Upper_torque = 40;

% Flux controller

plant PSI = tf([1/k_measurment_i], 2*tau_MO_sum_of_small^2)

2*tau_MO_sum of small 1);

[z,p,k] = zpkdata(plant_PSI);

step_PSI = stepinfo(plant_PSI);

disp(['stator current rise time:' num2str(step-PSI.RiseTime)]);

display(['stator flux rise time:' num2str(step-PSI.RiseTime)]);

% Flux controller tuned using PID tuner

kp_psi= 5;

ki_psi= 200;

% Reference speed, load_torque and noise generator seeds

seed_1= round (rand*(2^32-1));

seed_2= round (rand*(2^32-1));

seed_3= round (rand*(2^32-1));

seed_4= round (rand*(2^32-1));

seed_5= round (rand*(2^32-1));

seed_6= round (rand*(2^32-1));

seed_7= round (rand*(2^32-1));

seed_8= round (rand*(2^32-1));

System noise PSD = (Umax*0.01/error_ref inverse)^2*Ts;

noisepsd I = (Imax*0.03/erf inverse)^2*Ts;

t_stop = 6;

% Flux calculator (voltage model)

tau_dc = 30;

wc = 20;

kp_ortho = 0.01;

ki_ortho = 0.1;

psissat_ortho = 0.8;
```

```
% MRAC
kp_mrac = 100;
ki_mrac = 10000;
taining = 0
inputANN(:,k) = [a1;a2];
outputANN(:,k) = [k(1,:)';k(2, ;)'];
```

```
k= k+1;
norm_input =max(abs (inputANN’))’;
norm_inputANN= repmat (norm input’, max (size (inputANN)), 1)’;
norm_output = max (abs (outputANN’))’;
norm_outputANN = repmat (norm output’, max (size (outputANN)), 1)’;
X = inputANN./norm_inputANN;
Y = outputANN. /norm_outputANN;
k1 = 3;
k2 = 5;
[k3, pom] = size (Y);
net = feedforwardnet ([k1,k2]);
net.layers{1}.transferFcn = ‘tansig’;
net.layers{2}.transferFcn = ‘tansig’;
net.layers{3}.transferFcn = ‘purelin’;
net.divideFcn = ‘dividetrain’;
net.trainparam. show  = 5;
net.trainparam.epochs = 100;
display (‘Training...’);
net = train (net, X,Y);
gensim (net, -1);
net.userdata.norm={norm_input’ norm_output’];
```

Appendix C

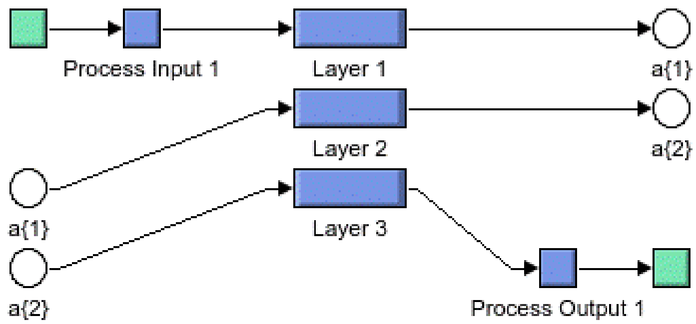

Figure C.1 Internal structure of artificial neural network

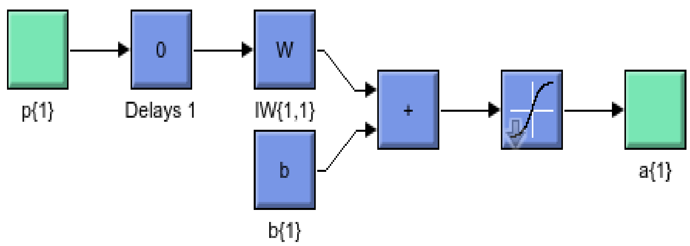

Figure C.2 Simulink model of layer one ANN

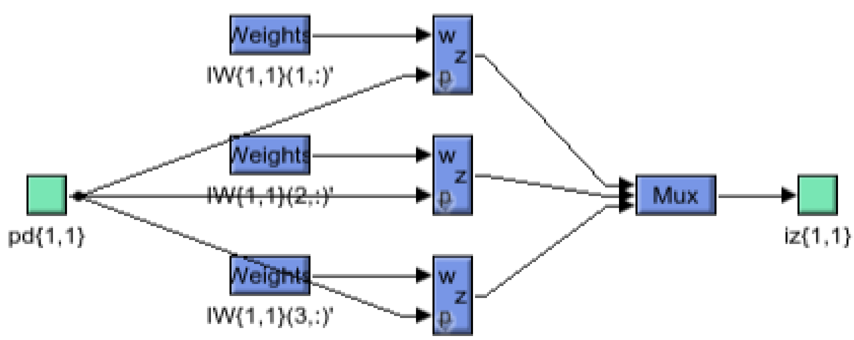

Figure C.3 Simulink model structure of ANN with weight estimation

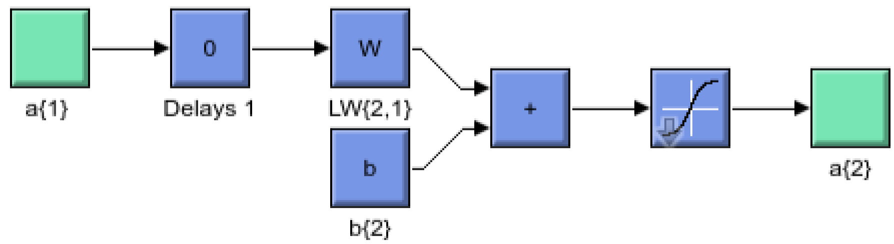

Figure C.4 Simulink model of layer two ANN

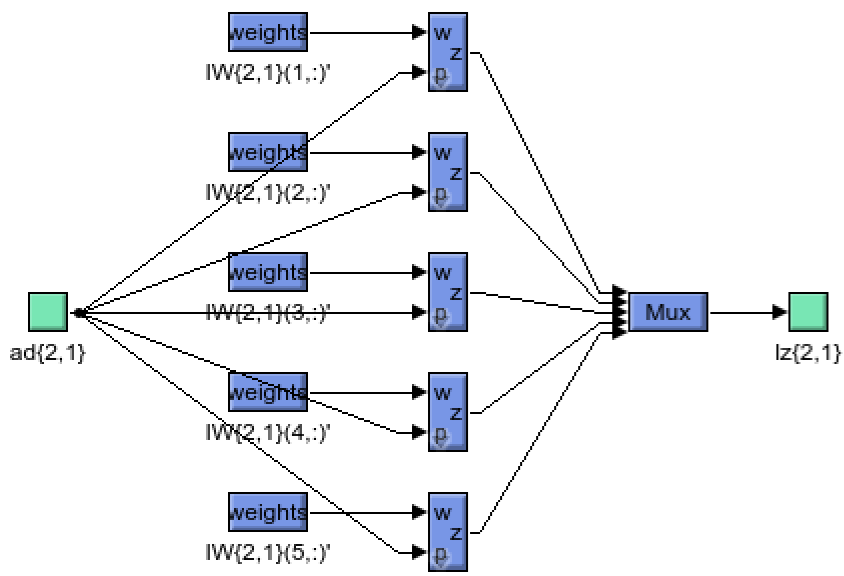

Figure C.5 Simulink model structure of ANN with weight estimation

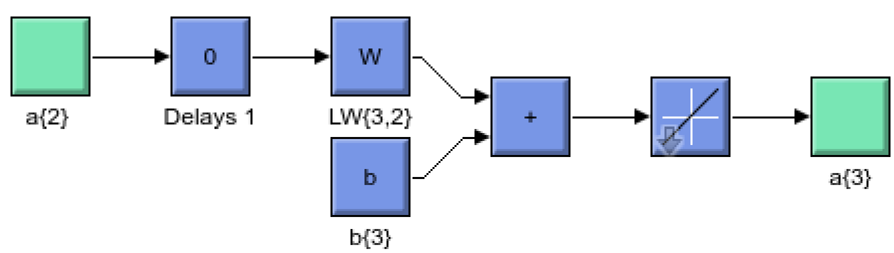

Figure C.6 Simulink model of layer three ANN

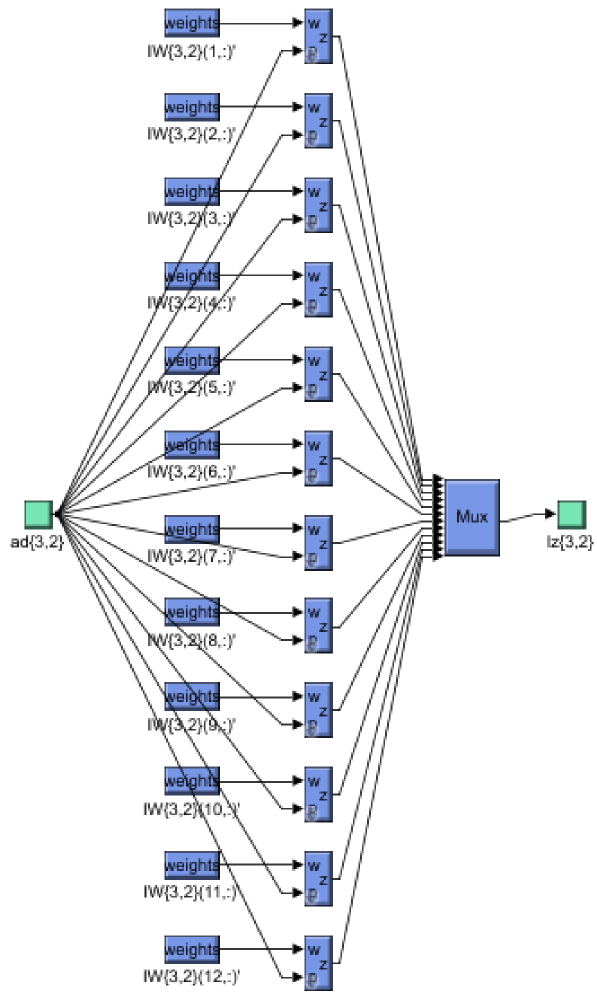

Figure C.7 Simulink model structure of ANN with weight estimation

Appendix D

Table 4.3 Technological advantages of the proposed controllers

Components	Description	Technological advantages
Sensorless Control of Motor Drive System	Control of an asynchronous motor without using physical sensors Estimating speed and rotor position using mathematical model.	Eliminates the need for additional hardware, reduces cost and maintenance requirements.
MRAC	To adjust control parameters based on a reference model to minimize the difference between actual and desired motor drive.	Provide adaptability and robustness by varying operating conditions and disturbances.
ANN	Computational model has inspired biological neural network used to approximate unknown nonlinear motor dynamics.	Captures complex, nonlinear motor behavior and enhance control performance.

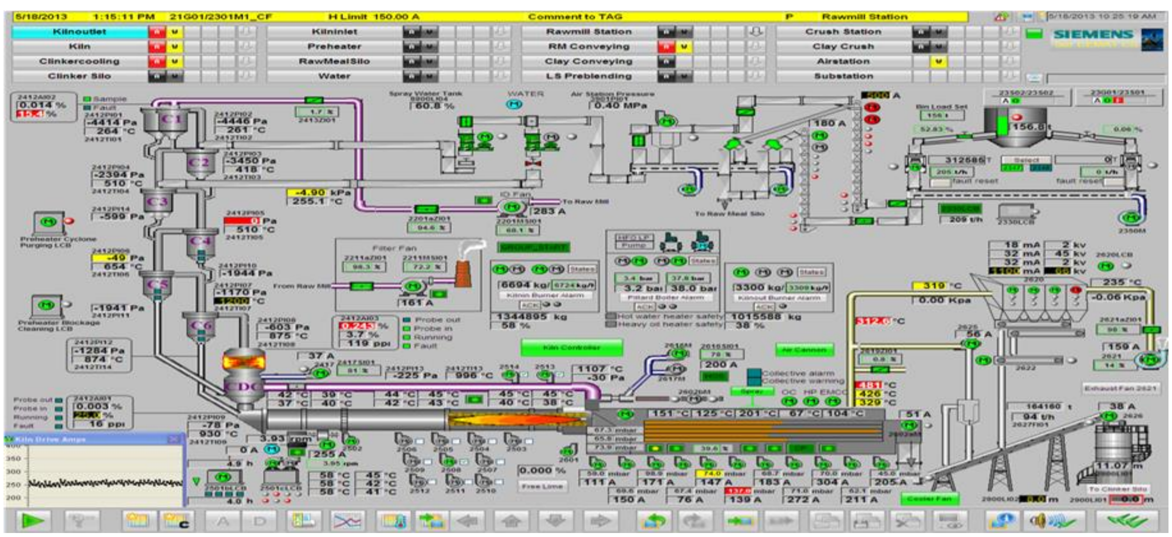

Figure D.1 Process operation and control of Cement rotary kiln from distributed control system (DCS) at Mugher cement factory.

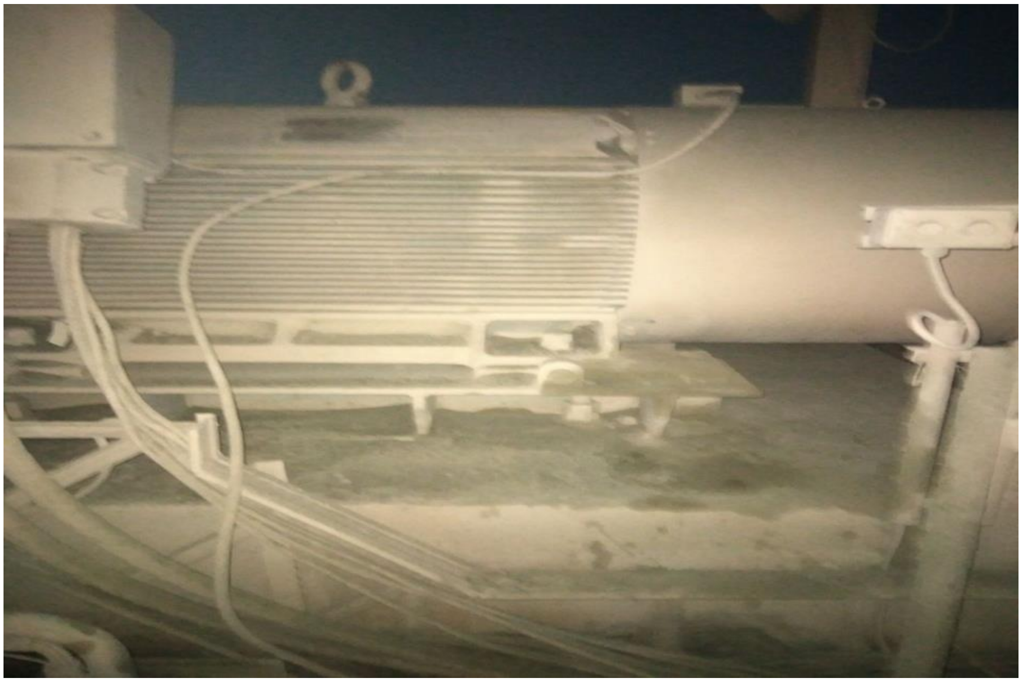

Figure D.2 Actual plant an asynchronous motor drive system for cement rotary kiln

Figure D.3 VFD controller installed with control panel of the kiln motor drive

Figure D.4 Adjustable Frequency AC Drive for kiln motor drive system