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Speed Control of Industrial Motor Drives–Current Developments

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Abstract— **Induction motors are widely used in industries because of several advantages including easier speed control. With the development of high-performance controllers, superior control of induction motor (IM) drives is becoming possible nowadays. For selecting the motor with different application requirements, the through study for latest controller-based drives is necessary and hence this paper examines, the various control techniques used for speed control of induction motor drives with modern controllers. The field of motor control has witnessed significant advancements over the years, driven by the need for energy efficiency, precise control, and improved performance in various industrial applications. This review paper has provided a comprehensive overview of the various methods and techniques employed for the speed control of industrial induction motors.**

***Keywords*—speed control, induction motor, sensorless, v/f, vector control, direct torque control**

I. INTRODUCTION

Induction motors are extensively utilized in industrial settings due to their myriad of advantages. In contemporary times, the latest controllers have facilitated significant progress in achieving efficient control of induction motor (IM) drives. The control methodology for an induction motor is executed by the modulation of the d-q components of the stator currents. These components are responsible for generating both torque and flux. Additionally, the control scheme involves selecting a suitable frame of reference, such as stationery, rotating, or synchronously spinning, to enable independent control of the motor [1].

In the realm of induction motor control, the utilization of voltage-to-frequency (V/F) regulation is a method employed to precisely regulate motor speed and torque. The efficacy of this control approach is contingent upon the manipulation of both the amplitude of the applied voltage and the corresponding frequency that is transmitted to the motor. In the context of vector control, the induction motor is divided into two orthogonal three-phase current components, allowing for independent regulation of torque and flux. The primary limitations are the sensitivity to the rotor time constant and imprecise measurement of flux in proximity to zero velocity. Various vector control approaches, such as Field Oriented Control (FOC), Direct Torque Control (DTC), and Model Predictive Torque Control (MPTC), are classified under this categorization. Due to the inherent variability of motor characteristics and the insufficient precision of speed prediction for meeting industrial demands, the calculation of flux vector in Field-Oriented Control (FOC) assumes a critical role. To get rotor flux alignment, the technique of vector control is used, which involves the mapping of stator currents onto a reference frame that revolves [2]. The division of torque and flux components in this transformation facilitates the simplification of motor control. The control system governs the motor's actions inside the newly established reference frame. The stator currents are moved from the stationary reference frame (typically the three-phase abc reference frame) to a rotating reference frame (the d-q reference frame), where they are aligned with the rotor flux. This transformation makes the control easier to use by separating the component that produces torque (the current in the d-axis) from the component that magnetizes it (the current in the q-axis. For the estimation of rotor speed and the stator resistance adaptation Lyapunov stability theorem the regular way of controlling three-phase induction motors (IMs) has been widely used in industries. The basic properties and extra electrical signals in voltage and current are directly influenced by changes in certain magnetic field directions. The fifth and seventh extra signals in the current of a closed-loop IM system are important due to their impact on voltage signals. Vector control can also be implemented with senseless techniques, eliminating the need for additional sensors like speed or position encoders. Senseless vector control reduces cost, complexity, and potential reliability issues associated with sensor-based control systems [3-4].

The model reference adaptive system (MRAS) to enhance senseless rotor-field oriented control (RFOC) in induction motor (IM) drives across all speed ranges. However, when faced with external disturbances and variations in parameters, the conventional linear tuning method of the Proportional Integrator (PI) controller within the MRAS adaptation mechanism can lead to a decline in motor performance. incorporating two adaptive mechanisms to generate slip speed and stator resistance estimates. Both reference and adjustable models are formulated in the synchronous rotation coordinate system (d-q frame). The efficacy of the control algorithm is assessed across diverse operating conditions using a specific senseless IM benchmark [31]. In comparison to the traditional 'PI' regulator, the 'Deadbeat' regulator demonstrates superior performance, showcasing improved response times and reduced overshot during the estimation process. certain limitations of the 'Deadbeat' regulator have been identified, specifically its reliance on accurate mathematical system models and its sensitivity to variations in parameters [32].

For selecting the motor with different application requirements, the through study for latest controller-based drives is necessary and hence this paper examines, the various control techniques used for speed control of induction motor drives with modern controllers. Section II presents the literature review of latest control techniques for induction motor speed control. Section III presents the sensorless speed estimation process. In Section IV, concluding remarks are presented based on latest advancements.

II. CONTROL TECHNIQUES

A. V/f Control Techniques

The development of a linear relationship between changes in voltage frequency and their ensuing impact on motor performance is the core tenet of V/F control. As the frequency of the provided voltage decreases, the motor speed and torque . output also fall correspondingly, and as the frequency increases, the motor speed and torque output increase. The V/f control system is frequently used in industrial applications with motor control specifications that can tolerate some degree of imprecision

Table I: Recent Advancements in V/f Scheme

S. No.	Technique	Result/Conclusion
1.	For the speed control of a three-phase induction motor a new constant V/f technique is introduced [5]	SVPMWM operates on the principle of constant voltage-to-frequency ratio, to boost the performance of an induction motor under steady-state conditions. The motor speed response, operating at 1300 rpm under constant V/f control, has a rise time of 0.13 seconds, a settling time of 0.164 seconds, no overshoot, and a total harmonic distortion of 19.26%.
2.	Uses conventional V/f control-based inverter [6]	Helps with high-speed air-braking start-up issues that plague the traditional v/f control approach. Because of the current controller, the suggested approach does not generate the peak current during the initial phase.
3.	New hybrid V/f control for senseless speed control of induction motor [7]	The speed torque of a vehicle using a non-linear observer in conjunction with the v/f pattern and the compensator. There is a mismatch between the command speed and the actual speed in V/f control, and the difference depends on the load. The hybrid V/f control also includes a compensation term, which is calculated by multiplying the anticipated torque with a gain
4.	MTPA control approach is proposed for the regulation of an induction motor by the voltage-to-frequency (v/f) method, with a specific focus on reactive power. [8]	The v/f ratio correction term was calculated as the difference between the observed reactive powers and the predicted reactive powers from the model. By using stator-flux, this technique lessened inductance compensation's reliance on machine parameters. When it comes to the temperature of the machine, the rotor resistance parameter is less crucial.
5.	New quadratic v/f control technique [9]	Due to the quadratic nature of the pumping load torque speed characteristic, this solution is used to guarantee optimal performance across the board. The suggested quadratic V/f control is preferable in terms of dynamic response and efficiency for all variations in solar radiation.
6.	V/f control technique with hybrid inverter for induction motor drive [10]	Using a hybrid inverter allowed for a constant THD in the motor current over the whole frequency range. The frequency range of hybrid inverter is 5 to 50 Hz using the v/f open loop technique. In the presence of uncompensated harmonics, this technique has been presented to estimate the fundamental component of the rotor flux and the stator current along the D-Q axis.

C. Field Oriented Control Techniques (FOC)

The concept of Field-Oriented Control (FOC) emerged during the early 1970s with the aim of enabling autonomous regulation of torque and flux, akin to the independent control exhibited by separately excited DC machines. The monitoring procedure encompasses the utilization of Park's and Clarke's transformations to disassemble the stator current into separate components that are accountable for torque and flux generation within the designated reference frame. The measurement is a determining factor in the calculation of the angle of the flux space vector. There exist two distinct approaches for the implementation of Field Oriented Control (FOC), namely Direct Field Oriented Control (DFOC) and Indirect Field Oriented Control (IFOC). The DFOC method employs the flux model of the machine, while the IFOC approach utilizes the estimated slip frequency and rotor flux to determine the angle of the flux vector.

To achieve efficient vector control, it is necessary to have an accurate calculation of the rotor flux. The torque that is generated by the motor may be controlled by adjusting the current that flows through the d-axis. This enables accurate torque control that is separate from the management of the motor speed. Modifications are implemented on the q-axis current in order to regulate the flux generated by the motor, hence exerting an impact on the motor's rotational velocity. The precise regulation of motor speed can be accomplished by manipulating the magnitude of electric current passing through the q-axis.

In electric motor drives, FOC is a form of control strategy used most often with induction motors and permanent magnet synchronous motors (PMSMs). The goal of FOC is to allow for efficient and accurate regulation of the motor's torque and speed by controlling the magnetic flux and torque components separately. a) Voltage oriented control: - Motor speed is controlled by adjusting the voltage and current supplied to the stator in voltage-oriented control (VOC), also known as conventional field-oriented control. First, it uses Park's transformation to convert the three-phase currents from the fixed to the rotating frame of reference. The torque and flux components may be uncoupled thanks to this transformation. The control system then adjusts the voltage references for the torque and flux components individually to get the desired results. As with PMSMs, induction motors make extensive use of VOC. b) Current oriented control: - Motor control through direct regulation of stator currents is the basis of current-oriented control (COC), also known as direct field-oriented control. There is no need, as in VOC, to convert currents to a rotary frame of reference. The necessary torque and flux components are instead achieved by direct control of the motor currents. Because of its superior dynamics, COC is often used in high-performance applications.

Both forms of FOC control are frequently employed in a broad range of industrial settings because of their respective benefits. The needs of the motor drive system and the required performance parameters will determine whether a VOC or COC is the better option.

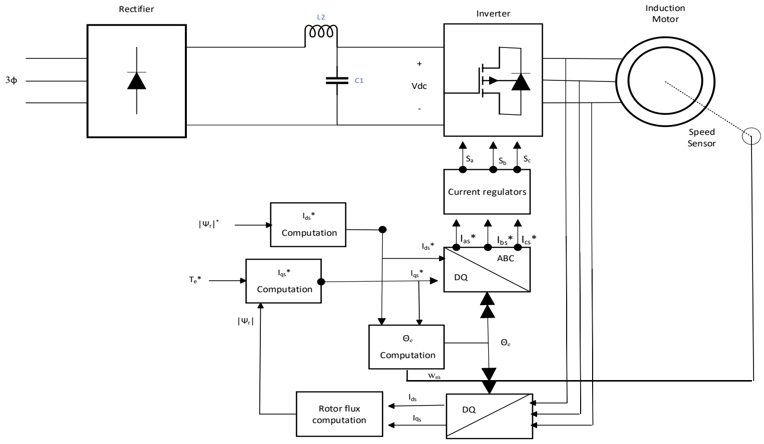

Fig.1 Field Oriented Control of IM Drives

D. Direct Torque Control Techniques (DTC)

The direct torque control method employs a voltage source inverter that is equipped with a pre-determined switching pattern and a look-up table in order to effectively manage the torque and flux components. The selection of the switching technique will be contingent upon the outcomes obtained from the torque and flux hysteresis controllers. then, the estimated torque and flux values are juxtaposed with the reference values, and the outcome is then modified to account for any inaccuracies inherent in the hysteresis comparator. The estimation of torque, flux, and the position of the flux vector in the machine is based on the input voltages and currents, as depicted in the diagram. The equation serves to elucidate the interdependence of torque, stator flux, and rotor flux, so providing guidance in the selection of voltage vector for torque management

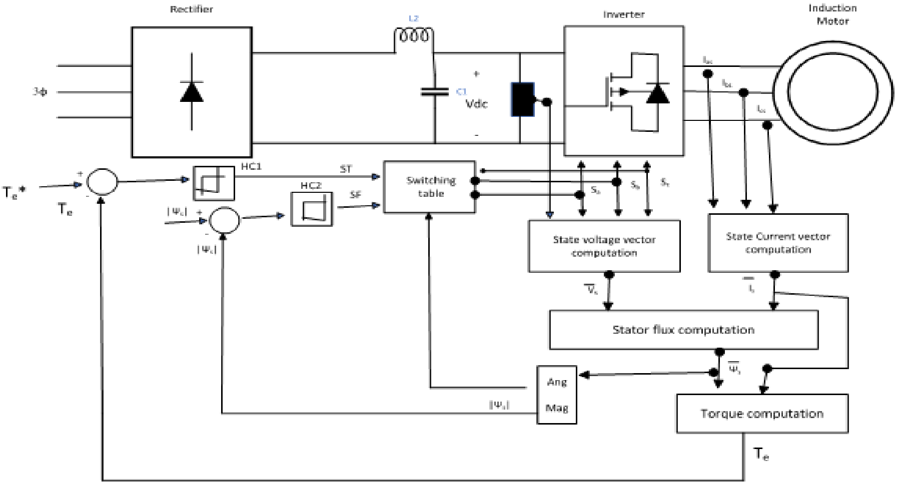

Fig.2 DTC Control of IM Drives

This method involves estimating motor magnetic flux and torque through measurements of voltage and current. The DTC technique stands out as a precise approach for achieving improved and rapid torque dynamics, particularly in applications emphasizing high efficiency. Direct Torque Control represents a novel approach to controlling induction motors, offering exceptional performance even in the absence of tach generator feedback. This method introduces fresh control capabilities like flux braking and rapid initiation. The implementation of DTC drives is poised to yield advantages across various drive applications, extending even to those traditionally reliant on DC and servo drives.

Table II: Comparison between FOC and DTC Scheme

Parameters	DTC Scheme	FOC Scheme
Reference frame	*Stationary d-q	Rotating d-q frame
Control parameters	*Stator voltage space vector	Stator currents
Torque calculation	*Direct controlled. *Controlled Torque ripple *High dynamic	High Torque ripples. Highly dynamics Indirectly controlled by stator current.
Estimated variables	*Torque *Stator flux.	Slip frequency. Rotor flux position.
Flux control	*Directly controlled *Fast Dynamics	Indirectly controlled by stator currents. Slow dynamics.
Implementation complexity	*Medium Complexity	High complexity. Calculations are highly complex.
Parameter sensitivity	*Sensitive to Variation of Stator Resistance	Sensitivity to variation of rotor time constant.
Regulators	*Torque Regulation *Stator Flux Regulation	Three stator current regulator
Measured variables	*Stator Voltage controlled *Stator Current	Rotor mechanical speed #Stators current.

III. SPEED SENSORLESS CONTROL

A. MRAS Scheme

Model reference adaptive system (MRAS) is considered one of the best systems for speed estimation due to its direct and reliable stability approach. The MRAS model consists of three components: model adjustment, reference model, and adaptation mechanism. The customizable model exhibits greater sensitivity to variations in rotor speed compared to the reference model. By employing the adaptation process, it is possible to reduce the disparity between the flexible model and the reference model. In our rotor-flux-based Model Reference Adaptive System (MRAS), the stator equation serves as the initial reference, while the rotor equation is employed for precise adjustment.

The MRAS technique is a type of adaptive control technique that is employed for the purpose of estimating both the state and parameters. The scheme is highly favored because of its uncomplicated structure and consistently good performance over a wide range of operations. This system offers exceptional durability and tracking capabilities for an induction motor's trajectory, even in challenging operating situations, especially at low speeds.

The performance of the proportional-integral (PI)-MRAS may be unsatisfactory due to the unanticipated operational uncertainties of the machine parameters and unmodelled non-linear dynamics. The proposed estimator removes the Proportional-Integral (PI) controller used in the traditional Model Reference Adaptive System (MRAS). This approach employs two loops and produces two distinct error signals based on the rotor flux and motor torques. The stability and dynamics of the SMC law are derived using the Lyapunov theory [33].

The suggested rotor fluxes the MRAS system relies on speed estimation and incorporates two adaptive mechanisms utilizing synergetic control. One mechanism is used to estimate slip speed, while the other is employed to estimate stator resistance. The parallel rotor speed and stator resistance estimator is employed to enhance the resilience of senseless speed control when operating at extremely low speeds with parameter fluctuations.

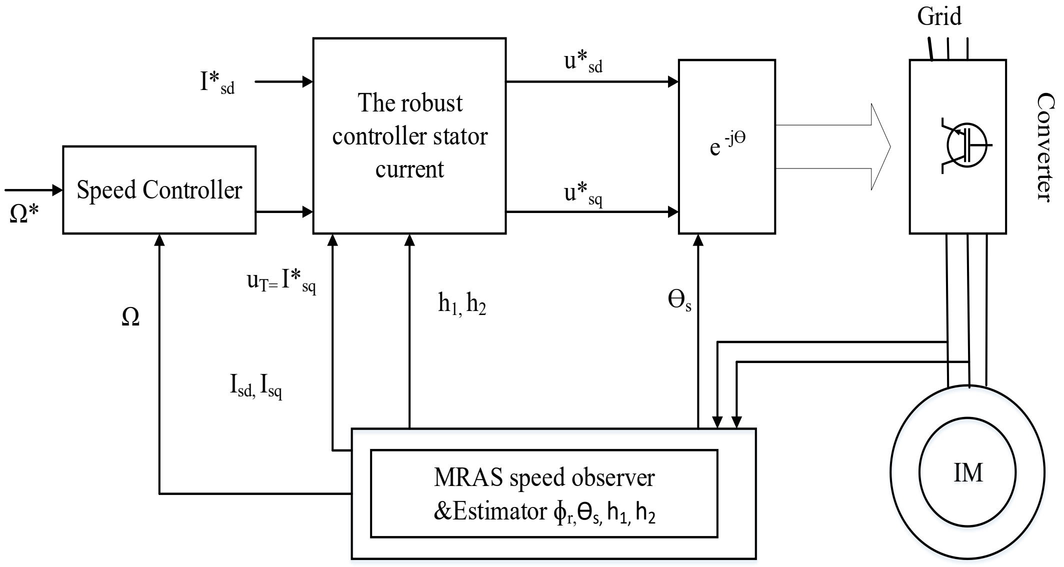

Fig.3 MRAS Scheme Control of Speed Control of IM Driver

B. MPTC Control Technique

The utilization of model-predictive torque control facilitates the achievement of high-performance control in induction motor (IM) drives. In contrast to direct torque control and MARS, it can be argued that MPTC exhibits superior efficiency and accuracy in voltage vector selection due to its integration of the system model with finite switching states. In the context of two-level inverter-supplied induction motor (IM) drives, it is important to note that the available voltage vector alternatives are restricted. Consequently, in order to achieve the best performance, it becomes necessary to employ significant multiple pulse time control (MPTC) sampling rates. The reduction of torque ripple can be achieved through the integration of a null vector alongside the chosen active voltage vector, a novel approach that has been developed in the field of Model Predictive Torque Control (MPTC) in recent times.

S. No.	Technique	Conclusion/Results
1.	They improve the fusibility of FOC using PI, PD, and PID controller without using any sensors [13]	Three separate controllers manage the velocities, positions, and currents. Compared to PD and PID controllers, PI controller is more effective. A 10 horsepower 460-volt 60 hertz 1,765 RPM induction motor is used for the simulation.
2.	The real-time implementation of an optimised hybrid (FOC-DTC) strategy. This strategy incorporates a Losses Minimization Algorithm (LMC) and a MARS for speed estimates. [14]	Benefits include faster dynamic response and less sensitivity to changes in machine settings. Better flux reference tracking and ideal decoupling are proposed benefits of the hybrid FOC-DTC approach. In varying velocity ranges, the MRAS observer provides reliable estimates. When used together, they produce optimal speed regulation for induction motors.
3.	DTIFOC and DTTFOC for IM are designed [15]	The continuous-time counterpart inspired the creation of both direct and indirect field-oriented controllers. The absence of a rotor flux observer in the proposed DTIFOC results in smoother responses than in the proposed DTDFOC.
4.	The MFOC approach, incorporating an optimal rotor flux, for the implementation of FTC procedures in the presence of a single-phase open fault. [16]	Calculating the optimal rotor flux under varying conditions is how the machine losses model finds the minimal losses. Improved efficiency, as well as steady-state and dynamic responses under both typical and SPOF situations, are some of the many strengths of the established technique.
5.	Selection of motor in Simulink with the help of an equivalent circuit for the space vector [17]	Direct torque control (DTC) or model-based informed control (MBIC) allows for regulation of the motor model. The graph for an induction motor's speed-maintaining omega is shown below.
6.	In this paper, FOC and DTC discussed in brief [18]	The advantages of both schemes make a definitive verdict on which is better—DTC or FOC—very challenging. In their most fundamental forms, both control methods offer similarly effective torque control and similarly sensitive control parameters.
7.	They introduce FOC method in their work for developing real time prototype of controller [19]	A novel controller based on a 150 MHZ Xilinx ARTIX-7 FPGA was proposed. In a DTC-fed induction motor drive, adjusting the motor's speed results in a shift in the machine's torque and a corresponding current shift.
8.	Develop fuzzy logic controller using FOC and direct & indirect both control technique was discussed [20]	A genetic algorithm hybrid fuzzy-fuzzy controller system for controlling the speed of a variable-speed induction is discussed, along with its simulation and experimental demonstration. using an eZdspF28335 digital signal processing experiment board to implement a space vector pulse width modulation-based IM drive.
9.	Design of the mathematical model by using FOC control technique [21]	The controller's power output can be regulated by adjusting various settings. This paper show clearly that FOC control is superior to v/f control in terms of speed range and dynamic performance.
10.	The speed estimation of the system is achieved by artificial neural network ANN [22]	A mechanical sensorless control system, complemented by an additional feedforward flux loop, has been implemented to improve the overall performance of submersible pumps. This approach not only reduces the need for sensors but also maximizes the pump's operational efficiency across its entire speed range. The enhanced SVM technique has been employed to implement the speed control of the drive and the current reconstruction.
11.	Single-variable-based extended FOC scheme for high power induction machine drive in operating in SWM [23]	To regulate the drive's SWM operation, a linearized relationship between the generated torque and the stator voltage angle was created. The drive can only enter SWM at higher operating speeds where the THD of the stator current and the percent torque ripple are within suitable limits.
12.	Using An IFOC, they develop a controller for the first- order-delay slip-angular-frequency [24]	This approach stabilises the secondary flux along the q-axis and allows for a complex torque current to be realised, even during transient responses. The effectiveness of an existing control system can be enhanced through decoupling. where decoupling between the primary IM's d- and q-axis improves torque-current responsiveness.

First, a candidate active vector is chosen using standard MPTC. MPTC is a control strategy used for induction motors (IM) to achieve precise torque control and improve dynamic performance. It is a model-based control technique that employs a mathematical model of the motor to predict its behavior and optimize the control actions. The control system utilizes a predictive model of the motor to estimate its future states, such as rotor flux, stator current, and torque. Based on these predictions, an optimization algorithm solves an optimal control problem to determine the optimal control actions that minimize a defined cost function. This optimization process is repeated at each control interval to continuously update the control actions. Optimization algorithms, such as quadratic programming or gradient-based approaches, are employed to address optimization problems by utilizing the motor model, cost function, prediction horizon, and restrictions. The algorithm determines the optimal control actions that minimize the cost function while satisfying the constraints.

The advantages of MPTC for induction motors include improved torque accuracy, fast torque response, reduced torque ripple, and better dynamic performance compared to conventional control techniques. MPTC can handle nonlinearities, uncertainties, and disturbances effectively through its predictive nature and optimization-based approach.

Additionally, accurate motor modeling and parameter identification are crucial for the effectiveness of MPTC. MPTC is an advanced control strategy for induction motors that leverages predictive modeling and optimization techniques to achieve precise torque control and enhance the performance of the motor system.

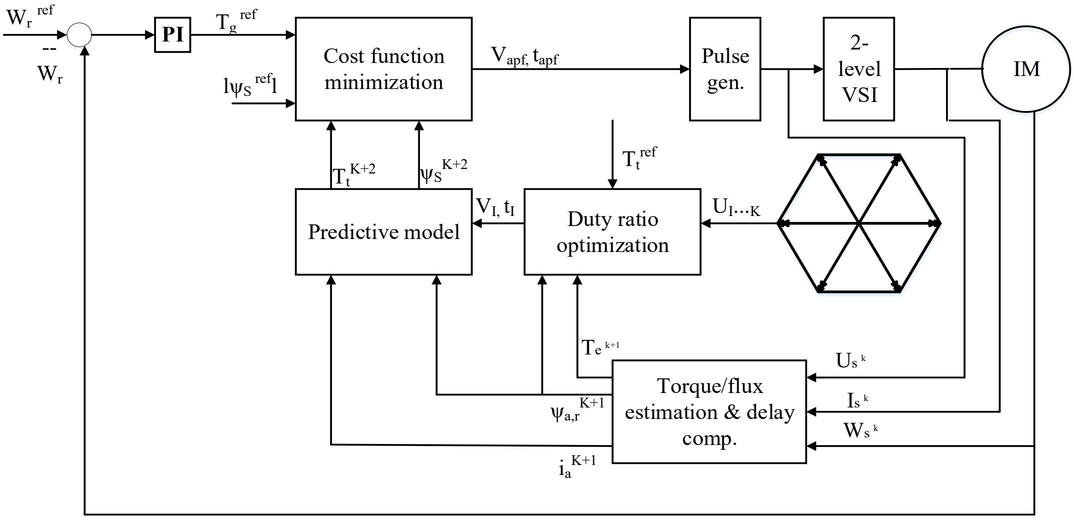

Fig.4 MPTC Senseless Control of IM Drives

C. KALMAN Filter Control Techniques

In simple terms, Kalman filtering techniques are like smart tools that can help control electric motors more accurately. They are especially useful in techniques called Field-Oriented Control or Direct Torque Control. In electric motor control, we want to control two important things: the magnetic power inside the motor (flux) and the twisting power (torque) that makes the motor move. This way, we can control the motor's speed and power precisely. The Kalman filter is like a detective that uses measurements from sensors (like current and voltage sensors) and predictions from a math model to figure out what's really happening inside the motor. It helps us estimate important things like the magnetic power and the motor's speed based on the sensor data. By getting accurate estimates of these motor states, our control algorithms can do a better job at making the motor work efficiently and smoothly. The Kalman filter considers any uncertainties or noise in the sensor data, so it gives us the most likely estimates. Estimating the magnetic power (rotor flux) is crucial because it helps us control the motor's magnetic field properly. By using the sensor data and the Kalman filter, we can figure out the magnetic power while considering how the motor behaves under different conditions.

Kalman filtering techniques are like clever tools that help us control electric motors more effectively by estimating important factors like magnetic power and speed accurately. This makes the motors work better, saving energy and improving their performance. A precise estimate of the rotor speed is necessary for closed-loop control, and here is where speed estimation comes in. Taking into consideration measurement noise and variations, the Kalman filter may be used to estimate the rotor speed from data collected by an encoder or other speed sensors [10].

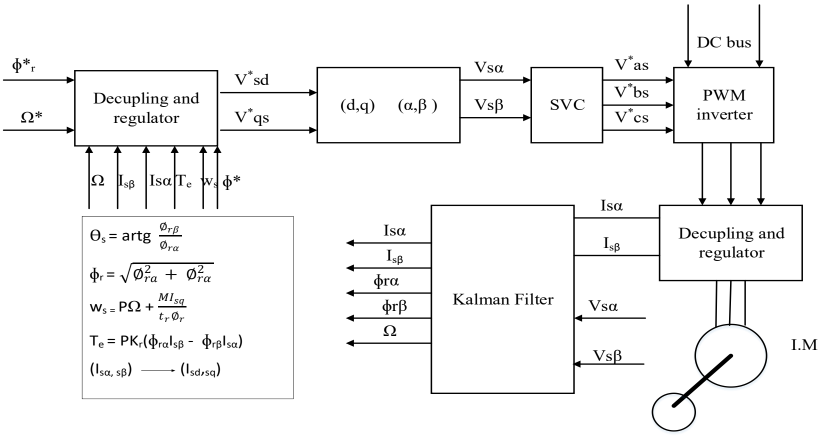

Fig:5 Kalman Filtering Senseless Technique to Speed Control of IM Drives

Kalman filtering may also provide senseless control, which eliminates the requirement for certain physical sensors like speed encoders. Senseless control is performed by calculating the motor's states, such as speed and rotor flux, using just available current and voltage data, hence lowering hardware complexity and expense.

D. Nueral Network based Sensorless Control Technique

A new way to control a three-phase induction motor using a neural network (NN) is proposed. The NN control approach is based on the rotor flux-oriented reference frame. Instead of using two separate controllers like in traditional methods, the proposed NN vector control uses a single neural network controller. The neural network is trained using the Levenberg-Marquardt method to make it work optimally.

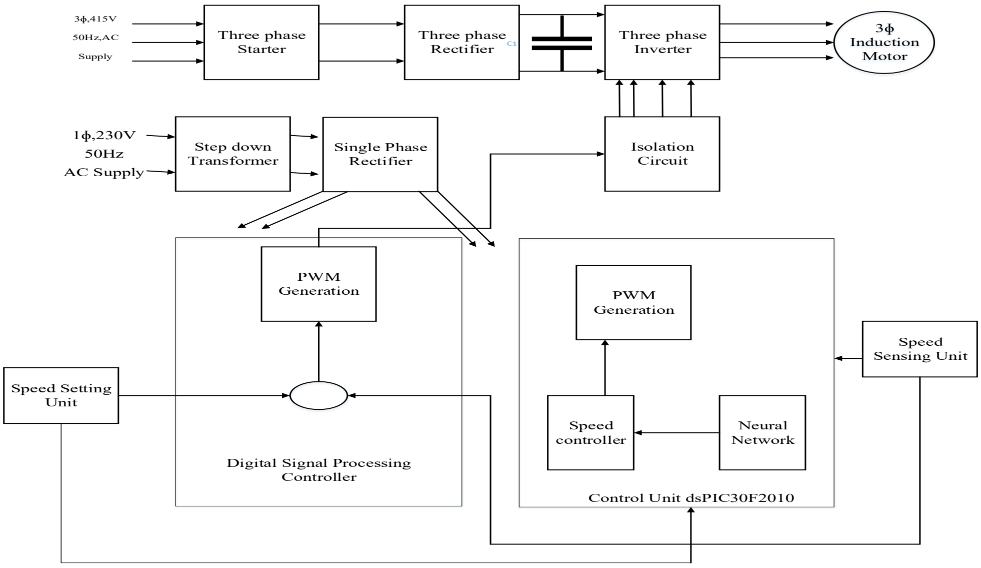

Fig.6- Neural Network Technique for Speed Control of IM Driver

To achieve this, a special algorithm called Forward Accumulation Through Time was created to get the necessary information for training the neural network. Simulations showed that the NN vector control performs better than traditional methods in tracking the current, leading to reduced oscillations and harmonics.

It is also more effective at avoiding detuning effects. Real-world testing confirmed the significant advantages of the NN vector control. It has the potential to make induction motor drive systems more efficient, smaller, and cheaper. Additionally, it can drive the motor without making much noise, even with lower switching frequency or sampling rate compared to traditional control methods [13].

E.Fuzzy based Sensorless Control Technique

Controlling electric motors using fuzzy logic-based senseless control eliminates the need for traditional sensors like speed encoders and position sensors. Fuzzy logic is used instead to estimate the motor's location, speed, or other states since it is a mathematical technique that can handle uncertainty and imprecision. Electrical signals, such as current and voltage readings, are used to observe and analyze the motor's behavior in a senseless control system.

Table IV: Comparison of various Control Techniques

Control Techniques	Advantage	Limitations
V/f Control	Implementation is simple	Poor dynamic response and steady state accuracy
Field Oriented Control (FOC)	Flux and torque are controlled independently	Inadequate dynamic control due to PI controller sensitive to load torque and parameter variation and entail a speed sending device
Classical direct torque (DTC)	Dynamic performance is high and torque response is fast	High torque ripple variable switching frequency and poor flux regulation
DTC-SVPWM	Hysteresis torque has been improved and flux control with SVM technique	More calculation and poor dynamic performance due to saturation in PWM outputs.
DTC-MPTC	Use optimization. With minimum switching losses	Tuning is tedious
DTC-IRRPC	No flux and torque estimation with simple observer	Speed sensor considered necessary.

After collecting these data, fuzzy logic methods are used to draw inferences about the motor's location and speed. This estimate method is well-suited for senseless control applications because it takes into consideration the nonlinear and complicated character of motor dynamics. It's worth noting that senseless control using fuzzy logic has its own set of drawbacks. Under extreme situations, such as low-speed operation or large fluctuations in load, its accuracy may degrade in comparison to sensor-based control approaches. Therefore, the use of senseless control based on fuzzy logic must consider the kind of motor, the required performance, and the accessible resources. It finds widespread usage in a wide range of devices, from fans and pumps to industrial motor drives.

IV. CONCLUSION

For selecting the motor with different application requirements, the through study for latest controller-based drives is necessary and hence this paper examines, the various control techniques applied for speed control of IM drives with modern controllers. The field of motor control has witnessed significant advancements over the years, driven by the need for energy efficiency, precise control, and improved performance in various industrial applications. This review paper has provided a comprehensive overview of the various methods and techniques employed for the speed control of induction motors.

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