Speed Control of Induction Motor through PI-ANN Controller

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DEDEICATION

I would like to dedicate my thesis to my HUSBAND

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Due praises are given to Allah Almighty, the Creator, and the Sustainer, without whose instruction not a single minute pass. He who has given us forte and blessed us with plenteousness without any measure. There are no words which can do justice to Him. I am empowered to Read and Write only by Him, who has bestowed upon me the knowledge I carry forward.

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ABSTRACT

An induction motor is also called an asynchronous motor – it is an AC electric motor used extensively in applications. This particular type of motor is utilized in the majority of industrial and commercial electrical applications because simple, durable and affordable. Induction motors find application in domestic equipment, automobiles, IT equipment's, industries, public life equipment, transports, aerospace, defense equipment, power implements, toys, vision & sound equipment & health & medical devices. This has become possible by the following reasons; high efficiency, fast response, light weight, precise and accurate control, high reliability and maintenance free operation, construction with no brushes, high power density and small size. Induction motors found its way easily into industrial systems because of its high speed. And so, when working to achieve stability and productivity of a system it is necessary to stabilize the actual speed of the AC motor existing in the automation system with reference to the set speed and maintain a speed which is higher than the load speed. AC motor is used in a number of industrial applications where large variability in speed and torque is demand. In the past, traditional feedback controllers like PI controller have been applied extensively in industrial processes but tends to exhibit certain shortcomings in handling nonlinearity and parameter fluctuations as well as load disturbances. In response to these challenges, this thesis proposes a new solution where Proportional Integral control is combined with Artificial Neural Networks to provide accurate control of the speed of induction motors. The proposed PI-ANN controller tries to integrate the concept of PI control and ANN to adjust the control parameter when changing the parameter of motor for optimum performance is needed. The system is simulated and validated on a squirrel cage induction motor using a voltage source inverter for voltage regulation. By training the ANN to change its behavioral pattern in terms of motor speed, load condition and system dynamics the proposed method far out performs the traditionally used PI controller. Records from the simulation studies, as well as experimental findings, confirm that the proposed speed control algorithm based on the PI-ANN excels the basic PI controllers in various aspects such as lesser overshoot, quicker time response, and better stability when the electrical load is variable. This class of hybrid control strategy provides a viable solution in high-performance motor control applications and hence forms a platform for enhancing more control strategies for the induction motors in the area of intelligent control systems.

Keywords: Renewable energy, Photovoltaic system, Artificial neural network, Proportional-Integral controller, Solar tracking, Maximum power point tracking (MPPT), Power electronics, Flux control techniques, Motor control strategies, Performance optimization.

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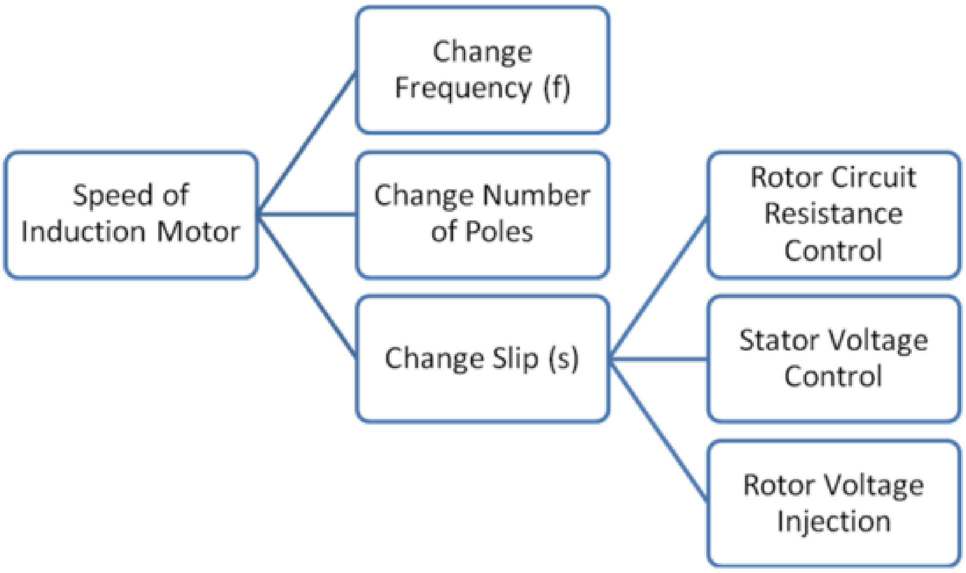
LIST OF ABBREVIATIONS

AC	Alternating Current
OC	Open Circuit
ESLL	Intra string line-to-line
ISLL	Inter string line-to-line
ODM	One Diode Model
NEPRA	National Electric Power Regulatory Authority
ANN	Artificial Neural Networks
PI	Proportional Integral Controller.

CHAPTER 1: INTRODUCTION

1.1 Background and scope:

Converting electrical energy into mechanical energy in modern industrialized countries, more than half of the total electrical energy used is converted by AC induction motors. Induction motors are widely used in industrial and domestic equipment and are responsible for more than 50% of the generated electrical energy. Single phase induction motors are commonly used in home appliances industries and control. Over the past few decades, speed and torque control of an asynchronous motor drive has become one with such an increasing concern. In this manner it has been possible to satisfy the induction-motor structural rigidity with the direct current-motor control ease and effectiveness. These changes led to replacement of the dc machines by induction motors in many applications in the last few years. Heretofore, neither ac motors were used for drives that contained variable speeds because of the ease of implementing different methods of speed control for dc motors [1]. The conventional methods of speed control of an induction motor were either too costly or too energy inefficient so that their application was restricted only up to constant speed drives. They are employed in the working of pumps, fans, compressors, mixers and agitators, mills, conveyors, crushers, machine tools, cranes, solids handlers etc. The mentioned type of electric motor is so popular because of its simplicity, relatively high reliability compared to other motors, fewer maintenance and the lowest cost. Presently, due to development of power electronics, micro controllers, DSPs etc electric drive systems have been advanced to a great extent. Earlier the concept of speed control applied to the induction motor was analytically studied considering conditions of steady state only. V/f control was the typical one for the open-loop speed control of drives with low dynamic performance demands. Controlling the speed of an induction motor is essential for various industrial applications, and several techniques are employed to achieve this. **Voltage control** involves adjusting the voltage supplied to the motor, which changes its speed and is typically used for small motors with variable torque loads like fans and pumps. **Frequency control**, achieved through Variable Frequency Drives (VFDs), varies the frequency of the supply voltage, allowing precise and efficient speed regulation over a wide range, making it popular in many industrial settings despite its higher initial cost. Another method is **pole changing**, which alters the number of poles in the motor's stator winding to change the synchronous speed, suitable for applications where discrete speed steps are sufficient, such as in multi-speed fans and pumps. Each of these techniques offers different advantages and is selected based on the specific requirements of the application.



Techniques for speed control of IM

The transition from DC motor drives to induction motor drives has marked a significant improvement in several areas, addressing many of the drawbacks associated with DC motors.

1.2 Area of Applications

Here are some key areas where speed control is extensively used:

1. Industrial machinery: Pump and fan, compressor and conveyor, and machine tool applications.
2. HVAC systems: Application of fan and blower, motor driven air conditioning and ventilation application for pumps.
3. Water and wastewater treatment: To power pumps, mixers and well-boring aerators.
4. Agriculture: The mineral is applied in the water irrigation systems, grain handling equipment, and farm machinery.
5. Automotive industry: Employed in operation of electric vehicles such as cars and transports.
6. Renewable energy systems: Used in wind mills and wave generators."
7. Domestic appliances: They are found in appearance in many devices such as refrigerators, washing machines, and vacuum cleaners.
8. Mining and extraction: In used in the industries of crusher, mill, conveyor, and pumps.

9. Petrochemical industry: Irrigation of large processes such as pumps and compressors used in the refined processes of refineries and chemicals plants.

10. Commercial and residential infrastructure: Require in elevator, escalators and automatic door.

1.3 Relevance to National Need:

A key application of variable speed control in induction motors is to satisfy the different national requirements, including energy conservation, industrialization, environmental protection, and infrastructure construction. Through the utilization of speed control in the flow rate of HVAC systems, pumps, and Industrial processes; efficiency improves, therefore lowering energy consumption costs, and minimizing the usage of traditional fossil fuels. Since this increase in energy efficiency aids in national energy security, it also helps slow the destruction of the environment through emissions of greenhouse gases. In the industrial sector of a car manufacture or production plant, accurate control of speed of manufacturing process improves the operation of the whole sector through improved productivity, quality of the manufactured product and operation flexibility. This increase in industrial efficiency fosters economic growth, employment opportunities, improvement of world competitiveness. Furthermore, speed-controlled induction motors play significant roles in transportation systems; electric trains, vehicles, and will enhance acceleration/deceleration, energy savings, pollution in towns, etc. This practice enhances sustainability in the planning and development of infrastructure within cities. In the context of renewable energy speed control optimizes the performance of Wi turbines and renewable energy systems to aid the conversion to cleaner energy to meet climate goals. In the sectors of water supply and waste disposal, high, adjustable frequency-controlled motors help pumps and compressor to adjust dynamically; resource utilization is made secure for the public while environmental conservation is enhanced. In general, research on incorporation of speed control in induction motors is important for forming the policy on managing energy at the national level, for economic development, and a sound infrastructure – all are significant reasons that make speed control the critical area in the policy. Control of speed of induction motors holds the central position in the fulfilment of national requirements with the help of the necessary figures and facts. Reducing speed in HVAC systems, pumps and further industrial usages could result in up to one third of the energy usage and that means; vast amounts would be saved and dependency on fossil fuels lessened. For example, motors in the industrial sector consume about 60% of the electricity, with minor adjustments in speed, energy consumption could be cut down by 20-30%, saving billions of dollars per year. Furthermore, there is much more precise speed regulation which makes productivity and operation versatility higher and there are investigations that prove improvement of manufacturing output by 15% and product quality by 10%. In transportation, self-synchronized speed-controlled induction motors in electric trains and vehicles will lead to improved energy efficiency by fifteen to twenty percent, help reduce urban pollution up to twenty-five percent, important since transportation contributes 13.9% of overall greenhouse gas emissions. These new scientific findings could be applied in renewable energy, specifically in turning the speed of wind turbines to capture energy more efficiently, as the speed increases the Renewable Energy Capture Rates by 5-10 % and/ or delivering on commitments made under international policies, including the Paris Accord to transition towards green energy. In addition, in context of water and waste management, speed control results in energy saving up to 50% in pumping applications thus keeping consumption in balance and supporting sustainable development. Such statistics provide a clear testimony to the crucial need to address the challenge of speed control of induction motors to help foster the achievement of national goals in efficiency of energy, economic productivity, and the state of the environment

.1.4 Advantages of Induction Motor Drives

1. **Reduced Maintenance**: In induction motors, it does not consist of brush and commutators which are the most prone components in dc motors. This translates to less frequency with which maintenance is necessary.

2. **Cost-Effectiveness:** Induction motor drives cost a little lot more initially than other conventional ac and dc motor drives but their cost is considerably low in the long run due to their long life and less maintenance requirements.

3. **Efficiency and Compactness:** Induction motors are more efficient with the fact that they tend to be lighter and smaller size than DC motors in most cases and as such they are easier to install in different systems.

4. **Self-Starting Capability**: Induction motors are self-starting, this is they start to rotate without the need for additional parts, as soon as power is applied.

5. **Versatility**: Crane and conveyor, traction system, fans, blowers, mill run-out tables, traction machine, traction vehicles, are some of the areas where induction motor drives are applied.

1.5 Challenges and Solutions in Starting Induction Motors:

Inrush Current Issue:

This is particularly so because one major deficiency with induction motors is the high inrush current, they demonstrate at start up. This initial surge of current if not controlled, poses great risk to motor windings. Starting Methods To mitigate the inrush current and protect the motor, several starting methods are employed:

1. Star-Delta Starter: This method first linking the motor windings in star form, which cuts down the voltage across each winding. After the motor reaches a certain speed, it switches to a delta configuration for normal operation. This reduces the starting current to about one-third of the current that would be drawn if the motor were started directly in delta configuration.

2. Auto-Transformer Starter: This method uses an auto-transformer to reduce the initial voltage supplied to the motor. By providing a reduced voltage at start, the inrush current is limited. Once the motor reaches a certain speed, it switches to full line voltage.

3. Reactor Starter: This method involves inserting a reactor (inductor) in series with the motor windings during startup. The reactor limits the initial current by introducing additional impedance. Once the motor reaches a certain speed, the reactor is bypassed.

4. Saturable Reactor Starter: Similar to the reactor starter, but the reactor in this method is designed to saturate at a certain current level, providing a gradual reduction in impedance as the motor speed increases, which helps in reducing the starting current more effectively.

5. Part Windings Starter: This method starts the motor using only a part of its windings initially, reducing the initial current. As the motor gains speed, the remaining windings are connected, allowing the motor to operate at full capacity.

6. AC Voltage Controller Starter: This method uses an AC voltage controller to gradually increase the voltage applied to the motor during startup, thus controlling the inrush current.

7. Rotor Resistance Starter for Wound Rotor Motor: For wound rotor induction motors, external resistors are connected to the rotor circuit during startup. These resistors limit the current and can be gradually removed as the motor accelerates to full speed.

By addressing the high maintenance requirements and improving efficiency, induction motor drives have become a preferred choice for many industrial applications. Their self-starting feature and various starting methods ensure reliable and safe operation, making them a robust solution for variable speed requirements.

1.6 Reason/Justification for the Selection of the Topic

Despite the effectiveness of the proposed control technique in speed control of Induction motors using PI controller the method is however not without some draw back. Here are some common issues that can arise when using a PI controller for speed control:

1. Limited Adaptability: The PI controller have fixed parameters that include proportional and integral constants that may usually be adjusted with the help of modeling or experimental approach. However, these parameters may not give the best results under different operating conditions, or when the motor characteristics alterations occur. Therefore, the PI controller may not provide robustness against system uncertainties or non-linearities and skewed load behavior.

2. Performance in Dynamic Systems: Looking at the features of the PI controller one may see that it is not very efficient in providing satisfactory performance in the processes that seem highly dynamic, for example, involving frequent changes in speed or load. The integral term of the PI controller can lessen the steady-state errors, on the other hand, there is an issue of overshoot or slow response in dynamic state which affects the accuracy of speed control and stability of the motor.

3. Non-linear System Response: Some of the common nonlinearity in induction motors include saturation effects, magnetic hysteresis as well as nonlinear friction. The PI controller's linear control action may not take into consideration such non-linearities and hence system performance degrades and control accuracy diminishes at high speed or under loads.

4. Sensitivity to Parameter Variations: The PI controller is subjected to temporal changes in motor parameters such as the armature resistance, inductance or mechanical inertia. If these parameters deviate greatly from those used in the controller design the performance un measures such as oscillations, instability, and sluggish response may occur.

5. Steady-State Error: Despite the presence of the integral term in the PI controller, errors at steady-state can be fully eliminated and there may be more errors pending. These include model errors, disturbances, or the fact that the gain has been limited in the controller can all lead to steady-state errors which may distort the motor ability to hold a precise value of speed reference.

6. Controller Tuning Challenges: Tuning the PI controller for optimum value can be a difficult or very time-consuming process for complex systems or systems with varying characteristics. The tangible tuning methods take some time and may need the professional knowledge of the acoustic engineer and the automatic tuning methods provide non-optimal performance in various operating conditions. When using PI controller for speed control of Induction motors these issues are relevant and should be taken into consideration. To overcome some of these limitations, in this research work, a hybrid system of using controller namely PI-ANN for controlling the speed of Induction motor will be implemented.

1.7 Motivation

The reason for selecting the topic "Speed Control of Induction Motor Using PI-ANN Controller" is multi fold: necessity and demand in industries, enhancing technology and trends, and the inefficiency of traditional motor control techniques. Here's a detailed exploration of the motivating factors: 1. There is an industrial demand for products and technologies that have higher efficiency and reliability than heretofore existing ones. Induction motors are essential parts of numerous industrial processes and widely serve as the drives of such machinery as manufacturing, HVAC, automotive, and others. These motors determine the operational cost and efficiency of industries since their effectiveness shapes the market. From the foregoing discussion it is evident that improved device controllers such as the PI-ANN controller can greatly increase the performance of these motors in as much as the speed is fine tuned to match dynamic operational requirements thereby diminishing energy use and wear. 2. Disadvantages of Conventional Control Methods Relative to the higher complexity of modern motor systems, the basic techniques of vector control and simple PI-controllers perform poorly because of the mentioned nonlinearities and parameter variations (due to temperature changes, aging, etc.) of common induction motors. These methods can be ineffective especially in contexts where system load variability be frequent or abrupt. The rationale for incorporating ANN with PI controllers lies in bridging such a challenge, given an Al system that quickly and precisely reacts to real-time variations. 3. The integration of machine learning in the task of predictive control the opportunity to use machine learning and, in particular, neural networks in the development of predictive control systems has emerged. Because of their desired architecture, they are able to extract high level features learned from data on past behaviors in motor control, therefore can be used in predicting future behaviors. This predictive ability can in turn be used to adapt the appropriate motor control parameters to prevent future failures and provide a stable and responsive and efficient operation. From this consideration, the motivation is to harness these capabilities to counterbalance the unpredictability characteristic of induction motor control. 4. The three academic and research innovations include: It is an active area of academic and research work to consider integrated approaches to control where theoretical classical control theory combines with machine learning methods. The PI-ANN controller is an example of such a combined strategy and the subject of further research concerning its enhancement and practical implementation. This topic is particularly appealing to researchers if they want to have practical impact on the development of motor control technology, which can be easily applied in industrial settings. 5. This work also discusses sustainability and Energy Consumption Concerns. It is more important than ever to increase efficiency of energy use because of increasing environmental problems and improved systems of utilizing energy efficiently. Since induction motors are massive consumers of energy, every effort must be made to ensure that they use energy and produce energy wastage and carbon emissions efficiently as possible. These goals are easily achieved with the aid of a PI-ANN system in which improved control enhancement is a highly significant reason for pursuing this subject. 6. In this chapter, technical challenges experienced by IT professionals are presented, as well as the solutions applied to overcome them. The combination with traditional PI controllers also poses technical questions, such as ANN design and training, as well as the integration of the ANNs into real-time control systems. These problems are not only an excellent answer to an intellectual challenge, as well as perfect for improving participants' competencies in working with actual control systems. The problem-solving aspect always mobilizes engineers and researchers stimulated by technical issues and creation of proposals.

1.8 Objectives

The objectives of this thesis work is to control the speed of Induction motor through PI-ANN controller.

- To design a Proportional Integral and Proportional Integral Artificial Neural Network Based Controller.
- To evaluate the performance of the proposed controller through simulations and compare it with other control techniques in terms of control accuracy.
- The PI controller and the ANN work together to control the speed of the motor, continuously monitoring the motor's speed and adjusting the controlling parameters for improved accuracy and robustness.

- Examine the findings at various reference speeds and their behaviors in Simulink.

1.9 Thesis Outline

In this thesis hybrid PI-ANN controller has been used. The novelty of this work is that speed of Induction motor has been controlled through hybrid PI-ANN. Further, this thesis is organized as follows:

Chapter 1: Introduction

This chapter introduces the research topic, presents the background and motivation, states the objectives, and outlines the structure of the thesis.

Chapter 2: Literature Review

This chapter reviews the relevant literature Induction motors and various speed control techniques. It provides a comprehensive understanding of the existing research and identifies gaps that this thesis aims to address.

Chapter 3: Proposed Methodology

This chapter presents the mathematical modeling of the Induction motor. Also, it focuses on the design of the PI-ANN controller for speed regulation of the Induction motor. It explains the principles behind the PI-ANN control algorithm and outlines the design methodology.

Chapter 4: Simulation and Results

This chapter describes the implementation of the designed controller in a hardware prototype. It presents the experimental setup, test procedures, and analyzes the performance of the proposed control system. A comparative study with conventional control techniques is also conducted.

Chapter 5: Conclusion & Future Scope

This final chapter summarizes the key findings and contributions of the thesis. It also suggests possible avenues for future research.

CHAPTER 2: LITERATURE REVIEW

This chapter presents a comprehensive review of the literature related to Induction motors. The purpose is to explore the existing knowledge and research efforts in the field of Induction motors, including their construction, operating principles, control techniques, and applications. The literature review aims to identify the gaps, challenges, and opportunities for further research in this area.

2.1 Induction Motors

Induction motors also termed as asynchronous motor comes second in electric motor ranking in terms of utilization and is most popular for use in industries. It is for these reasons that they are so widely used; they are easy to manufacture, long-lasting and inexpensive. Induction motors work by the concept of electromagnetic induction. The basic operation involves: Stator: The fixed section of the motor in which there are located coils which are provided with the AC in order to generate a rotating magnetic field. Rotor: The conductor or the secondary part which is induced by the magnetic field embracing the stator and rotates inside it. The rotor does not get supplied with electric power through power supply but by electromagnetic from the stator.

Figure 3: Induction Motor

Types of Induction Motors

Three phase induction motors that are widely used because of their reliability and efficiency are mainly classified according to the type of rotor. Here are the main types of induction motors:

The squirrel cage induction motor: These are the simplest of the induction motors which are named depending on the physical appearance of the rotor that resembles a squirrel cage. Construction: The rotor is cylindrical laminated steel core with parallel bars of aluminum or copper inserted in the surface are short circuited by rings at the both ends. This design minimizes the number of parts in a design while enhancing durability hence improving manufacturing processes. Operation: As we know the stator magnetic field rotates then the current produced in stator induce current in the rotor bars when the field intersects the rotor. When the current of these coils and the magnetic field interact, the rotor winds up being forced to turn. Advantages: They are construction ally simple in design, have a low tendency towards getting spoiled, and are inexpensive as compared to the other motors. Some of them include that they are highly enduring and strongly built. Applications: They are preferred in HVAC systems, pumps, fans, compressors and most small industrial applications up to small machinery where speed variation is unnecessary or occurs only when the equipment is loaded or blocked.

Wound Rotor Induction Motors are also known as Slip Ring Induction Motors. These motors are provided with a rotor which is similar to the squirrel cage, but contains windings which are connected to external circuits through slip rings. Construction: Same as the stator it has windings that are placed in slots in its structure which makes up the rotor. These windings are short circuited at slip rings fitted on the motor shaft and consist of both independent and series. Another design variant is the slip ring, through which external resistors or controllers, for example, can be connected brushes. Operation: The presence of slip rings and brushes enables the connexons of external resistances to the rotor circuit to enable better control of the motor speeds and torques. Advantages: Some of the features of wound rotor motors include very high starting torque although at higher current, speed control is by external resistance, they are ideal for heavy loads. Applications: Suitable for use in crane, elevator and hoist equipment, or for any application where the motor may be loaded heavily at start or where alternating load is excessive or where the motor will be frequently started.

Dual-Speed Induction Motors These motors are designed with two speeds and this is a subtype which can be present in novel cage and winding rotor machines. Construction and Operation: They both have two stator windings or a stator winding configuration that enables varying the number of poles that are supplied this alters the speed of the motor. Applications: Applied in those applications where the fan is needed to operate under different conditions, for example, in some fan systems the required airflow rates are different.

Multi-Speed Induction Motors These motors are dual and multiple speed motors with variations set by modifying the pole or winding connexons. Applications: Of frequent use in various large-scale industries where several processes need to be carried at varying rates.

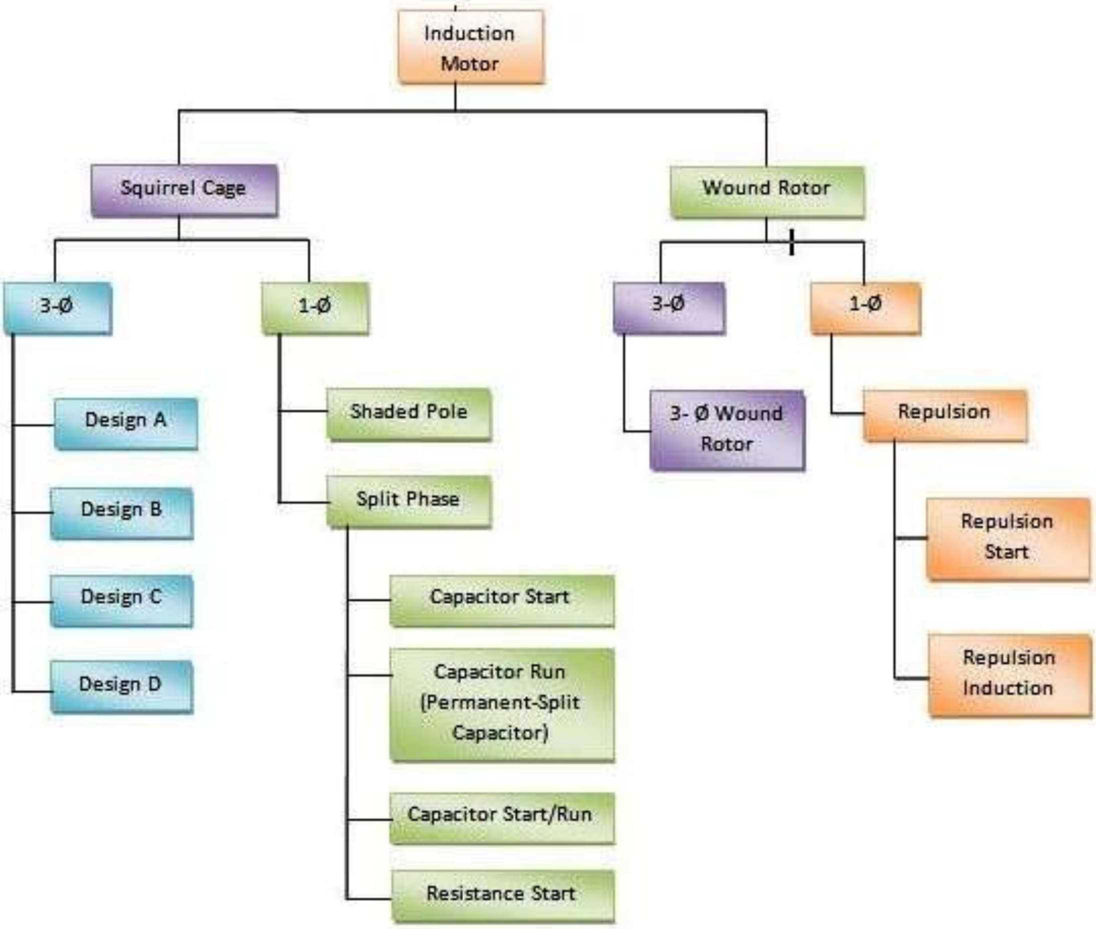


Figure 4: Types of Induction Motors

2.2 Squirrel Cage Induction Motors:

Compared with other types of motors, the squirrel cage induction motor, a typical AC motor, is appreciable for its ruggedness and simplicity. This motor is named by its rotor type which is known as squirrel cage; it has conductive bars normally constituted of aluminum or copper placed in a round pattern, and connected to the two ends of the rotor through rings that join the bars electrically. The stator which encloses the rotor consist wound coils which, when supplied with AC current produce a revolving magnetic field. This field create an electromagnetic force in the rotor bars which gives rise to current which forms a field in opposition to that of the stator. The interaction of these field produces torque and hence the rotor rotates. Squirrel cage motors are mostly affected by the frequency of the AC power supply, as well as its number of poles; the stator's magnetic field usually has a slightly higher speed than the rotor, which refers to slip. Rear slip is important in creating torque and for this reason this slip is necessary. Despite the fact that squirrel cage motors are actually old-fashioned devices, they are highly valued today due to their reliability, efficiency, and relatively low maintenances needs thanks to the fact that the motors do not contain brushes or commutators.

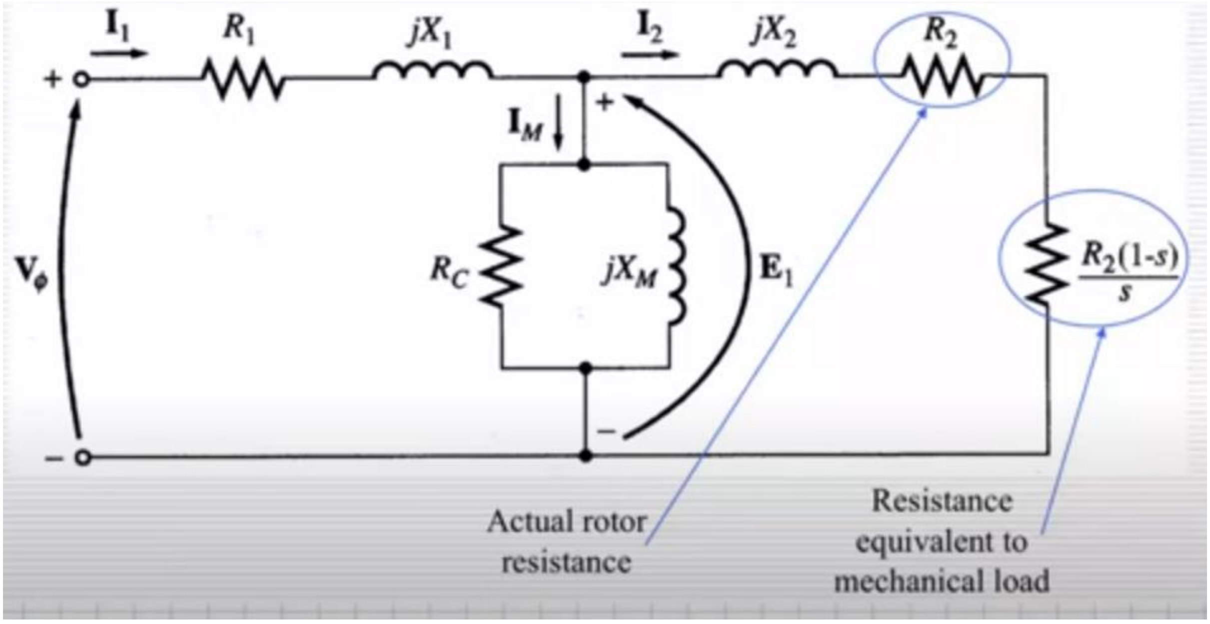


Figure 5: Equivalent Circuit of Separately Excited DC Motors

2.2.1 Working Principle of Induction Motor

The concept of operation of a squirrel cage induction motor is based on several electromagnetic concepts and the basic connection between the electric currents and magnetic fields. Here, I will explain the working of these motors in terms of operational structures and the formulas which control their functions.

Stator: It is the static component of the motor; comprises coils wound on laminated steel chips. These coils are energized with an AC supply this is because a transformer that is used to produce direct current (DC) will have its primary coils energized with a dc supply.

Rotor: Located inside the stator, the rotor is comprised of bars constituted out of conductive material connected with the help of metal rings at both ends thus creating a kind of cage.

Generation of the Magnetic Field Stator Windings and Rotating Magnetic Field: The AC current through the stator windings produced individual magnetic fields, because of the physical and electrical connection of the windings, the stator windings produce a rotating magnetic field The rate, which this field rotates is called synchronous speed. (Ns), is determined by the supply frequency (f) and the number of poles (P) in the motor:

Using figure 5,

Rotor current induction

Electromagnetic Induction: This phenomenon conforming to Faraday's Law, the magnetic field conducted by stator generates an induced EMF in the bars of rotor as these are placed in relative motion to the magnetic field.

$$E = -N\frac{d\Phi}{dt}$$

The EMF E induced in the rotor is proportional to the rate of change of the magnetic flux (Φ) and can be expressed as: where N is the number of turns (conductors) in the winding and $d\Phi/dt$ gives the rate of change of magnetic flux.

Production of Torque: Stator currents create EMF which induces current in the rotor bars and these currents create their magnetic field. These interactions and when applied to the stator, create a rotating magnetic field that in turn generates torque. The torque (T) developed by the motor can be calculated using the following general expression:

$$T = \frac{P \times f \times \Phi_{max} \times I_{max} \times \sin(\theta)}{2\pi \times N_s}$$

where:

- P is the number of poles,
- f is the frequency of the AC supply,
- Φ_{max} is the maximum magnetic flux per pole,
- I_{max} is the maximum rotor current,
- θ is the phase difference between the rotor current and the stator magnetic flux.

where: Here the symbols used are P the number of poles, f the frequency of the AC supply, Φmax the maximum magnetic flux per pole, $Imax$ the maximum rotor current. θ is the phase difference between the rotor current and the stator magnetic induced flux.

Slip Calculation: Slip (s) can be described as the rate of actual rotor speed (Nr) to the synchronous speed (Ns) which is in terms of fraction or in percentage:

$$s = \frac{N_s - N_r}{N_s}$$

Slip is very vital in an induction motor since it is proportional to the induced EMF in the rotor. Assuming that no slip occurs, there would be no EMF and hence no torque, which is another important finding.

2.3 Speed Control Techniques for Induction Motors

2.3.1 Proportional-Integral-Derivative (PID) Control

PID control is a widely used technique for speed control in Induction motors. Elgendy and Atkinson [7] also developed a direct torque control strategy for controlling the Induction motors using the PID control. The authors analyzed enhanced dynamic response and motor efficiency with reference to varying levels of solar irradiation.

2.3.2 Fuzzy Logic Control

Fuzzy logic control has been applied to speed control of Induction motors. Mazidi and Shadmand [8] Fuzzy control was explored on a Induction motor used in water pumping use, in the comparative study. The fuzzy logic control was well emphasized for interacting with speed control and its dependence on solar energy supply in their study.

2.3.3 Model Predictive Control (MPC)

Model Predictive Control (MPC) has shown promising results in speed control of Induction motors. Xu et al. [9] put forward a model predictive control approach for an induction motor in an effort to decrease the response time and increase the energy utilization efficiency.

2.3.4 Adaptive Control Techniques

Adaptive control techniques have been utilized to address uncertainties in solar energy availability and load variations. Li and Lin [10] presented a robust adaptive speed control method for Induction motors, which demonstrated improved performance and stability.

2.3.6 Optimization Algorithms

In the past theories of optimization have been used in improving the speed control of Induction motors. Shah and Savsani [11] developed a firefly algorithm for the control of speed of Induction motors and improved it with a feedback technique to deal with load variation.

2.3.7 Hybrid Control Approaches

Studies have also been conducted on a mixed control strategies i.e., two or more control methods for speed control of Induction motors. Ullah and Hong [12] discussed another control technique called, fuzzy proportional-integral control which provided improved performance, and stability.

2.3.8 Sliding Mode Control Sliding mode control

has been explored for the speed control of Induction motor drive systems. Ouali and Kasraoui [13] proposed a sliding mode control technique, achieving precise speed control and robustness against parameter variations.

2.4 Comparative Studies and Review Articles

Review articles and comparative studies are essential in synthesizing the current developments in the speed control of Induction motors. Improved adaptive perturb and observed maximum power point tracking was implemented in the solar powered Induction motors by Abhilash and Agelidis [14]. Comparative analysis of various control techniques for Induction motor drives, based on efficiency, robustness and performance under various conditions, was carried out by Bhosale and Sonawane [15]. About Five Important Findings and Research DirectAnimation algorithms have been employed to enhance the speed control of Induction motors. Shah and Savsani [11] proposed a firefly algorithm-based control strategy for Induction motors, optimizing their speed control by adapting to changing load conditions.

2.5 Key Insights and Research Trends

Several important findings and trends in the literature are identified from the review. Therefore, in this paper, Ho and Yaacob [16] presented a detailed survey and a comparative analysis of the MPP tracking methods to be used for the SP-IM applications together with their opportunities and challenges. Speed control was also described by Jain and Maheshwari [17], in their Induction motor drives for various purposes. Mellit and Kalogirou [15] discussed integration of artificial intelligence techniques; fuzzy logic and neural networks in photovoltaic system used in their study Induction motor speed control by solar energy by adapting to changing load conditions.

CHAPTER 3: PROPOSED DESIGN

The current chapter is based on the proposed design of research. In this chapter, a proposed methodology has been outlined related to the speed control of an Induction motor using a PI-ANN controller. In this approach, an Artificial Neural Network is used for estimating the parameters Kp and Ki of the PI controller. The research work is focused upon developing an effective adaptive control strategy for controlling the speed of an Induction motor. This chapter outlines the research design, system modeling, control architecture, and MATLAB/Simulink simulation setup to validate the proposed methodology.

3.1 The proposed design (An Overview)

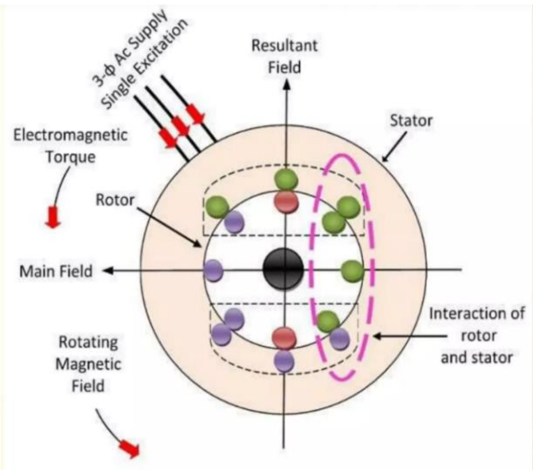
The theoretical analysis, simulation, and validation by experimentation is the research design for the current study. A comprehensive literature review has been conducted to gather all relevant information regarding Squirrel cage Induction motors and PI-ANN control methods. Based on the insights obtained from the literature review, a system model will be developed in MATLAB/Simulink that would indicate the simulated behavior of the Induction motor under the influence of the proposed PI-ANN controller.

The purpose is to design ANN-based parameter estimation process, and to evaluate its performance as compared to the conventional PI controllers.

3.2 System Modeling

3.2.1 Squirrel Cage Induction Motor Model

An induction motor works on the phenomenon of electromagnetic induction. An induction motor is most commonly utilized and has different applications, such as Industrial machinery, mechanical industries and domestic appliances.



An overview of its working and key components is stated below:

3.2.2. How It Works:

1.**Stator:**

The stationary part of the motor is known as stator and it carries coils of wire joined to an AC power supply. When AC voltage is provided to the stator, it creates a rotating magnetic field.

2.**Rotor**: The rotor is the rotating part of the motor and is located inside the stator. The rotor is typically constructed of a laminated iron core with conductive bars (usually made of aluminum or copper) embedded in it. These bars are joined at both ends by end rings, forming a narrow, closed loop known as a "squirrel cage" (hence the name "squirrel cage rotor").

3.**Electromagnetic Induction:** An electric current in the conductive bars of the rotor is induced, when the rotating magnetic field from the stator interacts with the rotor According to Faraday's Law of Electromagnetic Induction, this current produces its own magnetic field that opposes the stator's magnetic field.

By Faraday's Law of Electromagnetic Induction, a change in a conductor's magnetic environment inducts an electromotive force in the conductor. This basic phenomenon describes electric currents generated by changing fields. A more detailed explanation is given below:

3.2.3. Faraday's Law of Electromagnetic Induction:

Basic Concept:

•**Altering the Magnetic Field:** If the magnetic field around a conductor changes, an electric current is induced in the conductor. This can occur if the magnetic field strength changes, if the conductor moves through a magnetic field, or if the magnetic field itself moves relative to the conductor.

2. Mathematical Formulation:

- Faraday's Law can be expressed mathematically as:

$$\mathcal{E} = -\frac{d\Phi}{dt}$$

where:

  - $\mathcal{E}$ is the induced EMF (voltage).
  - $\frac{d\Phi}{dt}$ is the rate of change of magnetic flux (Φ) through the conductor.
  - The negative sign indicates the direction of the induced EMF (Lenz's Law).

3. Magnetic Flux:

- Magnetic flux is defined as:

$$\Phi = B \cdot A \cdot \cos(\theta)$$

where:

- B is the magnetic field strength.
- A is the area of the conductor through which the magnetic field lines pass.
- θ is the angle between the direction of the magnetic field and the normal (perpendicular) to the surface area of the conductor.

4.Lenz's Law (Discussion):

As an integral part of faraday's law, Lenz's Law states that the direction of the induced EMF and current will be opposite to the change in magnetic flux that created it. Faraday's Law is an emblem of electromagnetism and has vast applications in electrical engineering and technology, while Lenz's law ensures conservation of energy and discusses the reason of the negative sign that appears in the mathematical formulation.

5.Torque Production:

The relation between the stator's rotating magnetic field and the magnetic field induced in the rotor produces a force that causes the rotor to turn. This rotation continues as long as the stator's magnetic field rotates and the motor is connected to the power supply.

3.2.4. A discussion on the Dynamic Model of Induction Motor:

The dynamic behavior of an induction motor can be indicated by the voltage and the torque which are varying with time factor.

Assumptions for Simplification

- The rotor is short-circuited (no external electrical supply to the rotor).
- The induction motor is symmetric (all phases have identical properties).
- Magnetic saturation and core losses are neglected in the basic derivation (but can be added later for more accuracy).
- The system is balanced (no zero-sequence components).

3.2.3. Stator and Rotor Voltage Equations in Three-Phase Form

In the stationary reference frame, the voltage equations for the stator (A, B, C phases) are:

$$v_a = R_s i_a + \frac{d\lambda_a}{dt}$$

$$v_b = R_s i_b + \frac{d\lambda_b}{dt}$$

$$v_c = R_s i_c + \frac{d\lambda_c}{dt}$$

Where:

- v_a, v_b, v_c are the phase voltages.
- i_a, i_b, i_c are the phase currents.
- $\lambda_a, \lambda_b, \lambda_c$ are the flux linkages.
- R_s is the stator resistance.

Similarly, the rotor voltage equations (considering the rotor is short-circuited and hence, the rotor voltages are zero) are:

$$0 = R_r i_{a_r} + \frac{d\lambda_{a_r}}{dt}$$

$$0 = R_r i_{b_r} + \frac{d\lambda_{b_r}}{dt}$$

$$0 = R_r i_{c_r} + \frac{d\lambda_{c_r}}{dt}$$

Where:

- R_r is the rotor resistance.
- $i_{a_r}, i_{b_r}, i_{c_r}$ are the rotor phase currents.
- $\lambda_{a_r}, \lambda_{b_r}, \lambda_{c_r}$ are the rotor flux linkages.

4. d-q Transformation (Park's Transformation)

To simplify the analysis, the three-phase stator and rotor quantities are transformed into a two-axis rotating reference frame (d-q frame). The d-q transformation converts three-phase quantities into two orthogonal components, making the analysis easier:

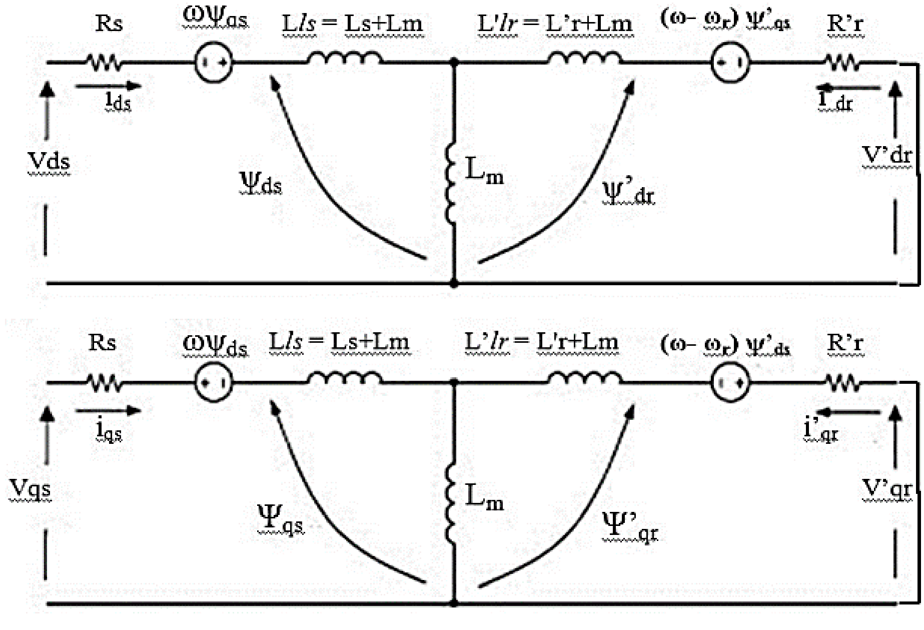
$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Where:

- i_d and i_q are the direct and quadrature axis currents.
- θ is the angle of the rotating reference frame (usually the electrical angle of the rotor).

This transformation applies to both stator and rotor quantities. The zero-sequence component i0 is zero in a balanced three-phase system and can be neglected.

The differential equations that belong to dynamic analysis of induction motor are so sophisticated, that with the change of variables the complexity of these equations decrease converting poly phase winding to two phase winding (q-d). In other words, the stator and rotor variables like voltage, current and flux linkages of an induction machine are transferred to another reference model which remains stationary. In stator inductance is the sum of the stator leakage inductance and magnetizing inductance (Lls = Ls + Lm), and the rotor inductance is the sum of the rotor leakage inductance and magnetizing inductance (Llr = Lr + Lm). From the equivalent circuit of the induction motor in d-q frame, the model equations are derived.



The flux linkages can be achieved as:

$$\frac{1}{\omega_b}\frac{d\psi_{qs}}{dt} = v_{qs} - \frac{\omega_e}{\omega_b}\psi_{ds} - R_s i_{qs}$$

$$\frac{1}{\omega_b}\frac{d\psi_{ds}}{dt} = v_{ds} - \frac{\omega_e}{\omega_b}\psi_{qs} - R_s i_{ds}$$

$$\frac{1}{\omega_b}\frac{d\psi_{qr}}{dt} = v_{qr} - \frac{(\omega_e - \omega_r)}{\omega_b}\psi_{dr} - R_s i_{qr}$$

$$\frac{1}{\omega_b}\frac{d\psi_{dr}}{dt} = v_{dr} + \frac{(\omega_e - \omega_r)}{\omega_b}\psi_{qr} - R_s i_{dr}$$

By substituting the values of flux linkages in the above equations, the following current equations are obtained as:

$$i_{qs} = \frac{(\psi_{qs} - \psi_{mq})}{X_{ls}}$$

$$i_{ds} = \frac{(\psi_{ds} - \psi_{md})}{X_{ls}}$$

$$i_{qr} = \frac{(\psi_{qr} - \psi_{mq})}{X_{ls}}$$

$$i_{dr} = \frac{(\psi_{dr} - \psi_{md})}{X_{ls}}$$

Where ȥmq and ȥmd are the flux linkages over Lm in the q and d axes. The flux equations are written as follows:

$$\psi_{mq} = X_{ml}\left(\frac{\psi_{qs}}{X_{ls}} + \frac{\psi_{qr}}{X_{lr}}\right)$$

$$\psi_{md} = X_{ml}\left(\frac{\psi_{ds}}{X_{ls}} + \frac{\psi_{dr}}{X_{lr}}\right)$$

$$X_{ml} = \frac{1}{\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}}$$

In the above equations, the speed wr is related to the torque by the following mechanical dynamic equation as:

$$T_e = T_{load} + J\frac{d\omega_m}{dt}T_{load} + \frac{J2}{p}\frac{d\omega_r}{dt}$$

Then w_r is achievable from above equation,

where:

p: number of poles.

J: moment of inertia (kg/m2).

These equations collectively describe the dynamic behavior of an induction motor in the d-q reference frame, capturing the interactions between the electrical and mechanical domains. This model is foundational for control strategies such as vector control (field-oriented control) and direct torque control, which are commonly used in modern motor drives to achieve precise and efficient performance.

Simulink Model:

The following parameters of the induction motor are chosen for the simulation studies:

A 1 HP, 3-phase, 415V, 50Hz, 1440 rpm star-connected induction motor has the following parameters: Stator resistance ($R\_s = 10.1, \Omega$), Stator reactance (X_s = 15.81 Ω), Rotor resistance referred to the stator (R_r' = 9.8546 Ω), Rotor reactance referred to the stator (X_r' = 15.81 Ω), and Mutual reactance (X_m = 245.8954 Ω).

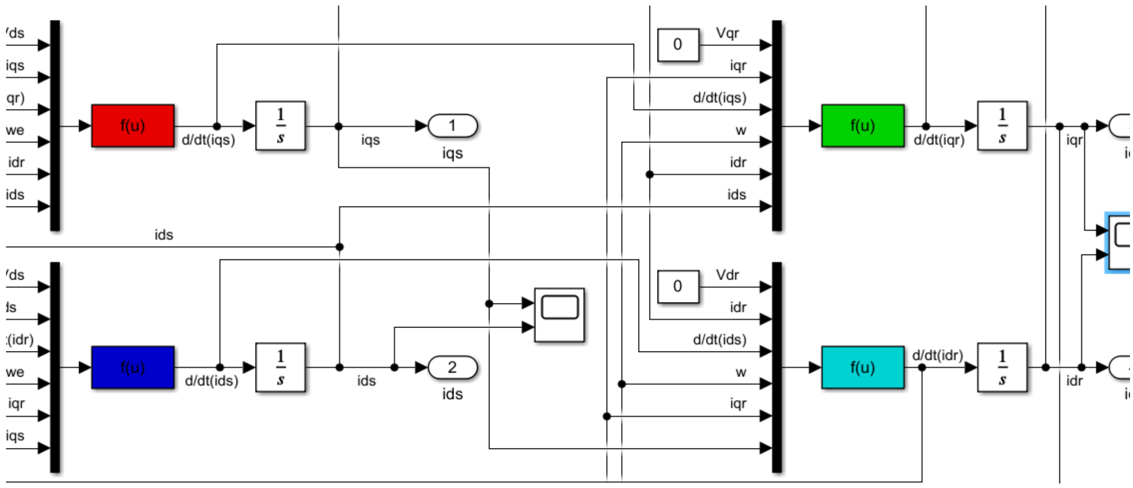


Figure 4: A Simulink Model of the Dynamic Model of Induction Motor: Motor Model

The Simulink model for speed control of a dynamic induction motor is designed to simulate and analyse the performance of an induction motor under varying speed conditions. The model consists of several key components: The induction motor model consists of several interconnected blocks representing different aspects of the motor's dynamics. The Motor

Equations Block models the stator and rotor voltage equations, flux linkage, and electromagnetic torque equations to capture both transient and steady-state behaviour. The question is that what are the inputs and outputs of this phenomenon? So, the Inputs usually involve the stator and rotor voltages, while outputs are considered the motor currents and flux linkages, which are significantly important for torque and speed calculations.

The Torque Calculation Block carries the current and flux linkages from the motor equations to evaluate the electromagnetic torque. This later affects the motor acceleration and deceleration processes. The Speed Calculation Block examines the rotor's speed by integrating the motor's acceleration, derived from the differences between the electromagnetic and load torque. To regulate the motor speed, Feedback mechanisms, such as PI controllers are used. The Speed Control Loop integrates the motor speed with a reference input and adjusts input voltage or frequency using a PI controller to acquire the desired speed despite load variations. The Load and Inertia Blocks simulate the external mechanical load and system inertia, allowing for the analysis of their effects on motor performance. Finally, the Output and Visualization Block provides data visualization for parameters like speed, torque, and currents, aiding in performance analysis.

Overall, this Simulink model provides a comprehensive platform for studying the dynamic behavior of an induction motor, including the impact of speed control strategies on motor performance under different operating conditions.

3.4 General Designing of Controller

3.4.1 PI Controller

A Proportional-Integral (PI) controller is a kind of feedback control system that is commonly used in engineering and automation to regulate and stabilize processes. It is a combination of two control actions: proportional control and integral control.

- **Proportional Control:**

Numerically, the Proportional Control Action is represented as this equation below:

$$u(t)=Kp \cdot e(t)$$

Wherein, u(t) refers to the control signal. It is corrective action for the system at time t.

Kp is referred to as the proportional gain. This denotes the control action strength. It's a constant, scaling up the error signal.e(t) denotes the error at time t. Here, the setpoint value is subtracted from the process variable and is found as:

$$e(t)=SP-PV(t)$$

(SP: setpoint value, PV: process variable).

The proportional control action delivers a control signal which directly varies with the error. It reduces the steady state error, although it is not capable of completely nullifying the steady-state error and is particularly true for systems that experience different forms of disturbances.

In a proportional controller, the output control signal is proportionally related to the difference between the desired set point and the measured process variable. The error is thus the difference between the desired value and the current process variable value.

- **Integral Control:**

  The integral control action is mathematically represented as:

$$u(t) = \mathrm{Ki} * \int_0^t \mathrm{e}(\tau)\mathrm{d}\tau$$

where:

K_i is the integral gain, a constant that determines the strength of the integral action.

$e(\tau)d\tau$ is the integral of the error from the start of control (time t=0) until the current time. The integral control action continuously corrects the control signal based on the accumulated error. This helps eliminate the steady-state error and enables the system to reach the setpoint accurately, even in the presence of disturbances.

PI combines the proportional and integral control actions, such that it experiences a response time faster than the case of I-only control; besides, there is elimination of system fluctuation in the case of PI control. System return to the setpoint is accomplished in addition to eliminating steady state error by using the PI control. Yet, it still experiences 50% slower response times compared with P-only control. With the aim to enhance its response time, PI control is often associated with the D-only control to establish a PID controller.

The PI controller's behavior is mathematically represented as follows:

$$m(t) = K_p\, e(t) + K_i \int e\,(t)$$

where:

m(t) is the controller output,

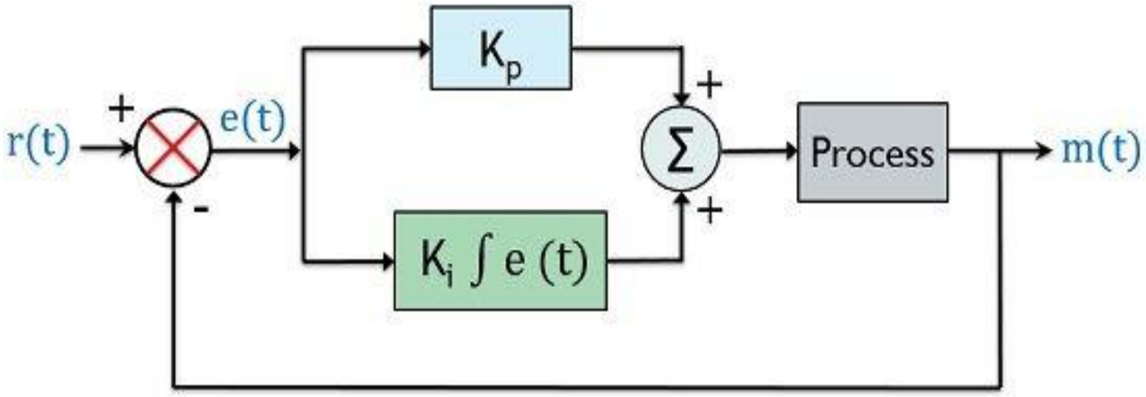


Figure 12: Block Diagram of PI Controller

The PI controller can be viewed as a simplified PID controller with a zero-derivative term. It is also a combination of the P-only and I-only control equations. The P-only control acts when the system is not at the setpoint (error is non-zero), while the I-only control operates when the system is at the setpoint (error is zero). The integral action acts as a bias term in the P-only control. A graphical representation of the PI controller output for a step increase in input at time is shown in Figure 5. The graph combines the qualitative behaviors of P-only and I-only control.

Overall, the PI controller is widely used in control systems due to its simplicity, effectiveness in reducing steady-state error, and ability to provide faster response compared to I-only control. When faster response is required, combining PI control with derivative control (PID) can further improve the system's dynamic performance.

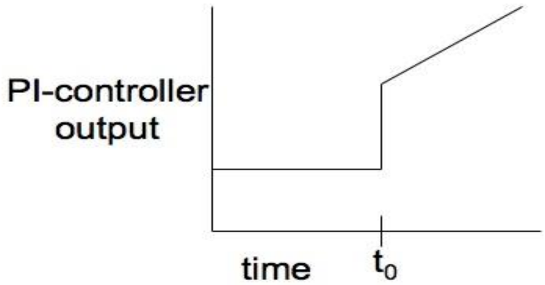


Figure 13: Dynamic Performance of PI Controller

3.4.2 PI Controller in frequency domain:

Transfer Function of a PI Controller:

A Proportional-Integral (PI) controller has the following time-domain equation:

$$u(t) = K_p e(t) + K_i \int e(t)\, dt$$

Taking the Laplace transform:

$$U(s) = K_p E(s) + \frac{K_i}{s} E(s)$$

The transfer function of the PI controller is:

$$G_{PI}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s}$$

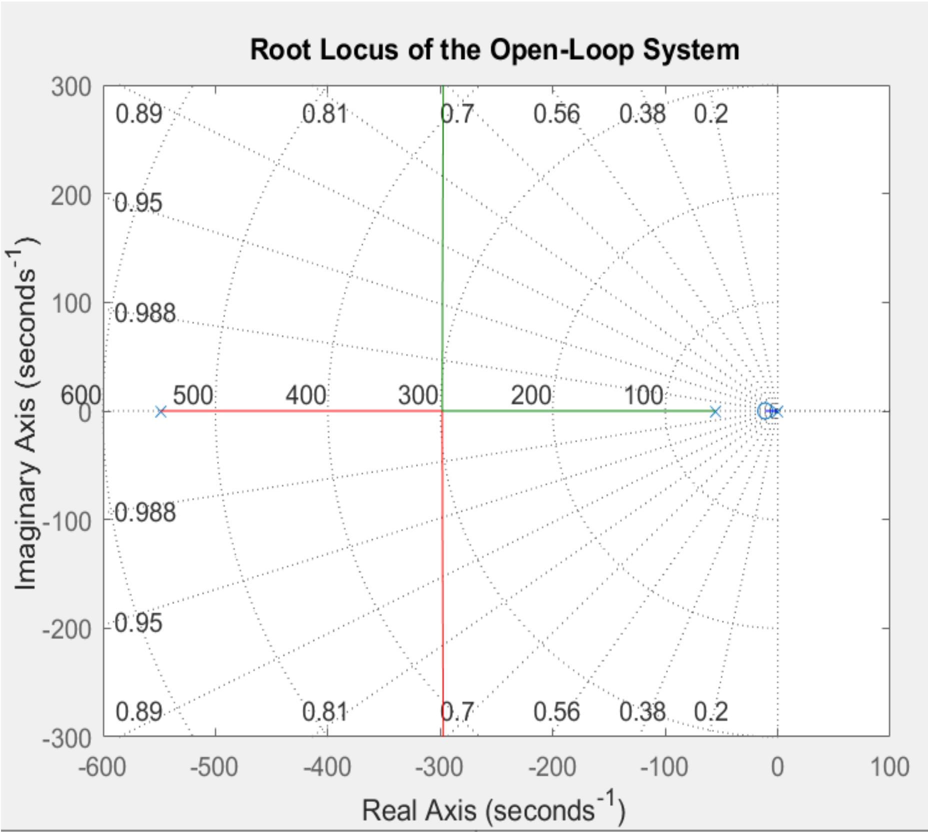
Combined Transfer Function:

The open-loop transfer function is:

$$G_{\text{OL}}(s) = G_{PI}(s) \cdot G_{\text{motor}}(s)$$

$$G_{\text{OL}}(s) = \left(\frac{K_p s + K_i}{s}\right) \cdot \frac{K_T}{(Js+B)(Ls+R)}$$

$$K_p = \frac{2\zeta\omega_n}{K_T} \qquad K_i = \frac{\omega_n^2}{K_T}$$



System	Stable
Poles	-548.8889, -55.5556
Ki	8.84
Kp	0.79
Rise Time	0.2622 sec
Transient Time	0.5288 sec
Overshoot	0.00%
Peak Time:	1.0468 sec

3.4.3 Artificial Neural Networks

Neural networks (NNs) are systems which compute connected by links taking into account information that is similar to the basic principles of the functioning of the human brain. As for the control of speed of the induction motors, the use of neural networks can be advantageous in making the input variables learn the nonlinear dynamics between them and the corresponding motor control actions. Here the reader can find the information about the application of neural networks.

Input Layer: The input variables of the motor operation like voltage, current, rotor speed and torque are some of the input variables received by a neural network. These inputs can also comprise of error values between the actual speed and a desired speed.

Hidden Layers: The use of one or many hidden layers is desirable in the network so that the needed complex mappings of inputs to outputs can be learned. These layers are made of neurons which performs activation functions on weighted sum of input. The number of neurons and layers depends on the threshold of the supreme application problem.

Output Layer: The output from the neural network contains the control signals for changing the speed of the motor in most cases. It could be a direct call to change the frequency of voltage to the motor or improve other control parameters that are within a Voltage Source Inverter (VSI).

Learning Phase: It is trained with the past data of the motor operation in different circumstances. The training requires organizing the weights and bias of the network to affect the lowest forecast error about the data, and normally involves the back propagation process. Bagging as an Integration in Neural Networks Bagging also known as Bootstrap Aggregating, is an ensemble learning technique intended for reducing the variance of learning algorithms. This is where more than one model is trained on separate sections of the main data set then the classification is arrived at by taking a mean of the individual predictions. Here's how bagging can be integrated with neural networks for induction motor speed control:

Data Preparation: The speed, voltage, torque, etc., that is available, is randomly divided into several partitions, and possibly, some partitions share elements (bootstrap analysis).

Training Multiple Models: Neural networks, different from one another, are trained on each kind or type of data. Each model is trained to predict the motor speed control parameters separately, and hence, different aspects of the data variation.

Aggregation: Thus, joining multiple models is performed at the end of the training phase, from where a single average, the output, is given. This aggregation also cuts down on the variations with the prediction hence strengthening the control against overfitting and noises within the data.

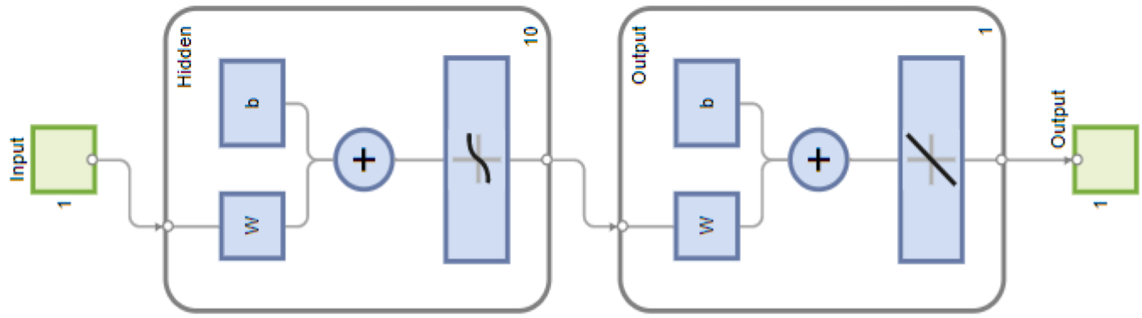


Figure 14: Architecture of ANN

Applying ensemble methods like bagging with neural networks to control the speed of induction motors requires coming up with other models (sub-models) which work from different datasets. This approach enhances the strength and reliability of the system that can accomplish the task accurately.

In this case, let me describe how this can be done in practice with the 15,000-sample dataset by splitting it into fifteen sets, and training a neural network on each.

Step 1: Data Preparation and Division Dataset Collection: The starting point involves having a propensity sample of 15000 samples with those measurement inputs that are fundamental in regulating the induction motor including speed, voltage, current, load torque and temperature.

Preprocessing: Normalization: Normalize the features to avoid letting any of the features swamp the input to the neural networks because of the size of its features.

Error Calculation: Find the difference between the desired speed and actual speed, which is to be taken as one of the input variables of prediction of the control action needed.

Dividing the Data: Split the dataset into fifteen overlapping subgroups of the sample size using bootstrap sampling technique. Under bootstrap sampling, each subset is constructed from the dataset by employing random sampling with replacement, thus, some of the samples can be included in more than one subset or none at all.

Step 2: Model Construction Neural Network Architecture: In other words, each neural network could have the same type of topology, but each one would be different because it is optimized on a particular control task. An example architecture, and often the simplest or starting point is an input layer, one or more hidden layers and an output layer.

Input Layer: SIZE is the number of the input features (speed error, voltage, current, etc.). **Hidden Layers:** Several hidden layers, though with many neurons to handle interactions between variables. Other popular ones are ReLU or tanh activation function is commonly used.

Output Layer: Provides the control signals required to change velocity of the motors; usually the modulation signals for a VSI.

Network Configuration: It is common practice to use an identical configuration on each of the networks, so any variation is due to the difference in data, not structure.

Step 3: Training the Networks Backpropagation: We should use backpropagation to train each of the networks. Localize the weights and the biases to make a local minimum of a loss function which is defined mostly as a mean squared error for the difference between the predicted control actions and the actions that were required to achieve the required speed. **Regularization Techniques:** In order to reduce overfitting degree of the respective networks, apply dropout, L2 regularization or early stopping mechanisms, so that all of them are successful in unseen data. Inputs, processes the information, and generates the appropriate control signal to adjust the motor speed.

Training Epochs and Batches: E = Depending on the size of networks and the computational demands of each network, random a number of epochs for training, Thus, batch size = n/ X where n= number of samples.

Violations of validation loss must then be used to adjust these parameters correctly.

Step 4: Aggregating Model Outputs Model Aggregation: Subsequent to training, apply each network to predict the control signals given new input data. Generalize these decisions in arriving at the final decision. In general, aggregation is usually done by computing the average output values of all the networks.

Variance Reduction: This step unbalances the prediction variance, as the averages of multiple predictions are normally less influenced by a single bias of some particular networks.

Step 5: Implementation and Testing Integration into Control System: Introduce the ensemble model into the control of the induction motor; The ensemble provides the final control signals that control the VSI to change the motor speed.

Real-Time Testing: Use the ensemble model in one real operating condition to determine how it would work in operational existence. This means that the actors can fine tune the ensemble depending on the results of the performance assessment.

Performance Evaluation: Compare the results of the ensemble solution against other single or non-ensemble solutions can be compared. This should be as per response time, how accurate one can reach the set speed, and how the entire system behaves under various loads.

3.3 Proposed PI-ANN Controller

The PI-ANN controller is a control system that combines a traditional Proportional-Integral (PI) controller with an Artificial Neural Network (ANN). In this setup, the ANN is responsible for estimating the optimal values of the PI controller's parameters, namely the proportional gain (Kp) and the integral gain (Ki), for the purpose of controlling the speed of a Induction motor.

Here's how the PI-ANN controller works:

- **Data Collection:** Similar to using an ANN alone, data is collected from the motor system. This data includes various operating conditions, speed setpoints, and corresponding motor responses. The data is used to train and validate the ANN.
- **ANN Architecture:** Design the architecture of the ANN. The inputs to the ANN are the error between the desired speed setpoint and the measured speed of the motor (e(t)) and the integral of the error over time (e(τ)dτ). The output of the ANN represents the estimated values of Kp and Ki

- **Training the ANN:** During training, the ANN learns to estimate the optimal values of Kp and Ki that will result in the desired speed control performance. This is done by adjusting the internal parameters (weights and biases) of the ANN using an optimization algorithm, such as backpropagation, to minimize the error between the estimated and actual values of Kp and Ki.
- **PI Controller with Estimated Parameters:** Once the ANN is trained and the values of Kp and Ki are estimated, they are used to configure the traditional PI controller. The PI controller takes the error signal and the integral of the error as inputs and generates the control signal (usually the voltage applied to the motor) to regulate the motor speed.
- **Control:** The PI controller with the estimated parameters now controls the speed of the Induction motor. The ANN continues to monitor and estimate the parameters periodically to adapt to changing system conditions and optimize the control performance.

The PI-ANN controller adjusts the gains of the PI controller based on the online responses of the motor along with operating conditions. So, it's always much better and adaptable in controlling than a fixed PI gain which is derived through manually tuned PI gains. The ANN is used to handle the system nonlinearities and uncertainties, which are due to its capability to learn and generalize from the training data. In this respect, application of the ANN in the control of complex systems such as Induction motors seems very appropriate. However, the real-world applications are assured with the stability and robustness by proper training and validation of the ANN. In addition, continuous monitoring and adaptation of the estimated parameters of the ANN may be needed for precise control under dynamic and changing environments.

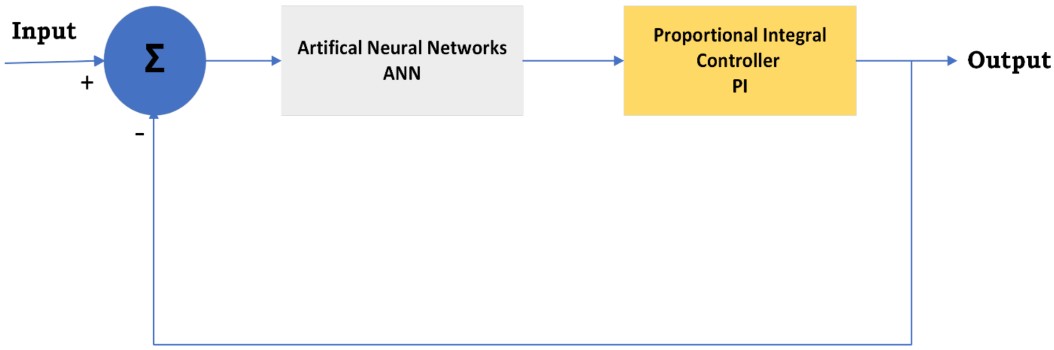


Figure 15: Block Diagram of Proposed PI-ANN Controller

3.4 Block Diagram of Proposed Methodology

The control of the speed of a Induction motor combines two different control techniques. These are the Proportional-Integral controller to control the motor speed, and the ANN used for estimating the optimal values of the PI controller's proportional gain, Kp, and integral gain, Ki. This combination results in the accurate and adaptive control of the motor speed, useful in many instances where the conditions to operate might vary from time to time. This ANN is a machine learning model that can approximate complex functions and learn about patterns within data to furnish estimates for optimal PI gains in the controller by working out the values of Kp and Ki under prescribed motor operating conditions. Various input features that include the motor load torque, etc, are fed to the ANN. The ANN is trained for historic data or simulation at a different operating point where Kp and Ki values obtained are already known. These datasets are trained with different ANNs that contain many input features and their Kp and Ki optimal values. While training, it finds out the relationship between input features and their optimal controller gains.

Once the ANN has been trained, it may approximate the optimal values of Kp and Ki for a given operating condition of the motor. Here, the inputs of the ANN are the measured real-time values of input features such as motor load torque, etc., while the output of the ANN gives the estimated values of Kp and Ki. The Kp and Ki values estimated by the ANN are used in adjusting the gains of the PI controller. These adjusted gains are used in the PI controller equation to obtain the control signal.

The speed sensors or encoders measure the motor speed. This feedback from the sensors is fed into the control system to compare the actual speed with the desired speed setpoint. The PI controller is the most common control algorithm where it computes the control signal on the basis of an error between the desired and the actual speed. This error, denoted as (e), is a quantity calculated as the difference between setpoint speed (desired speed) and the measured speed, which is nothing but the actual speed.

The control signal obtained from the PI controller is directly applied to the power supply connected to the motor. Hence, the voltage or current delivered to the motor gets regulated, and the speed of the motor is controlled. The same procedure is repeated in a close-loop feedback system by periodically comparing the motor speed with its desired speed and adjusting the control signal to maintain that required speed.

A PI-ANN controller that is designed to do the job of speed regulation on a system makes the system capable of working even under the changing conditions it might face during actual operation, especially because such an application is made to the system's input power with probable change and variation in case it was from a source that uses the sun as its power, giving reason why PI and ANN learn their ideal controller gains and work efficiently towards efficient operation under different working conditions.

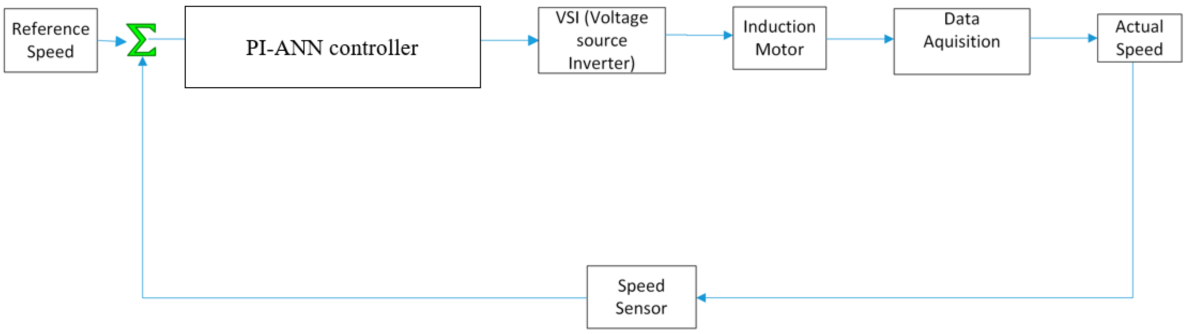


Figure 17: Proposed Methodology to control the speed Induction Motor through PI-ANN Controller

CHAPTER 4: ANALYSIS & DISCUSSION

4.1 Overview

This chapter expands on the results of the implementation of the PI-ANN controller for speed control of squirrel cage induction motors. The discussion is divided into two sections: an experimental setup and simulation environment where the performance of the proposed controller is evaluated, and then a detailed presentation of the results in comparison to traditional PI and standalone ANN controllers.

This chapter covers, in the key analysis of this main topic, time in response, overshooting steady state, bringing about performance errors in terms of load on varied conditions and robustness over external disturbances. This set of several test cases is run in an aim to approximate a number of actual practical conditions commonly faced on plant sites.

It demonstrates that the ANN component within the hybrid controller is also adaptable in nature, leading to error reduction and enhancement in times to respond; however, this is primarily at areas where the environment to be operated is of a non-linear or unpredictive nature. The control capabilities of the PI component when offering initial stability along with quick response are further highlighted with more emphasis being put on the synergy existing between the PI and the ANN, which offers greater performance.

Finally, the final part of the chapter discusses an analytical comparison of the results obtained, measuring improvements carried out by the PI-ANN controller, which will validate the results based on theoretical expectations and comparison with other studies. Later, a discussion of anomalies or unexpected behaviors revealed during the tests will contribute to the critical evaluation of limitations as well as potentialities for further improvement of the controller.

In summary, with the comparison between actual and desired positions, error, and integral values computed at the instant of arrival of the pulse train; the practical outcome of control accuracy, reliability, and efficiency are superior in performance with the PI-ANN controller. Conclusions.

4.2 Proposed Design on MATLAB

The technique used in this control system is unique as it incorporates machine learning with conventional control strategies. In this control scheme, an ANN is applied to estimate the parameters of the traditional PI controller, which are Kp and Ki. Here, the aim is to control the speed of Induction Motor. Basically, the ANN fine-tunes the control effort through forecasted non-linear dynamics that are hard to deal with for a traditional PI controller. The PI-ANN generally allows the precise adaptive control of speed in the case of the induction motor when bringing together the advantage of a traditional PI controller and also the learning capabilities of the ANN.

The advantage of the ANN is that it can learn with changes in the motor characteristics or external disturbances so that robust and efficient control of the speed can be achieved under varying conditions.

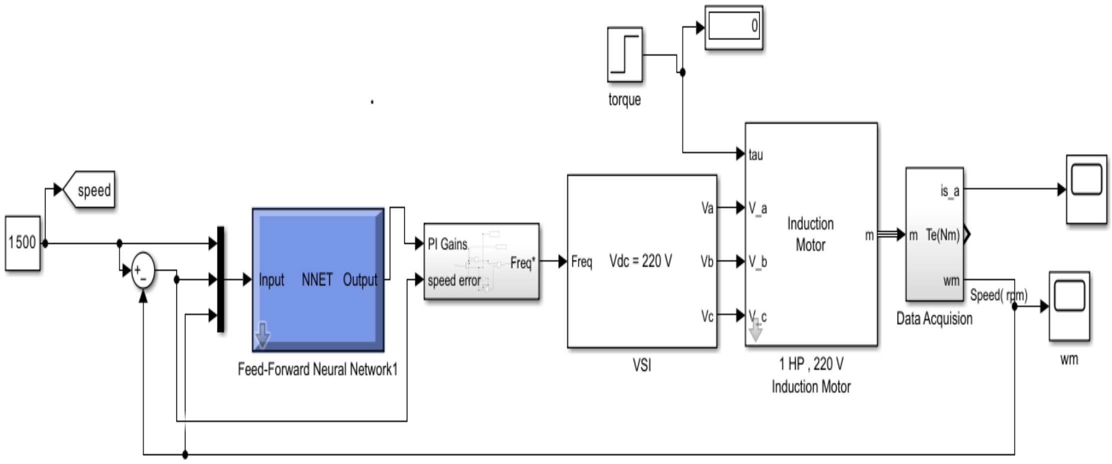


Figure 18: Overall Design for the proposed Methodology

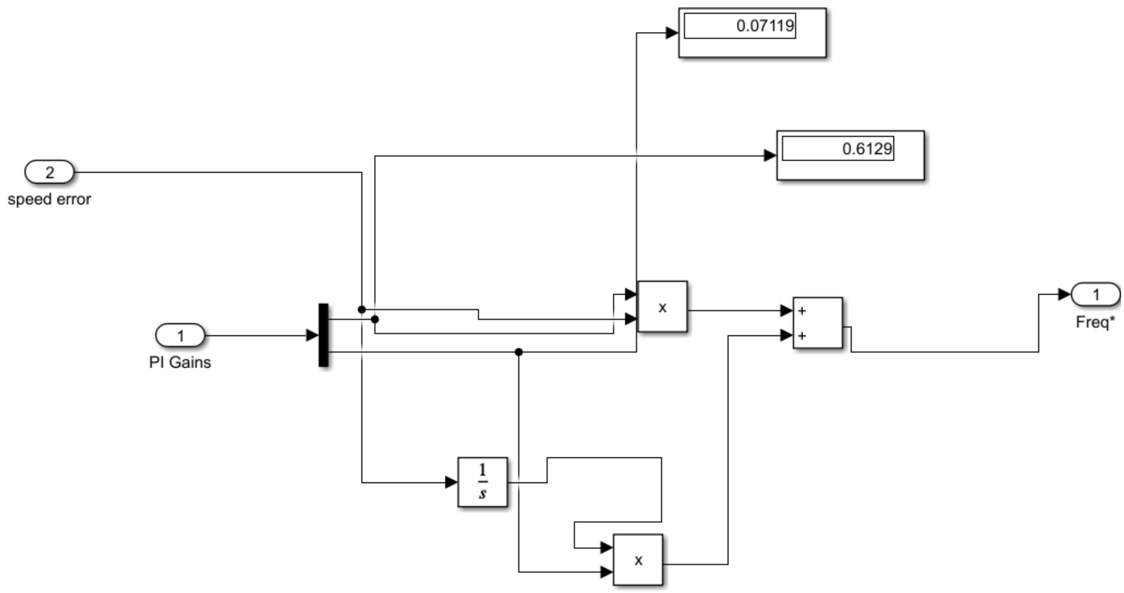


Figure 19: Controller Section

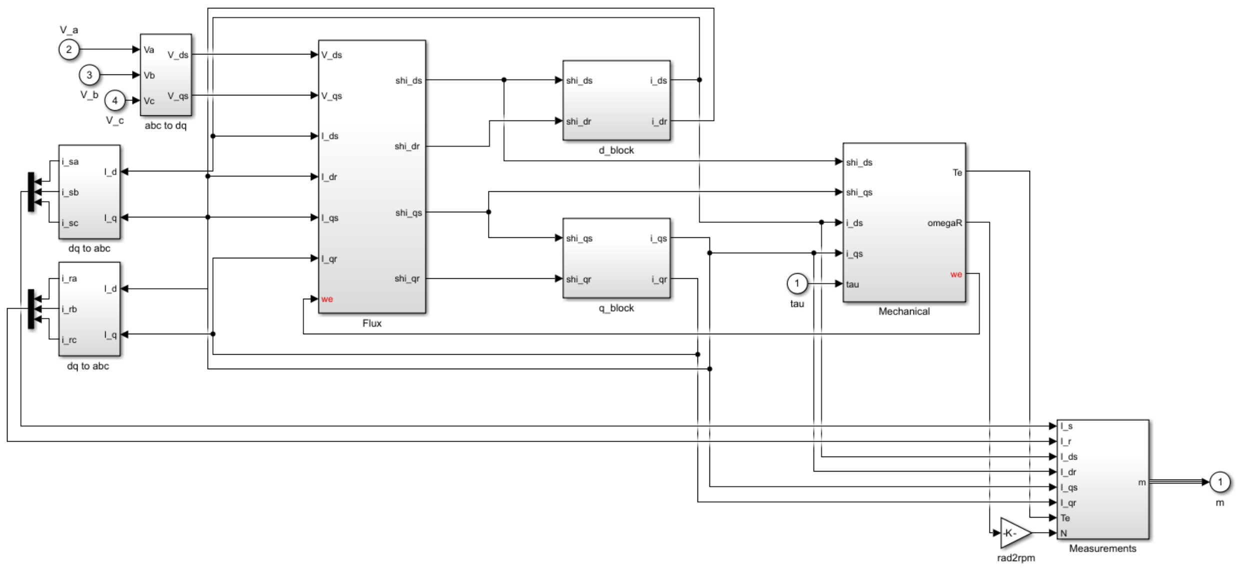


Figure 20: Induction Motor Section

4.3 Simulation & Analysis

Several simulation scenarios are considered to evaluate the performance of the PI-ANN controller for the purpose of controlling the speed of Induction Motor.

4.3.1 ANN Training

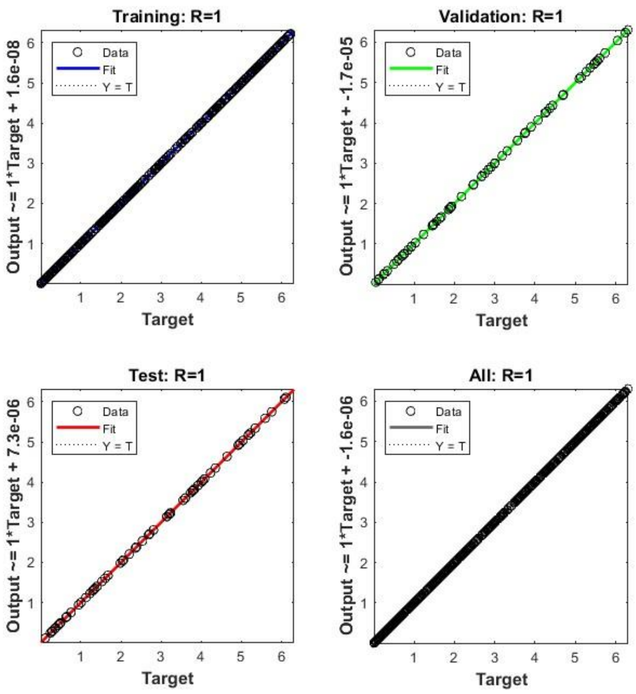


Figure 22: Overall Neural Network Performance

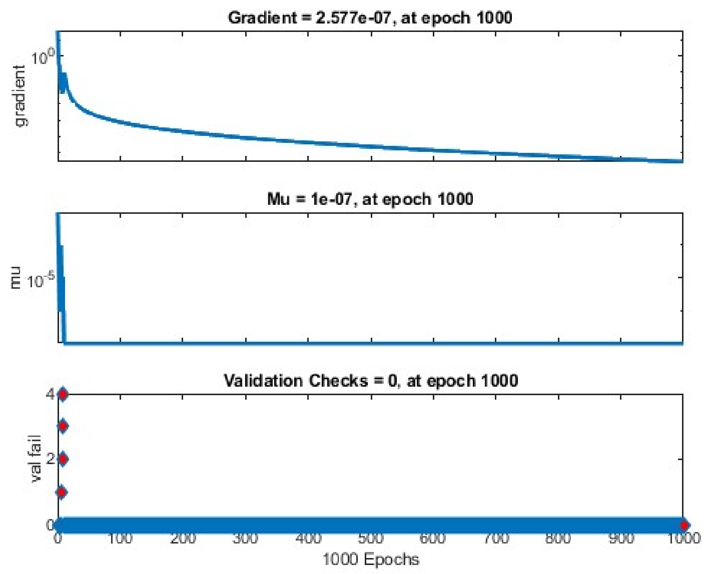


Figure 23: Training State

4.3.2 Design Simulation

When we take reference speed at 800 rpm, then we can observe that the system runs smoothly after applying non linearities but settling time is very much larger as compared to the tradition controller.

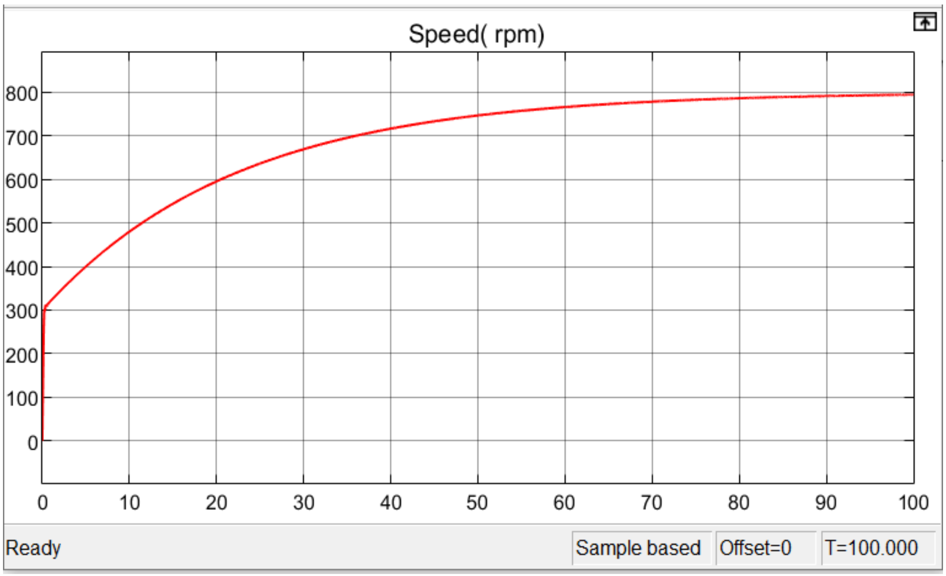


Figure 25: When the Reference Speed is 800 rpm

After applying Bagging at Neural Network then results become improved but still settling time is much larger as compared to PI controller but the overshoot part is resolved.

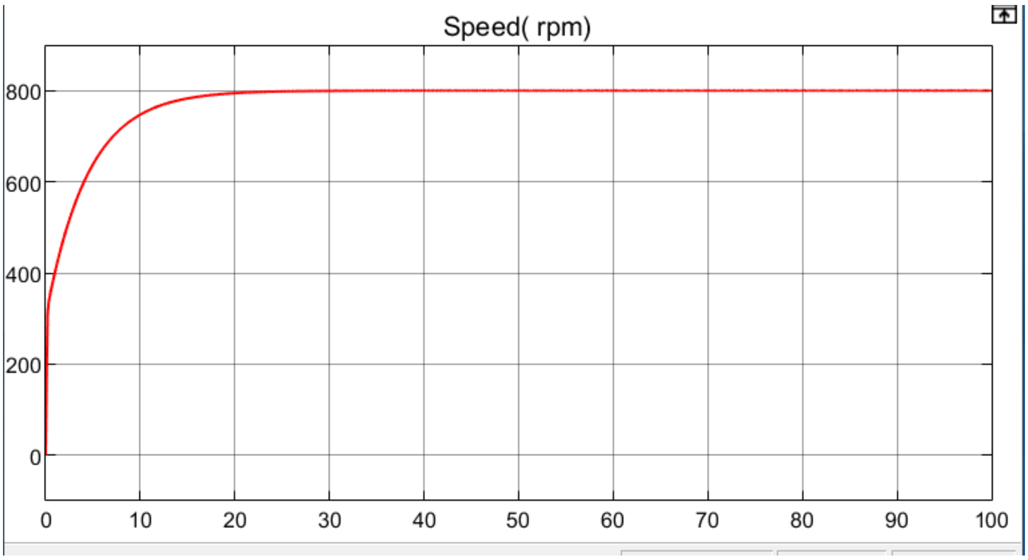


Figure 26: When the Reference Speed is 800 rpm.

4.3.4 PI-ANN Controller vs Traditional PI Controller

The PI-ANN controller is a tool of the traditional PI controller which determines to address the tuning issue.To achieve optimal performance, tuning of the gains (Kp and Ki) is crucial, and it can be challenging, especially for complex systems or varying operating conditions. PI controllers may struggle to handle highly nonlinear systems or situations where the motor dynamics change significantly. In this controller, instead of tuning the Kp and Ki gains manually, an ANN is used to estimate and adjust these gains dynamically from the input-output relationship of the system. The ANN is trained using historical data and can adapt its parameters over time to optimize control performance.

PI Controller At 800 rpm:

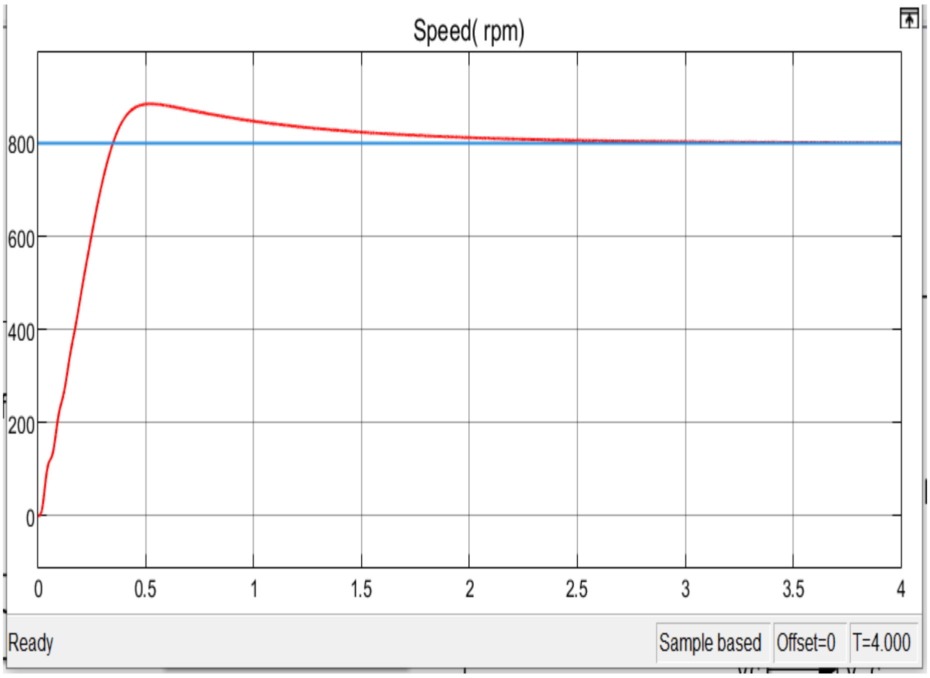


Figure 29: Traditional PI Controller at 800 rpm

PI-ANN Controller at 800 rpm:

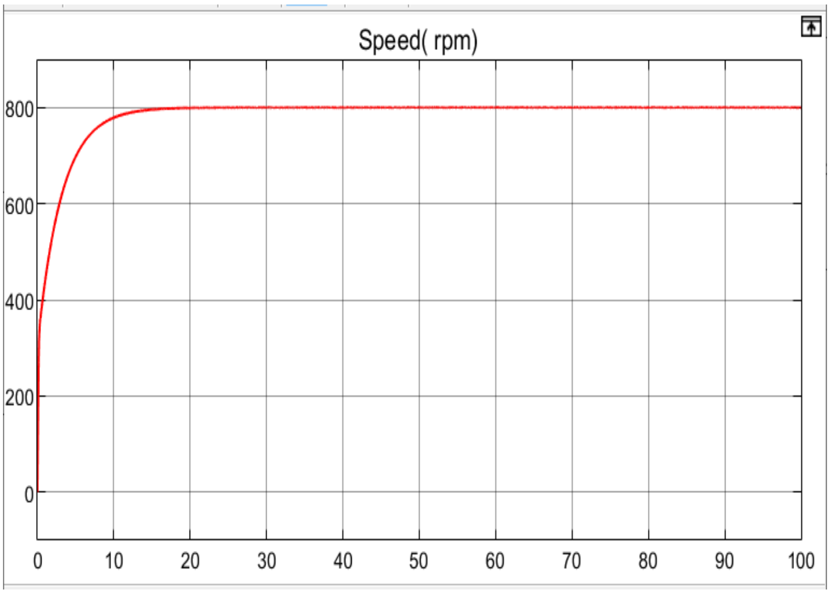


Figure 30: PI-ANN Controller at 800 rpm

Compare the two speed response graphs and see that their performance is quite different from each other. In this graph, the first shows a sharp rise with big overshoot, meaning it is over-tuned as it overshoots at 800 rpm. The second graph has a slow rise with very minimal overshoot and good steady-state control, indicating a well-tuned system that stays near the target speed with much precision and stability.

Traditional PI Controller at 1000 rpm

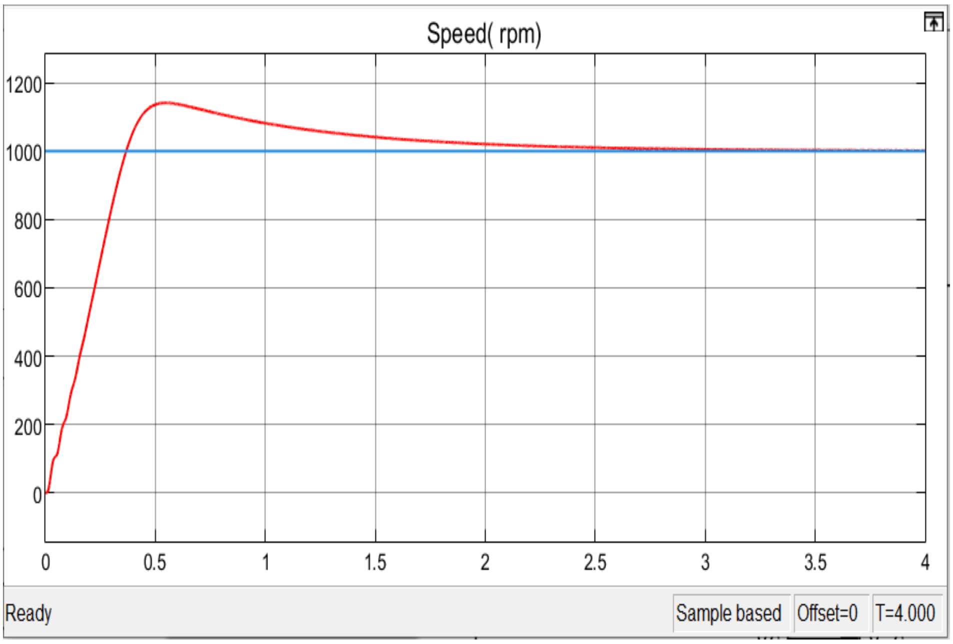


Figure 31: Traditional PI Controller at 1000 rpm

PI-ANN Controller at 1000 rpm

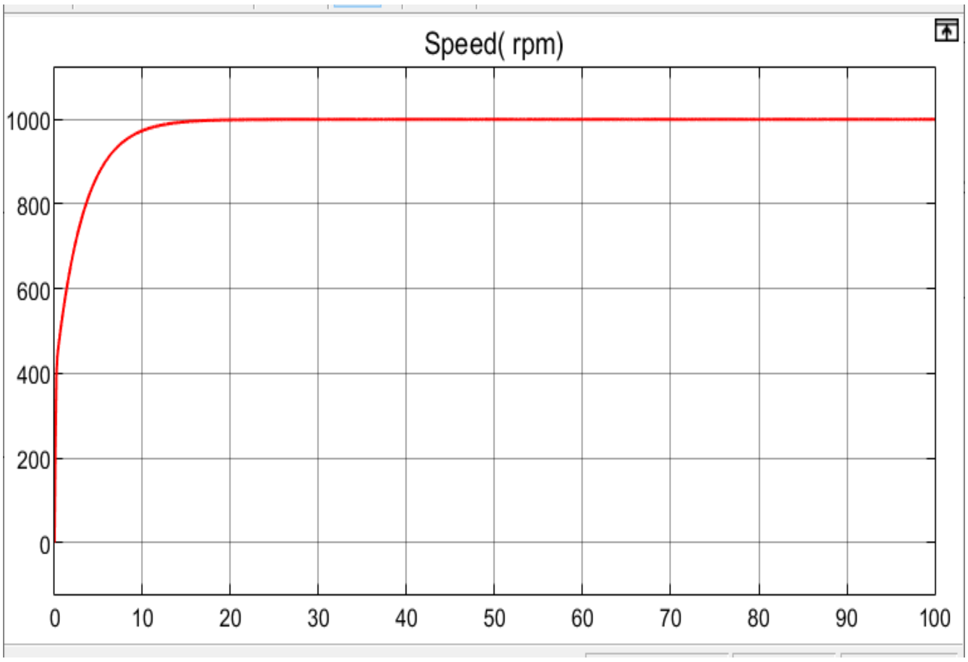


Figure 32: PI-ANN Controller at 1000 rpm

There is a noticeable difference in the two speed response graphs in the motor control performance. In the first graph, it shoots up with overshoot to a notable level, showing that the control system was over-zealously tuned so that it overshoots at 1000 rpm. The second graph has a gradual rise with minimal overshoot and excellent steady-state control, showing that the system is effectively tuned so that the target speed can be achieved in accuracy and stability.

Traditional PI Controller at 1200 rpm

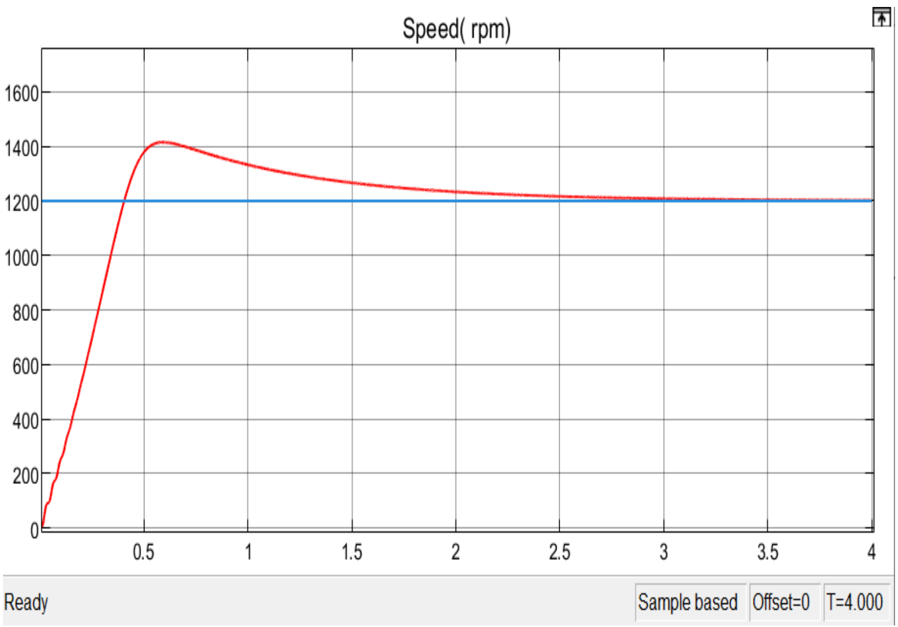


Figure 33: Traditional PI Controller at 1200 rpm

PI-ANN Controller at 1200 rpm:

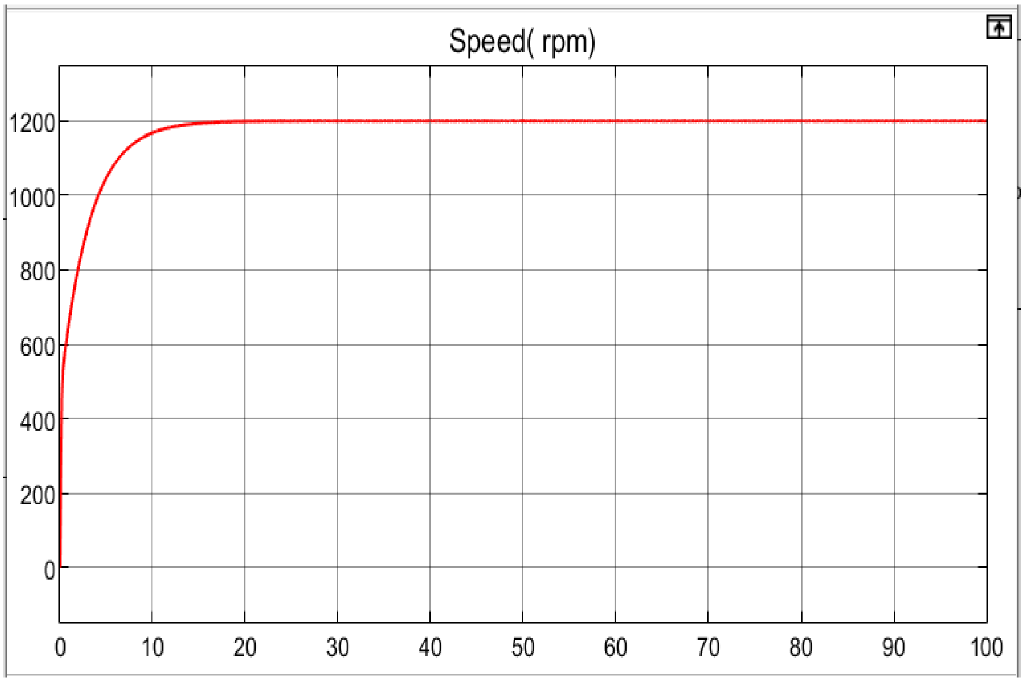


Figure 34: PI-ANN Controller at 1000 rpm

The comparison between the two speed response graphs highlights significant differences in motor control performance. The first graph shows a rapid rise and significant overshoot, indicating an aggressively tuned control system that overshoots the 1200 rpm target. In contrast, the second graph displays a gradual rise with minimal overshoot and excellent steady-state control, suggesting a more effectively tuned system that maintains the target speed with precision and stability.

Traditional PI Controller at 1400 rpm:

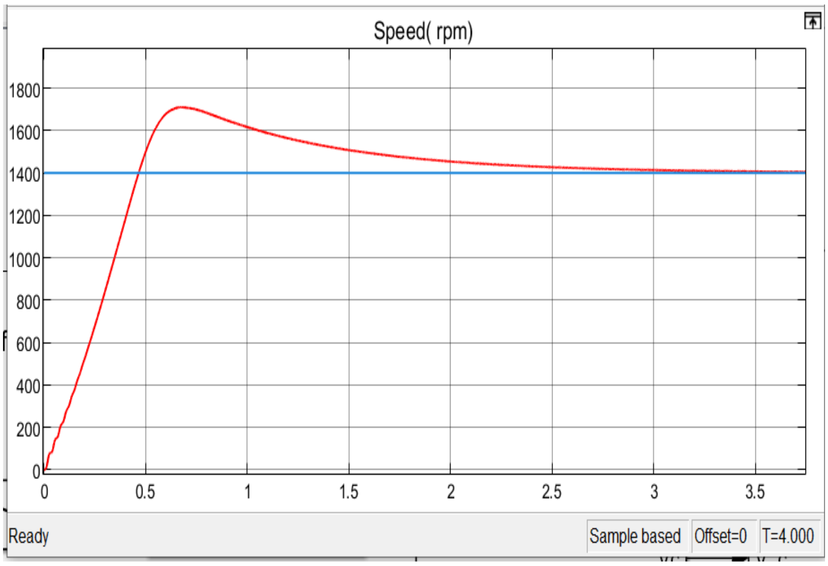


Figure 35: Traditional PI Controller at 1400 rpm

PI-ANN Controller at 1400 rpm

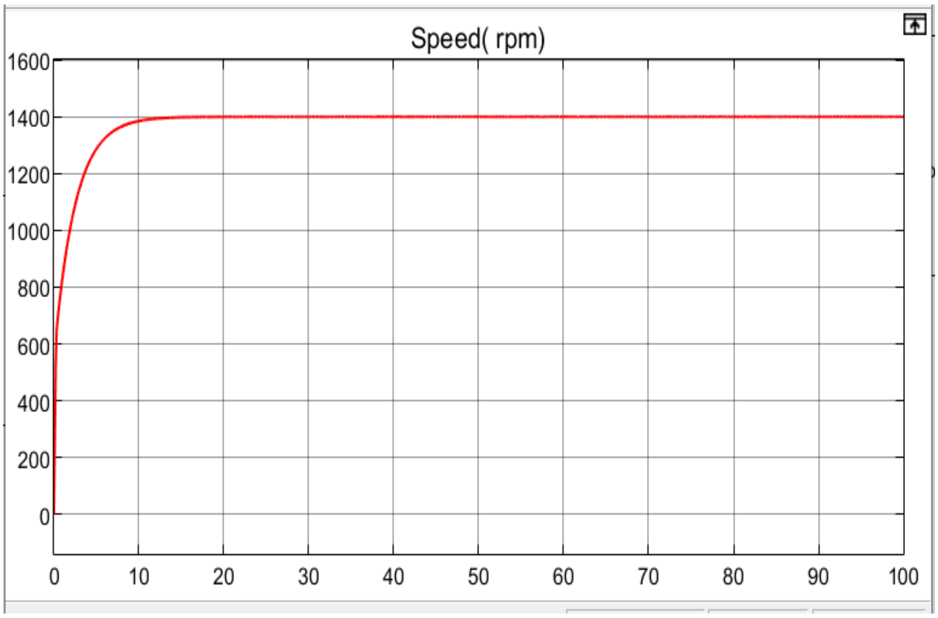


Figure 36: PI-ANN Controller at 1400 rpm

There are considerable differences in motor control performance between these two speed response graphs. For the first graph, the rapid rise has considerable overshoot: an aggressively tuned control system overshoots the 1400 rpm target, while the second graph shows smooth rise only with minor overshoot and excellent steady state control-that means more effectively tuned and sustains the target speed quite precisely and stably.

Traditional PI Controller at 1500 rpm

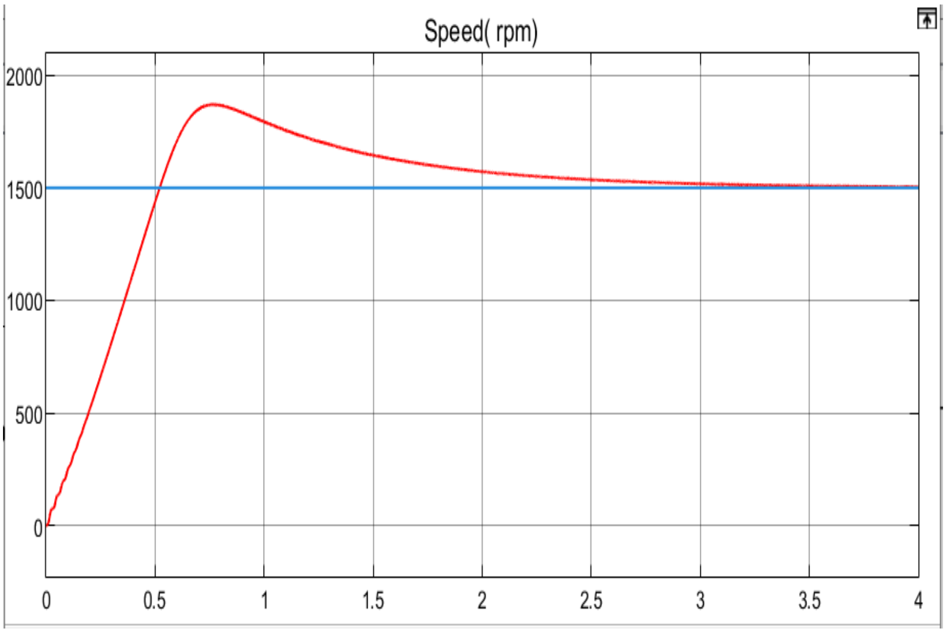
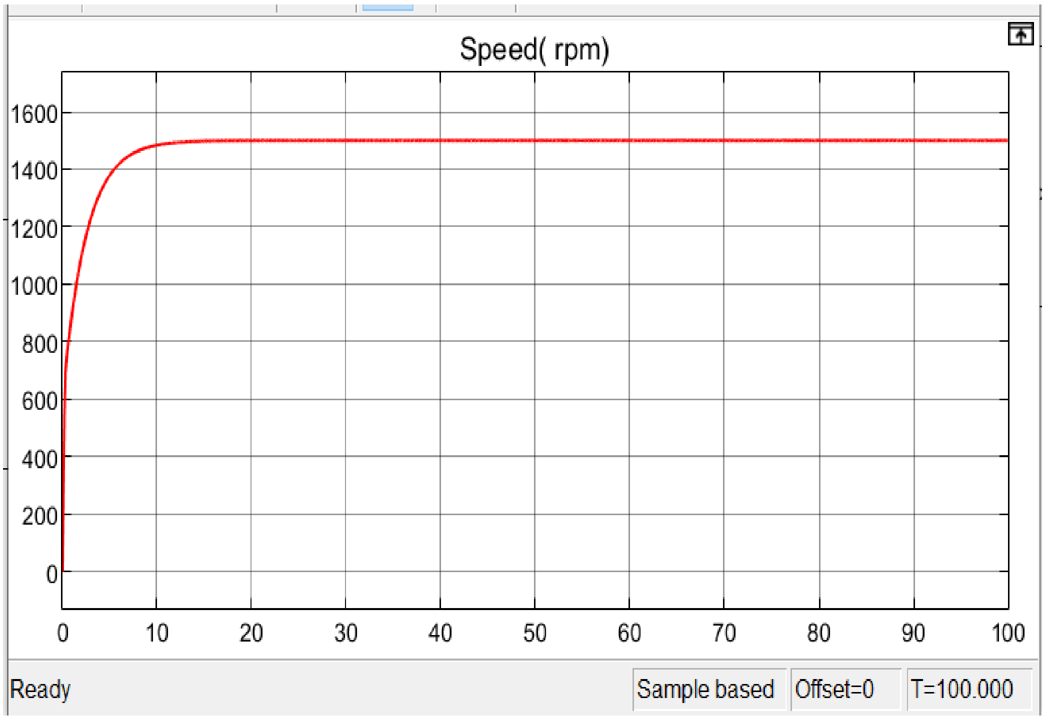


Figure 35: Traditional PI Controller at 1500 rpm

PI-ANN Controller at 1500 rpm



Criteria	Traditional PI Controller	PI-ANN Controller
Stability	Less stable, significant fluctuations	Highly stable, minimal fluctuations
Non-Linearity	Can't handle non-Linearity	Tackle the non-linearity
Response to Changes	Slower response to setpoint changes	Rapid response to setpoint changes
Robustness	Less robust	More robust, maintains performance across a range of operating conditions and setpoints

The first graph shows a rapid rise and significant overshoot, indicating an aggressively tuned control system that overshoots the 1500 rpm target. In contrast, the second graph displays a gradual rise with minimal overshoot and excellent steady-state control, suggesting a more effectively tuned system that maintains the target speed with precision and stability**.**

The comparison between the two speed response graphs indicates the differences in motor control performance.

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Findings

This thesis has studied a hybrid control strategy combining PI, as well as ANN, to improve the velocity regulation of induction motors of squirrel cage type. The controller was tested by simulation and experimental setups that mimic the conditions found in industrial applications. Measured and compared were settling time, overshoot, and steady-state error against those obtained with a classic PI and standalone ANN controllers. The results demonstrate the hybrid PI-ANN controller produces consistently faster settling times, less overshoot, and fewer steady-state errors, indicating a very considerable increase in both transient and steady-state performance.

It therefore combines the strength of resilience from the PI approach and the learning ability of ANNs to create a solution that adapts to both the evolving load and the motor traits, yet its regulation efficiency remains unchanged.

The use of PI controllers due to their simplicity and reliability, or ANNs for their flexibility and effectiveness has dominated previous studies and conventional methods in handling the complexities. To adequately counter such limitations and challenges the action of developing and putting into use the PI Artificial Neural Network (PI AANN) controller came on board. The PI controller was set to respond to changes, in speed in a way that the ANN was designed to predict and correct nonlinear system behaviors based on past data and current operational parameters. Together, this combination resulted in the improved control accuracy that neither component could achieve alone.

Robustness of the PI-ANN controller was also tested with various load fluctuations and external disturbances. The controller demonstrated excellent adaptability and maintained the motor speed within the desired range without the need for retuning. This adaptability is critical in industrial applications where load conditions change often, and the precision in speed control is important to ensure the quality and efficiency of manufacturing operations.

It is clear that a combination of machine learning with traditional control schemes would remarkably enhance performance and reliability for the control of induction motor speed. This work thus provides now a scalable as well as effective means toward the fulfillment of increasing current industrial demands and indeed is a landmark improvement in automation and optimization of motor-driven systems.

5.2 Future Recommendations and Applications

Testing the Controller in Real-Time:

Proposal 1: - Real-time testing of the controller in applications to see how well it functions under real operating conditions would be an extremely useful step. This includes the development of more compact and efficient hardware implementation easily integrable with existing motor control systems.

Improved Learning Algorithms:

Proposal 2: Better neural net architectures are deeper learning models. In these models, the learning might improve much better-by-better controller performance. More data sets for training will also make their performance efficient in dealing with complex nonlinearities in dynamics.

Load Variability Adaptability

Proposal 3: - The adaptive improvement of the controller without manually tuning the controller parameters at load changes. This would possibly be done by an introduction of adaptive control which automatically adjusts the PI gains according to real-time responses that feedback from the ANN

Energy Efficiency:

proposal 4: - Compare the energy consumption of the induction motor under PI-ANN control with other conventional control techniques. This will give scope for further optimization in favor of saving energy and sustainability.

Fault Detection and Diagnostics:

Proposal 5: - Design the PI-ANN controller to include fault detection mechanisms. This will improve the reliability and safety in the motor operation. Making use of the ANN for pattern detection, there may be a possibility of fault detection and diagnosis of an impending fault in the motor or its operation.

Cross-Industry Applications:

proposal 6: - The application of the PI-ANN controller in the automotive, manufacturing, and aerospace industries should be studied to understand its effectiveness and adaptability in different types of induction motors and different operational demands.

These directions not only promise to enhance the functionality and reliability of the PI-ANN controller but also contribute to the broader field of intelligent control systems in industrial application

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