International Journal on Emerging Technologies **10**(1): 97-105(2019)

ISSN No. (Print) : 0975-8364
ISSN No. (Online) : 2249-3255

Control Strategies Governing Induction Motors as Industrial Drives– A Technical Review

***Sudeshna Ghosh*[1]*, Pankaj Swarnkar*[1] *and D.M. Deshpande*[2]**
[1]*Electrical Engineering Department, Maulana Azad National Institute of Technology,*
Bhopal (Madhya Pradesh), India
[2]*Retd. Professor, Electrical Engineering Department, Maulana Azad National Institute of Technology,*
Bhopal (Madhya Pradesh), India

(Corresponding author: Sudeshna Ghosh)
(Received 27 February 2019, Revised 25 April 2019 Accepted 05 May 2019)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Induction motors are the main building blocks of the industrial drives employed in industries and foremost element in energy conversion. The variable frequency drives (VFDs) have completely reformed and over taken the constant speed drives along with the advantage of substantial energy saving. Proper design of controller for the VFDs improves the efficacy as well as enhances drive performance. The paper aims to provide an exhaustive evaluation of numerous control techniques for the induction motor drives. A detailed study of various controllers employed for the induction motors have been investigated. The paper attempts to critically analyze the benefits and limitations of the different control techniques and alternative schemes are suggested to overcome the shortcomings of various strategies.

Keywords: Variable Frequency Drives (VFD), Space Vector Modulation (SVM), Fuzzy Logic Controller, Adaptive Controller, Model Reference Adaptive Scheme (MRAS), Pulse-width modulation (PWM).

I. INTRODUCTION

The various market research analysts predict that the global VFD market is growing steadily at an annual growth rate of nearly 8%. The development of medium-voltage (MV) drives started in the mid-1980s along with the development of high-power converters [1]. The power electronic switching devices have rapidly evolved into the key areas of high-power applications due to excellent switching characteristics, reduced power losses, ease of gate control, and snubberless operation. The high power drives have found extensive applications in various engineering and manufacturing sectors. These are used in the petrochemical industry, fans, pumps, compressors, conveyors, traction, robotics, electric vehicles, elevators; rolling mills etc. which is about 85% of the total drive share in the market, remaining 15% are non-standard drives [2-4].
Investigations show that hardly 3% of the total drives are controlled by VFDs while 97% of the presently installed MV motors still operate at a fixed shown in Fig.1 and 2. The VFD has numerous advantages over the fixed speed drives which can be quantified as:

- Controlled Initial Current
- Reduced Power Line Disturbances
- Lower Power Demand on Start
- Adjustable Operating Speed
- Adjustable Torque Limit
- Energy Savings
- Reverse Operation
- Mechanical Drive Components are completely eliminated
- Controlled Stopping
- Controlled Acceleration

Induction motors are primarily used as VFDs or adjustable speed drives (ASDs) which consume a considerable portion of nearly 60% the total energy of the plant. Before the advent of power electronic switches DC drives ruled the industry. DC drives though deal with high torque applications, but at the same time requires high maintenance. Consequently, DC motor drives were essentially replaced with AC motor drives in the past few decades.

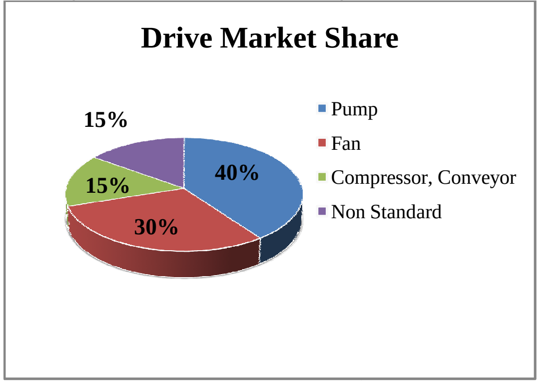

Fig. 1. Load types for the MV drive.

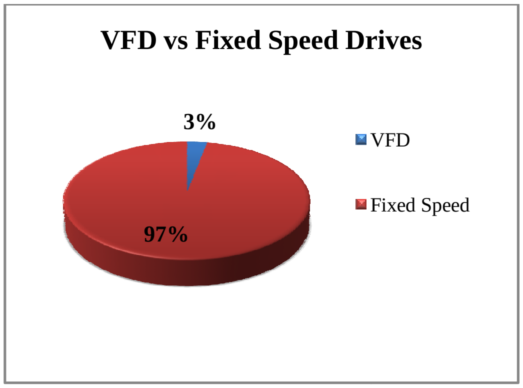

Fig. 2. Fixed Speed vs VFD Drive Share.

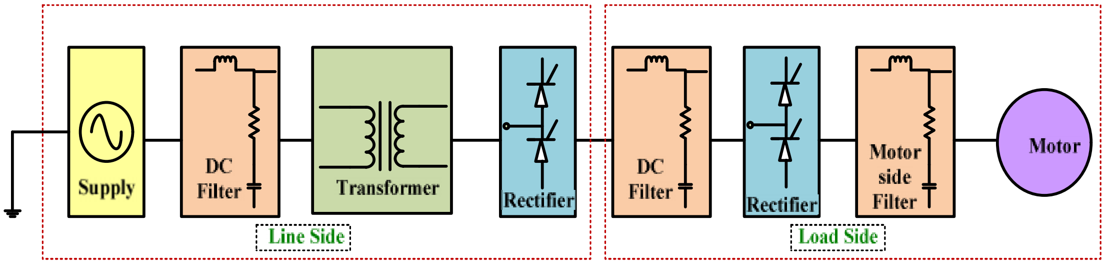

Fig. 3. VFD Block Diagram.

This replacement by the AC drives is equally supported by the unprecedented development at a remarkable pace in the inverter technology [2]. The complete block diagram of the VFD is shown in Fig.3.The solid-state inverters can be categorized according to circuit arrangement into two categories depending on the input source on the DC side (either voltage or current) as a voltage or a current source inverter. Generally, Voltage Source Inverters (VSIs) have high capacity capacitorconnected across the DC source to keep the input voltage constant. They provide voltage with required control over the magnitude, frequency and phase and type of application decides the nature of voltage and frequency whether constant or variable. Voltage source inverters have proved to be a boon in the field of medium and large power segment industrial applications by increasing the reliability and faster dynamic response despite the presence of other circuit topologies. This notable rise was supported by the initiation of fast switching devices with elevated ratings as well as expansion of sophisticated control techniques [5-6].

As stated earlier threephaseinduction motors (IMs) are largelyused inindustrial sector, consumingas large as60%of total electricity of the plant. Therefore, it is mandatory to use motors of high efficacy thus providing reliable operation, thereby providing extensive saving in energy.Theemployed control strategy also decides the performance of AC drives.Thebest possible parameters of the drive can be extracted by selecting a specific controlscheme.Thechoice of a specific controller also depends on the simplicityof thecontroller. The controllers are predominantly divided into vector and scalar based controllers [7-8]. The scalar control strategies have promising advantages out of which few can be enumerated as modeling not depending on parameters, stable controlling in medium to high speed operation, simple design and structure, better steady-state performance, lesser cost and hence, motivated researchers to utilize the scalar control strategy along with DSP [9-11,15]. The vector control technique has emerged as a promising alternative because of exceptional controlling performance for induction motor drives, which can be utilized for position control of flux, current and voltage vectors [12-14, 16-18]. Although the vector control scheme has coupled flux and electromagnetic torque and at the same time the controller shows sensitivity to induction motor parameters which are the two main drawbacks. Hence to overcome these issues direct field oriented control (DFOC) and indirect field oriented control (IFOC) were developed by researchers [8].

Induction motor drives have witnessed the evolution of numerous control techniques. The chronological development was observed with the Proportional Integral Derivative (PID) controllers. Due to their simple design, cost effectiveness they showed an encouraging development. On the other hand, rigorous parameter estimations are required for the PID controller [36-37].

Continuous research and development in the domain of artificial intelligence and optimization techniques has given new dimensions to the controller's altogether. Out of which, controllers based on fuzzy logic became very popular. These have the potential of adapting according to the unexpected changes occurring in the system and are suitable for both linear and non-linear systems. Fuzzy theory is the basis of such controllers and it is based on linguistic rules emulating human brain [25, 39, 41].The fuzzy controller is designed in three steps: 1) fuzzification: converting the inputs into fuzzy sets 2) inference engine: defining the fuzzy rules relating output with input and 3) defuzzification: combining the results of the fuzzy rules, and deduces the decision, which is then converted from fuzzy sets to a crisp value.

Another controller that has attracted many researchers is the sliding mode controllers (SMC) [31].Sliding mode control (SMC) is a nonlinear control method possessing higher degree of accuracy, robustness, and fine tuning and implementation. SMS systems are devised in such a manner, driving system states onto sliding surface. On reaching the sliding surface, states are kept on the close vicinity of the sliding surface. Hence the sliding mode control designs the controller in two parts. In the first part sliding surface is designed so that the sliding motion satisfies design specifications. The second is associated with the proper control law selection thereby attracting the system state to the switching surface. However, chattering phenomenon makes the SMC less desirable. To overcome this issue, few researchers have suggested the fuzzy sliding mode controller (FSMC). Although, the FSMC drastically improves the stability and robustness and has the capability to handle the chattering effect but designing the rules of the FSMC systems is the key challenge in the use of FSMC.

Another technique commonly used in induction motor control is Pulse width modulation (PWM) driving three-phase voltage source inverter [32, 36, 37]. The VSIs are used to regulate the output voltage (AC) and frequency from a supply voltage (constant DC). The key features of the PWM technique are that the output voltage has minimum harmonics, low distortion, high efficiency and low switching losses.

Numerous intelligent techniques and algorithms such as evolutionary algorithms (EA) which are used for the optimization of the controller performance have been reported in the literature [24, 25, 33, 34, 38, 41]. The working principle behind the development of EAs is natural genetic evolution, the Darwin theory and other evolutionary theories.

The neural network proves to enhance the performance of the fuzzy logic speed controller in induction motor drives [40]. Although, the optimization techniques discussed above have capability to improve performance of the control methods, however, these techniques have limitations on optima trapping, local minima, global minimum, trial-and-error procedure and long computational time to attain best optimization performances.

In this paper, various control schemes to enhance the performance and reliability of the variable frequency drives has been compiled. The advantages and limitations of each method are highlighted for various applications of the induction motor drives. Various optimization algorithms have been suggested to overcome the limitations of the control schemes for the development of advanced control system.

Rest of the paper has been structured as follows: Section II presents review of control techniques based on sensors and without sensors. Section III provides review of sensor-less control schemes. Section IV gives the critical analysis of the literature review and finally, Section V presents the conclusion of this paper.

II. CONTROL TECHNIQUES BASED ON SENSORS

Variable frequency drive control techniques for speed, torque, flux, voltage and current control are mainly classified as scalar control technique and vector control technique. The classification of VFD control schemes has been shown in Fig. 4.

A. Scalar Control

The whole induction motor drive systems comprises of the induction motor, load, motor drive (inverter) and control system. The interconnection of these parts and the block diagram of the complete system are shown in Fig. 5. The scalar control was introduced in 1960 for Induction Motor (IM) control. The variable voltage and variable frequency (V/f) control is based on the open and close loop control system of the IM speed while the variable voltage and frequency of the IM is a closed loop control system. The V/f control method is applied to IM drives to achieve the dynamic response and stable performance of the IM. This strategy delivers many benefits including simple design and structure, cheap price and has a minor steady-state error. The V/f control keeps the ratio of scalar voltage and frequency unchanged which maintains the maximum magnetic flux in the air gap. The actual speed has been measured through encoder (speed sensor) and has been utilized as a feedback. The difference of measured speed with the reference speed has been given as an error signal to the proportional-integral controller for generating reference fundamental frequency. The reference fundamental stator frequency helps to obtain amplitude of the fundamental stator voltage. Notably, if open loop control system configuration has been adopted then the speed regulation will be poor and heavily depends on the motor load. On the other hand, the close loop control system can achieve good speed response but still the system not suitable for precise torque control.

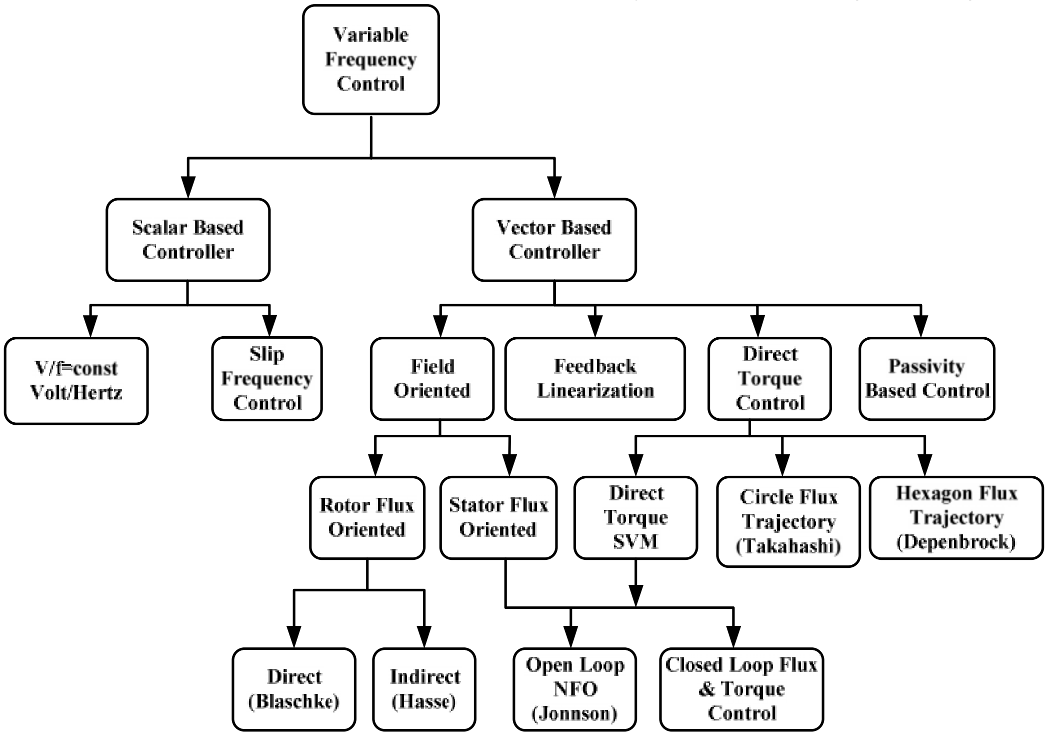

Fig. 4. Induction Motor control schemes.

B. Vector Control

Due to its high performance, the vector control technique is widely used in many induction motor control applications. The magnitude and phase of supply voltages or currents is utilized by the vector control technique to control induction motors. Due to involvement of the phase information, the vector control technique is able to control the position of the flux, voltage, and current vectors of the induction motor. The Clarke and Park transformations are the mathematical tools utilized by the vector control technique for generating torque and flux, respectively. The main drawback of these transformations is the coupling between electromagnetic torque and flux. To address this issue, field oriented control (FOC) has been introduced by various researchers [3, 7, 8, 15, 17].

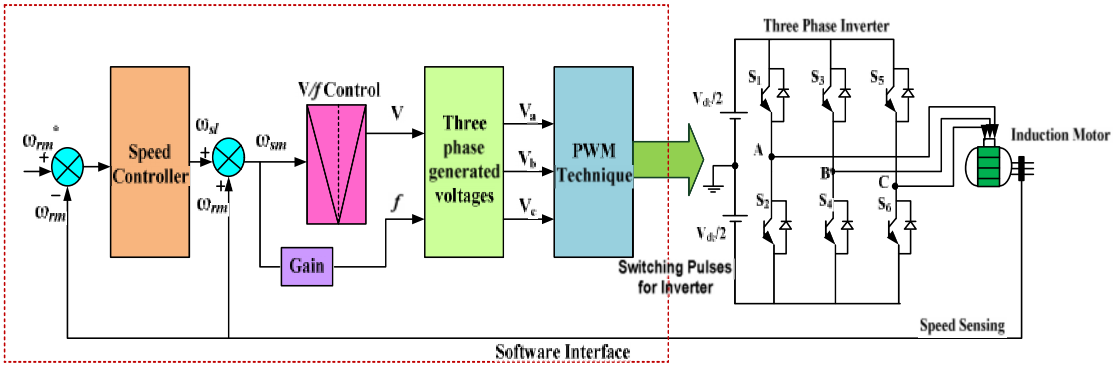

Fig. 5. Closed Loop Scalar Control of Induction Motor.

Field Oriented Control (FOC). FOC was proposed by the Hasse and Blaschke. Many researchers have worked on the improvement of the FOC and now it has become an industrial standard control strategy shown in Fig. 6. FOC scheme utilizes the dynamic model of the induction motor where the fluxes, voltages and currents are represented in space vector forms. The space vector representation is valid for both steady and dynamic conditions and exceptional dynamic response can be achieved due to this feature of FOC. In the rotor flux FOC scheme, the quantities which rotate at synchronous speed appears as DC quantities. In rotating flux reference frame, the 'd' and 'q' components of the stator current represent the flux and torque component respectively if the flux is aligned to the 'd' axis. Thus, in FOC control scheme, the torque and flux components are decoupled thereby providing control of induction motor similar to that of a DC motor [7-8].The FOC can be categorized as: 1) Direct field oriented control (DFOC), in which the information of the terminal variables and rotor speed determines the flux position. 2) In indirect field oriented control (IFOC), in which the summation of the slip position and rotor position give the information of flux position.

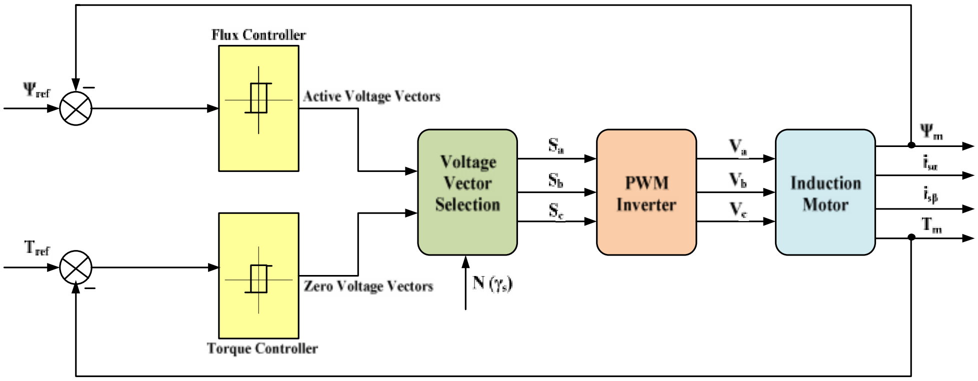

Fig. 6. Direct Torque Control strategy.

Direct Torque Control (DTC). Although FOC was capable to approve the response of the motor but FOC has several drawbacks in its implementation as it needs computationally complex algorithm to transform reference frame. Dependency on the motor parameters and rotor speed makes FOC less preferable. To overcome the challenges posed by FOC, researchers came out with the new control strategy namely; direct torque control (DTC) [1]. Recently, direct self-control (DSC), and classical DTC [13, 19, 20, 22, 23, 26] have emerged as the solution for upgrading of the conventional DTC.

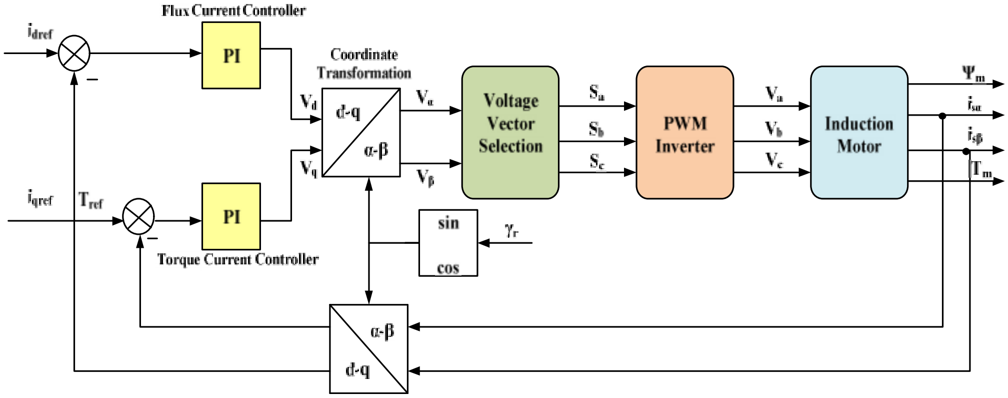

Fig. 7. Direct Torque Control strategy.

The DTC control scheme has an edge over the other strategies like highly reliable, simple, almost insensitive to variation in motor parameters and fast dynamic response. In DTC control scheme, the errors of the flux and torque status are measured and then sent to the hysteresis comparator for digitization. The location of the voltage vector has been identified through the status of the inverter switches. The status of the inverter switches is calculated using a switching table. The principal short comings of using DTC controller are higher ripple content in motor torque and flux and the inconsistent inverter switching frequency. The block diagram of the basic DTC control scheme has been shown in Fig. 7. The comparison of the various control schemes has been summarized in Table 1.

Traditional Controllers. There are different categories of conventional controllers such as PI, PD and PID controllers to regulate Speed, torque, current and voltage [36, 37, 41]. Out of these, the PID controller is considered as most efficient control. PID controller has a simple structure, easy design, low cost and is extensively used to control IM in the industrial application. The structure of a PID controller is depicted in Fig. 8 that takes measured signal and reference value to obtain the error signal for controlling signals such as an error in speed, torque, flux, current, or voltage.

Table 1: Comparison between scalar and vector control techniques.

Control Type	Torque Control	Flux Control	Response	Advantages	Disadvantages
Scalar Frequency Control	None	None	Low	No encoder Simple	No requirement of encoder Simple
Flux Vector Control (FOC)	Indirect	Direct	High	High accuracy Good torque response	Higher accuracy Good torque response
Direct Torque Control (DTC)	Direct	Direct	High	No encoder Moderate speed accuracy Excellent torque response	No encoder Moderate speed accuracy Excellent torque response

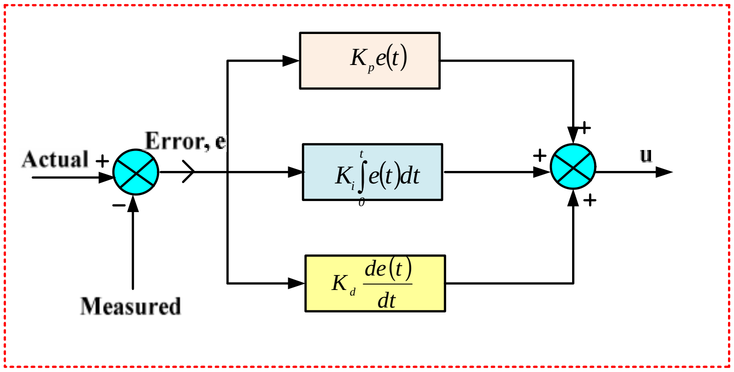

Fig. 8. PID Controller structure.

The output signal of this controller contains the sum of errors that include proportional, integral and derivative of that error, as presented in the equation below:

$$u(t) = K_p e(t) + / K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad \ldots(1)$$

Where *e* is the error e = (x_{actual}-$x_{measured}$), u presents the output signal, K_p, K_i,K_d represents proportional, integral and derivative gain respectively. By wisely selecting the PID parameters performance of the controller can be enhanced. Each of the three parameters significantly contributes in regulating the IM as shown in the Table 2.

Though PID controller has a simple structure, it has many short comings; like sensitivity of the model towards variation in parameters and temerature. Also, the model needs mathematical computation and has a rapid change in reference speed and load disturbances. Furthermore, the choice of the suitable parameters for stability improvement is a tedious process. Hence, various methodologies adopted for fine tuning of PID parameters are Cohen-Coon method, Lambda tuning method, Ziegler-Nichols and visual loop tuning method, and soon. However, these methods prove to pose some drawbacks such as need a mathematical model and some calculation operations, some trial-and-error and process upset. Therefore, optimization techniques ascerta into provide the optimal parameters of PID controller.

Table 2: PID Control Parameters.

Type	Rise time	Overshoot	Settling time	Steady state error
K_p	Reduces	Escalates	Negligible variation	Reduces
K_i	Reduces	Escalates	Escalates	Eliminate
K_d	Negligible variation	Reduces	Reduces	No change

III. SENSORLESS TECHNIQUES

In critical applications of induction motor like compressors, blowers, fans, machine tool, nuclear power plants, off-shore pumping stations and electric vehicles; Sensorless controltechniques could achieve excellent results as far as efficiency and energy savings are concerned.

Sensorless induction motor drives operate without speed sensor and thus are helpful in cost saving and to achieve high reliability [13, 15, 18, 20]. The terminal quantities such as current and voltage are used to estimate the speed. This section of the paper briefly describe the sensorless control methods for induction motor drive for the purpose of energy saving and sustainable reliability. As described in Fig. 9 & 10, sensor-less control techniques could be divided into two categories 1) Model based scheme 2) Signal injection scheme. Details of both schemes have been given below.

A. Modal based Scheme

Mathematically, induction motor in general reference frame could be described by Equation (2) to (5). This mathematical representation of the induction motor could be used in sensorless control schemes to estimate the speed of the induction motor provided that all parameters of the motor are known.

$$V_s = R_s I_s + \frac{d\psi_s}{dt} + j\omega_y \psi_s \qquad \ldots(2)$$

$$0 = R_r I_r + \frac{d\psi_r}{dt} + j(\omega_y - \omega_r)\psi_s \qquad \ldots(3)$$

$$\psi_s = L_s I_s + L_m I_r \qquad \ldots(4)$$

$$\psi r_s = L_r I_r + L_m I_s \qquad \ldots(5)$$

In open loop speed identification, stator flux can be obtained by integrating equation (2), and thus rotor flux can be estimated indirectly. The open loop speed estimation suffers from the drawbacks of sensitivity towards the stator and rotor parameters. Any change in the motor parameters is seriously going to cause degradation of the motor performance employing open loop speed estimator [13, 15]. In order to nullify this impact, closed-loop speed estimator/observer is suggested. Such types of estimators are: i) Model Reference Adaptive System (MRAS): The schematic of the MRAS scheme is depicted in Fig.9. On minimizing the error signal the estimated speed will equal to the actual speed. The MRAS scheme gives better performance within the low speed range of 30-100 rpm [18, 19].

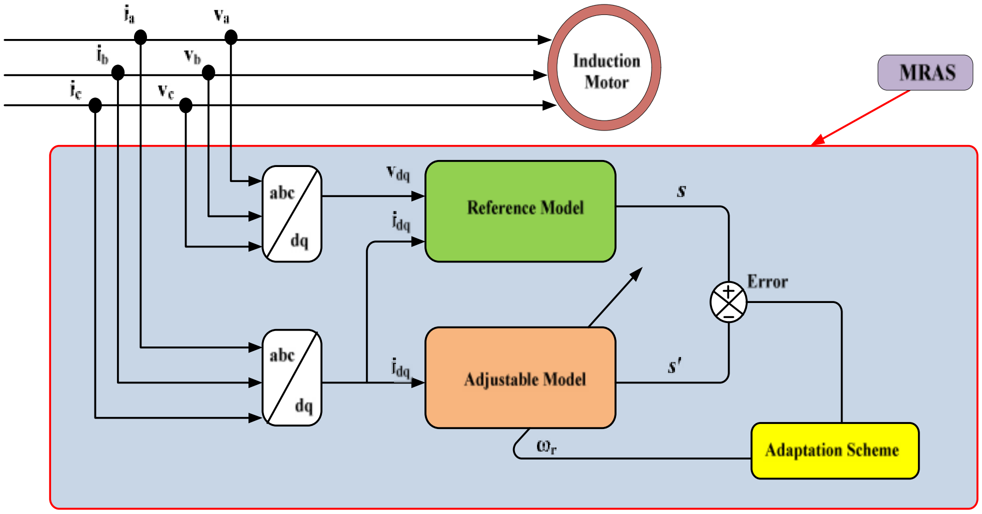

Fig. 9. MRAS Speed Estimation System.

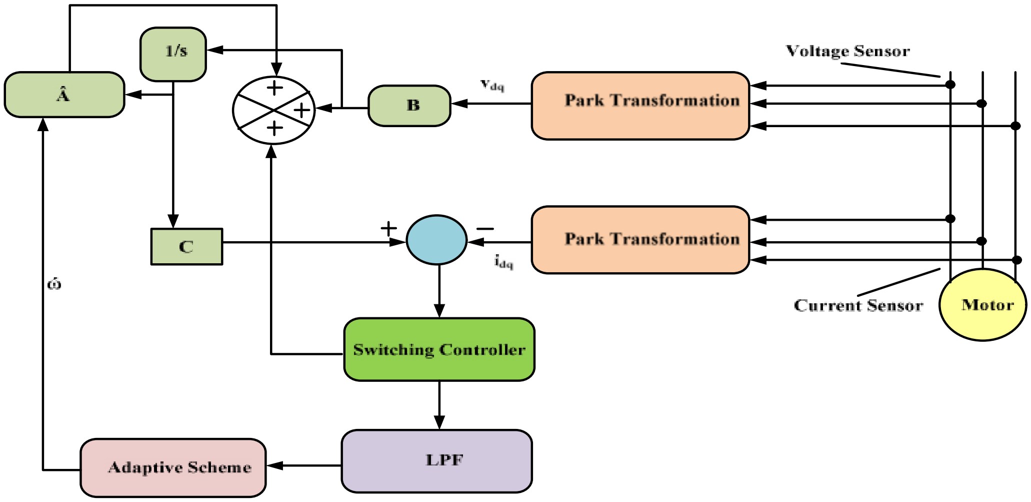

Fig. 10. SMO Speed Estimation Scheme.

However, the performance of the MRAS gets deteriorated due to environmental noise and non-linearity of the power converters, and could not provide acceptable results for speed less than 30 rpm. ii) Full or Reduced Order Observer: This is a highly efficient method for estimating the speed especially during the low speed operations of the motor drive. iii) Sliding

Mode Observer (SMO): This method has significant advantages due to its easy implementation, less design constraints, simplicity, lesser calculations and less sensitive to parameter variations [35]. These features make SMO an effective estimator. However, SMO performance is affected by chattering phenomenon. The block diagram of the SMO is shown in Fig. 10.

B. Signal Injection Scheme

A relatively innovativemethod based on signal injection has gained attention of researchers in recent decade because the model based speed estimation technique has issues of performance degradation due to parameter variations and rotor speed estimation problem at zero stator frequency. SI method is established on the injection of low level signals in the induction motor.The machine will generate the current and voltage through which the speed information could be extracted easily. The essential characteristic is the appropriate selection of magnitude and frequency of the injected signal. Small signal to noise ratio could be maintained by selecting smaller magnitude of the injected signal, though torque ripples would be resulted on selecting larger magnitude of the signal. Similarly, on selecting low frequency of the injected signal, it would be challenging to discriminate it from the fundamental frequency signal. Thus proper choice should be made in selecting the frequency and magnitude of the injected signal. The challenges in this method are to tackle poor signal to noise ratio, low spectral separation and to achieve required frequency tracking. These challenges could be addressed through modern signal processing techniques [42,43]. The general block diagram of the SIS is shown in Fig. 11.

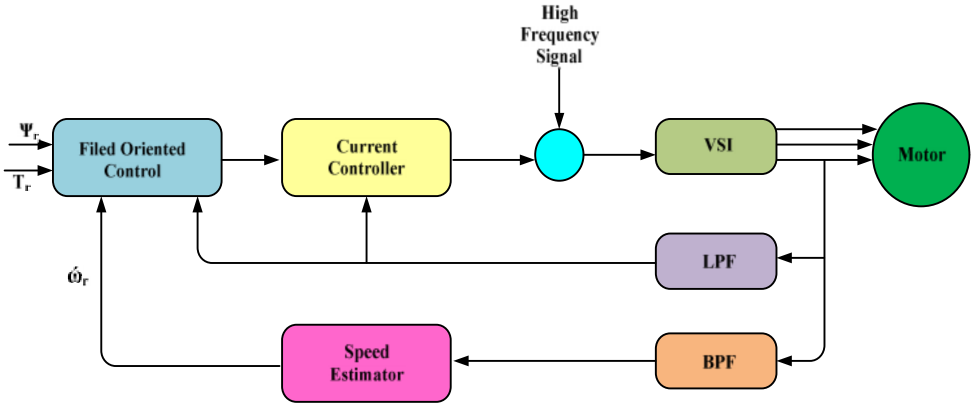

Fig. 11. Signal Injection Scheme Block Diagram.

IV. DISCUSSION AND SUGGESTIONS

Induction motor performance could be improved through various controller techniques. However, there are some challenges in implementing the control techniques. Implementation of the traditional controllers like PID and fuzzy based for induction motor control necessitate appropriate parameters of induction motor which are difficult to attain. Additionally, the sensitivity towards the motor parameters in conventional controllers makes it difficult to design a perfect mathematical model. Any unexpected changes in the loading condition, ambient temperature or reference speed will worsen the performance of the controller [8, 14, 19, 20]. These issues in conventional controllers could be properly taken care by using optimization techniques. The design and development in the electric vehicle technology has tremendously pushed the newest developments in the control techniques of induction motor. The induction motors are used in modern electric vehicles and it is important to develop a control scheme to enhance the performance of the whole system. Although FOC has been the famous control strategy for induction motor but it needs rigorous computation, has low torque response and also produces torque ripples. To overcome these issues of FOC for electric vehicle applications, DTC technique for induction motor control could be alternate choice as it needs simple computation and has faster transient response [13,15,19,32].Although the scalar and vector control systems have been proved to be highly effective control techniques for improving the performance of the induction motors, however, these schemes use expensive speed sensor for the measurement of rotor speed.

Table 3: Summary of the control and speed estimation techniques for improving controller performance.

Reference	Control technique	Speed Estimation/Optimization technique
3	Vector Control	Adaptive
4	FOC	MRAS
10,17	Vector Control	MRAS
12,34,43	DTC	Model Predictive Control
13	DTC	MRAS
15	Vector Control	Sliding mode MRAS
18,19,20	Direct Vector control	Sensorless technique
23	DTC	Lyapunov based control
25,31,33	DTC	Adaptive neuro fuzzy
27	FOC	Adaptive flux observer
29,30	Vector Control	MRAS/PI
31	FOC	Sliding mode/Predictive control
36,37,40	DTC	Fuzzy/PID
39	Vector Control	MRAS/Neural Fuzzy

These speed sensors require access to the motor but sometimes access to the motor is not imaginable in some critical application like nuclear power plants, off-shore pumping stations, blowers, fans. Thus, sensorless control scheme could be a substitute to improve reliability, and reduce high cost of the sensors. In sensorless control scheme, model based control method is best suitable for medium to high speed applications while signal injection method is best suitable for low speed applications. Combination of both will generate good performance for all variable speed drives. Thus, after going through the literature an effort is made to summarize the various control schemes that can be implemented in induction motor drives, which are tabulated in Table 3.

V. CONCLUSION

Induction motors have have emerged as the most powerful machines for energy conversion in industrial sector. The choice of appropriate control scheme can improve efficiency as well as enhance performance significantly and result in considerable power saving.This paper attempts to review various control techniques and recognize their advantages and drawbacks. It has been concluded that choice of proper optimization technique can minimize the limitations of the conventional control schemes. It has also been found from the literature that DTC technique has an upper hand in control applications where fast dynamic response is desired like in electric vehicles, turbines and railway tractions. It has been realizedthat the sensorless topologies are cost effective and highly reliable techniques where applications doesn’t allow access to the motor for speed sensor installation and maintenance.

REFERENCES

[1]. Takahashi and T. Noguchi, (1986). “A new quickresponse and high efficiency control strategy of an Induction motor,” *IEEE Transaction on Industrial Application*, Vol. **22**, Issue 5pp. 820-827.

[2]. S. Malik and D. Kluge, “ACS1000 World’s First Standard AC Drive for Medium-VoltageApplications,” ABB Review.

[3]. Colin Schauder, (1992). “Adaptive Speed Identification for Vector Control of Induction Motors without Rotational Transducers,”. *IEEE Transactions on Industry Applications*, Vol. **28**, No. 5, pp.1054-1061.

[4]. Li Zhen, and Longya Xu, (1998). “Sensorless Field Orientation Control of Induction Machines Based on a Mutual MRAS Scheme,” *IEEE Transactions on Industrial Electronics*, Vol. **45**, No. 5, pp. 824-831.

[5]. P. K. Steimer, H. E. Gruning, *et al.,* (1999). “IGCT— A New Emerging Technology for High Power Low Cost Inverters,”. *IEEE Industry Application Magazine*, pp. 12–18.

[6]. R. Bhatia, H.U. Krattiger, A. Bonanini, *et al.,* (1998). “Adjustable Speed Drive with a Single100-MW Synchronous Motor,”*ABB Review*, No. 6, pp. 14–20.

[7]. Domenico Casadei, Francesco Profumo, Giovanni Serra, and Angelo Tani, (2002). “FOC and DTC: Two Viable Schemes for Induction Motors Torque Control,”. *IEEE Transactions on Power Electronics*, Vol. **17**, No. 5, pp. 779-787.

[8]. H.A. Toliyat, E. Levi, and M. Raina, (2003). “A review of RFO induction motor parameter estimation techniques,” *IEEE Trans. Energy Conversion*, Vol. **18**, No. 2, pp. 271–283.

[9]. S. Rizzo and N. Zargari, (2004). “Medium Voltage Drives: What Does the Future Hold,”. *4th International Power Electronics and Motional Control Conference (IPEMC),* pp. 82–89.

[10]. Chul-Woo Park and Woo-Hyen Kwon, (2004). “Simple and robust speed sensorless vector control of induction motor using stator current based MRAC,” *Electric Power Systems Research,* Vol. **71**, Issue 3, pp. 257-266.

[11]. Chul-Woo Park and Woo-Hyen Kwon, (2004). “Time-delay compensation for induction motor vector control system,”. *Electric Power Systems Research*, Vol. **68**, Issue 3, pp. 238-247.

[12]. Geyer T., Papafotiou G. (2005). “Direct Torque Control for Induction Motor Drives: A Model Predictive Control Approach Based on Feasibility. In: Morari M., Thiele L. (eds) Hybrid Systems: Computation and Contro, HSCC Lecture Notes in Computer Science, Vol. **3414**. Springer, Berlin, Heidelberg.

[13]. Maurizio Cirrincione, Marcello Pucci, (2005). “Sensorless direct torque control of an induction motor by a TLS-based MRAS observer with adaptive integration,” *Automatica*, Vol. **41**, Issue 11, pp. 1843-1854.

[14]. D. Casadei, G. Serra, A. Tani, And L. Zarri, (2006). “Assessment of direct torque control for induction motor drives”, *Bulletin of The Polish Academy of Sciences Technical Sciences*, Vol. **54**, No. 3, pp.237-254.

[15]. Mihai Comanescu, and Longya Xu, (2006). “Sliding-Mode MRAS Speed Estimators for Sensorless Vector Control of Induction Machine,” *IEEE Transactions on Industrial Electronics*, Vol. **53**, No. 1,pp-146-153.

[16]. John W. Finch, and Damian Giaouris, (2008). “Controlled AC Electrical Drives,” *IEEE Transactions On Industrial Electronics,* Vol. **55**, No. 2, pp. 481-490.

[17]. Suman, Maiti, Chandan, Chakraborty, Yoichi, Hori, and Minh C. Ta, (2008). “Model Reference Adaptive Controller-based Rotor Resistance and Speed Estimation Techniques for Vector Controlled Induction Motor Drive Utilizing Reactive Power,” *IEEE Transactions on Industrial Electronics*, Vol. **55**, No. 2, pp. 594-60.

[18]. M. Menaaa, O. Touhamib, R. Ibtiouenb, M. Fadel, (2008). “Sensorless direct vector control of an induction motor,”. *Control Engineering Practice*, Vol. **16**, Issue 1, pp. 67-77.

[19]. Kyo-Beum Lee, and Frede Blaabjerg, (2008). “Sensorless DTC-SVM for Induction Motor Driven by a Matrix Converter using a Parameter Estimation Strategy,”. *IEEE Transactions On Industrial Electronics,* Vol. **55**, No. 2.

[20]. A. Abbou and H. Mahmoudi, (2009). “Performance of a Sensorless Speed Control for Induction Motor Using DTFC strategy and Intelligent Techniques,” *Journal of Electrical Systems*, Vol. **3**, No. 5, pp.64-81.

[21]. M.R. Arahal, F. Barrero, S. Toral, M. Duran, R.Gregor, (2009). “Multi-phase current control using finite-state model-predictive control,” *Control Engineering Practice*, **17**, pp. 579–587.

[22]. Badii Bouzidi, Abderrazak Yangui, Abdessattar guermazi and Ahmed Masmoudi, (2009). “DTC Based Position Control Induction Motor a Comparison Between Different Strategies,” *6th IEEE International Multi-Conference on Systems, Signals and Devices*.

[23]. Miran Rodic and Karel Jezernik, (2009). “Lyapunov Based Predictive DTC Algorithm for Induction Motors,” *13th IEEE European Conference on Power Electronics and Applications*, pp. 1-10.

[24]. H. Ibrahim Okumus and Mustafa Aktas, (2010). “Adaptive hysteresis band control for constant switching frequency in DTC induction machine drives,” *Turkish Journal of Electrical Engineering & Computer Science*, Vol. **18**, No.1, pp.59-69.

[25]. Fayez G. Areed, Amira Y. Haikal, Reham H. Mohammed, (2010). “Adaptive neuro-fuzzy control of an induction motor,” *Ain Shams Engineering Journal*, Vol. **1**, Issue 1, pp. 71-78.

[26]. Vahid Faraji and Davood Arab Khaburi, (2011). “A New Approach to DTC-ISVM for Induction Motor Drive System Fed by Indirect Matrix Converter,” *2nd IEEE Power Electronics, Drive Systems and Technologies Conference,* pp. 367-372.

[27]. Mohamed S. Zaky, (2011). “A stable adaptive flux observer for a very low speed-sensorless induction motor drives insensitive to stator resistance variations,” *Ain Shams Engineering Journal,* Vol. **2**, Issue 1, pp. 11-20.

[28]. M. Farasat and E. Karaman, (2011). “Speed Sensorless Electric Vehicle Propulsion System Using Hybrid FOC-DTC Induction Motor Drive,” *IEEE International Conference on Electrical Machines and Systems.* pp 1-5.

[29]. Missula Jagath Vallabhai, Pankaj Swarnkar, D.M. Deshpande,(2012). “Comparative Analysis of PI Control and Model Reference Adaptive Control Based Vector Control Strategy for Induction Motor Drive,” *International Journal of Engineering Research and Applications (IJERA)* Vol. **2**, Issue 3, pp. 2059-2070.

[30]. Missula Jagath Vallabhai, Pankaj Swarnkar, D.M. Deshpande,(2012). “PI Control Based Vector Control Strategy for Induction Motor Drive,” *Internatonal Journal of Electronics Communication and Computer Engineering*, Vol. **3**, Issue 2, pp.328-335.

[31]. Seyed Alireza Davari, Davood Arab Khaburi, Fengxiang Wang, Ralph Kennel, (2013). “Robust sensorless predictive control of induction motors with sliding mode Voltage model observer,” *Turkish Journal of Electrical Engineering & Computer Sciences*, Vol. **21**, pp.1539-1552.

[32]. Bhoopendra Singh, Shailendra Jain, Sanjeet Dwivedi,(2013). “Torque ripple reduction technique with improved flux response for a direct torque control induction motor drive,” *IET Power Electronics*, Vol. **6** , Issue: 2, pp. 326-342.

[33]. M. Hafeez, M. Nasir Uddin, Nasrudin Abd. Rahim and Hew Wooi Ping,(2014). “Self-Tuned NFC and Adaptive Torque Hysteresis-Based DTC Scheme for IM Drive,”. *IEEE Transactions On Industry Applications*, Vol. **50**, No. 2, pp. 1410-1420.

[34]. Petros Karamanakos, Peter Stolze, Ralph M. Kennel, Stefanos Manias and Hendrik du Toit Mouton,(2014). “Variable Switching Point Predictive Torque Control of Induction Machines,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol. **2**, No. 2,pp. 285-295.

[35]. Fethi, Farhani & Zaafouri, Abderrahmen & Chaari, Abdelkader, (2014). “Gain-scheduled Adaptive Observer for Induction Motors: An LMI Approach,” *Acta Polytechnica Hungarica.* **11**. pp.49-61.

[36]. Vahedpour, M., Noei, A. R., and Kholerdi, H. A., (2015). “Comparison Between Performance of Conventional, Fuzzy and Fractional Order PID Controllers in Practical Speed Control of Induction Motor,” *2nd International Conference on Knowledge – Based Engineering and Innovation (KBEI), Iran University of Science and Technology, Tahran, Iran.*

[37]. Wei Xie and Jianmin Duan, (2015). “The Design and Simulation of Fuzzy PID Parameter Self-tuning Controller,”. *TELKOMNIKA Indonesian Journal of Electrical Engineering,* Vol.**14**, Issue 2, pp.293-297.

[38]. Nagamani Chandra sekara, Somanatham R, Chaitanya Kumar U, (2015). “Design and Analysis of Drive System with Slip Ring Induction Motor for Electric Traction in India,”. *International Journal of Power Electronics and Drive Systems,* Vol. **5**, No.3, pp.374-381.

[39]. V. S. S. Pavan Kumar Hari, and G. Narayanan, (2016). “Space-Vector-Based Hybrid PWM Technique to Reduce Peak-to-Peak Torque Ripple in Induction Motor Drives,”*IEEE Transactions On Industry Applications*, Vol. **52**, No. 2, pp.14789-1499.

[40]. Venkadesan Arunachalam, Himavathi Srinivasan and A. Muthuramalingam, (2016). “A novel NN based rotor flux MRAS to overcome low speed problems for rotor resistance estimation in vector controlled IM Drives,” *Frontiers in Energy*, Vol. **10**, Issue 4,pp. 382-392.

[41]. Mohamed E., El-Shimy and S.A. Zaid, (2016). “Fuzzy PID Controller for Fast Direct Torque Control of Induction Motor Drives.” *Journal of Electrical Systems*, Vol. **2**, Issue 4, pp. 687-700.

[42]. Roslina Mat Ariff, Dirman Hanafi, Wahyu Mulyo Utomo, Nooradzianie Muhammad Zin,Sy Yi Sim, Azuwien Aida Bohari, (2017). “Takagi-Sugeno Fuzzy Perpose as Speed Controller in IndirectField Oriented Control of Induction Motor Drive,” *International Journal of Power Electronics and Drive System (IJPEDS),* Vol. **8**, No. 2, pp. 513-521.

[43]. Wenxiang Song, Shengkang Le, Xiaoxin Wu, and Yi Ruan, (2017). “An Improved Model Predictive Direct TorqueControl for Induction Machine Drives”, *Journal of Power Electronics*, Vol. **17**, No. 3, pp. 674-685.

How to cite this article: Ghosh, Sudeshna, Swarnkar, Pankaj and Deshpande, D.M. (2019). Control Strategies governing Induction Motors as Industrial Drives–A Technical Review. *International Journal on Emerging Technologies,* **10**(1): 97-105.