Advanced Control Methods of Induction Motor: A Review

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Abstract: ***In this paper, various types of advanced control methods of the induction motor are discussed, and a comparision between these methods have been brought out. This paper also discusses about the application areas of these new methods. The objective of this review is to conclude which method is the best control scheme among all of these methods. The related block diagrams for various control schemes are also illustrated along with various steps involved in the implementation of those schemes. Advantages and disadvantages of the schemes are also presented.***

Keywords: Scalar Control, Vector Control, Direct Torque Control, PID controller, SMC Control

1. Introduction

In 1891, Nikola Tesla presented prototype of a poly-phase induction motor at the Frankfurt exhibition [27]. From that onwards, the Induction motor is widely used in many residential, industrial, commercial, and utility applications like Large fans, centrifuges, long conveyor belts, electric vehicles, water pumping etc. Induction motors are so popular because of its low manufacturing cost, wide speed range, high-speed efficiencies and robustness [1]. All such application required constant speed drive as well as variable speed drive. There are various conventional methods for variation of rotor speed. Some of them are inserting a rotor resistance in series with the three-phase winding [2], changing the no of stator poles [3], Stator voltage control [4], Supply frequency control [5] etc. All of the above control methods are not economical and less efficient. In the applications where accurate control is required, they are not feasible. So looking for an advanced control scheme is necessary. Due to the development of power electronics devices, speed can be controlled to a larger extent. Even though, efficiency has not much improved. In order to achieve all such desired condition of a drive, it requires advanced control schemes. So, new controlling methods are being built up nowadays. Some of them are not yet practically implemented.

2. Background Details

Three phase Induction motors are the self-starting motors. It is also a constant speed motor. Hence it is difficult to control its speed; while controlling the speed of induction motor, it has to sacrifices its efficiency and power factor.

In electrical ac machines, there are two speed-related terms - synchronous speed and rated speed. Synchronous speed is the speed at which magnetic field rotates. It is theoretical speed when there is no load on the shaft and friction in the bearing. Synchronous speed depends upon the two factors- frequency and pole.

Synchronous speed in RPM, $N_s = 120f / P$ .... (1)
Where f = frequency (Hz)
P = No. of poles

Rated speed is the maximum speed of the motor, at which motor is allowed to achieve to work properly. It depends upon the power input to the motor.
$N = N_s (1\text{-}s)$ .... (2)
Where N_s = Synchronous speed, s = slip
N = speed of rotor

The percentage difference in synchronous speed and shaft speed is called slip, given by

$s = (N_s - N_r) / N_s$ .... (3)
Where N_s = Synchronous speed
N_r = Rotor speed

Shaft speed of Induction motor is always less than the synchronous speed when driving the load.

Torque produce by Induction motor depends upon the following parameters - rotor EMF, rotor resistance, inductive reactance and synchronous speed.

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \quad \text{.................. (4)}$$

Where, E_2 = the rotor emf
N_s = the synchronous speed
R_2 = the rotor resistance
X_2 = the rotor inductive reactance

At the starting stage, torque must be high and speed will be less. In the running stage, speed is high and torque reduces. Hence, torque can be increased by varying the above parameters. By varying rotor resistance and inductive reactance, it adds extra cost; also it can be applied only in the slip ring induction motor. So, the best way for controlling torque is voltage.

$$N_s \infty \frac{f}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

From the above equation, it can be seen that synchronous speed is directly proportional to frequency and inversely proportional to the pole number. The number of poles of a given machine is fixed, so the speed varying can be done by varying frequency.

3. Control Methods of Induction Motor

3.1 Scalar Control (V/F)

The Scalar Control method is an open loop control scheme, in which no feedback system is required. Synchronous speed can be control by varying the supply frequency f. The voltage induced in the stator is directly proportional to ϕ, where ϕ is the air-gap flux. As we can neglect the stator voltage, we obtain terminal voltage directly proportional to ϕ. Thus reducing the frequency without changing the supply voltage will cause an increase in the air-gap flux, which is considerable. Hence, whenever frequency is varied, the terminal voltage is also varied in order to maintain the V/F ratio constant. Thus by maintaining a constant V/F ratio, the maximum torque of the motor can keep constant for changing speed [6,7].

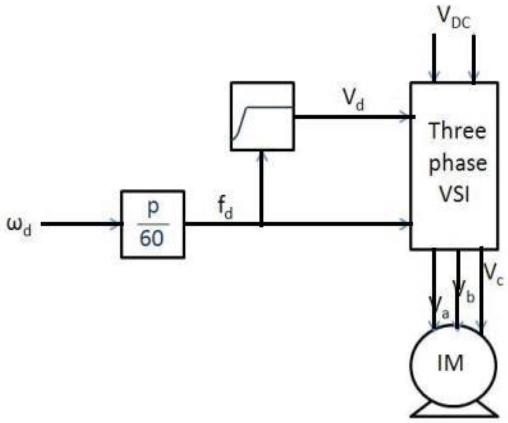

Fig. 1: Open loop V/F control of IM [8]

3.2 Vector control

Vector control is controlling of an ac motor similar to a dc motor by the use of feedback control. It is compulsory to perform d-q transformation [9,10,11,12]. By this method, fast torque response can be achieved.

Steps followed in vector control:

1. d-q transformation
2. Speed estimation
3. Generating error signal from reference and measure speed
4. The error signal is fed to the controller to generate a torque reference signal
5. Calculation of current for d and q axis, the position of rotor flux and transformation into a real model
6. Generation of PWM signal for an inverter.

There are two methods to detect rotor flux position:

i) Direct vector method
ii) Indirect vector method

i) Direct vector method

In this method, flux sensing coils or the Hall devices are used to measure the flux. It adds extra cost, also the result is not highly accurate [13,14].

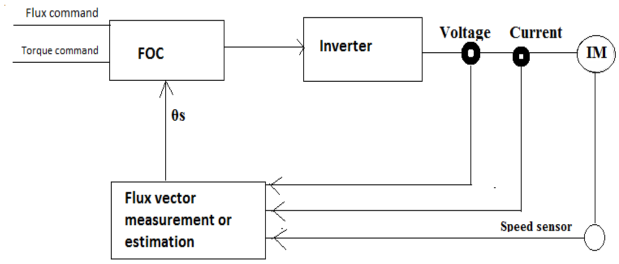

Fig. 2: Direct vector control [14]

ii) Indirect Vector method

In this method, flux angle is not measured directly; instead, it is estimated from the equivalent circuit diagram, measurement of rotor speed, stator current and voltage [14].

Application: Robotics and factory automation.

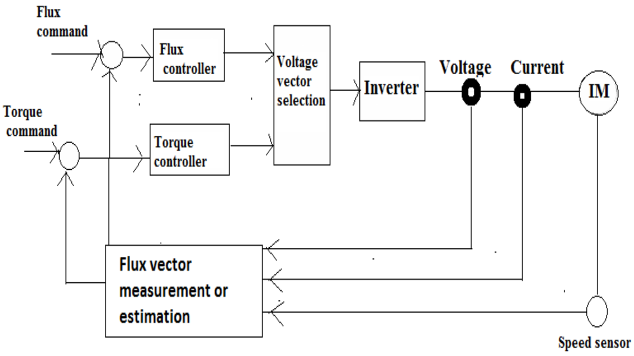

Fig. 3: Indirect vector control [14]

3.3 Direct Torque Control (DTL)

The DTC scheme is no need for d-q transformation. In this case, torque and the stator flux are estimated and directly controlled by applying the appropriate stator voltage vector [15,16].

Advantages:
1. Fastest response time
2. Eliminating the need for a rotor speed sensor
3. Elimination of feedback devices
4. Reduce mechanical failure.

Disadvantages:
1 Inherent hysteresis of the comparator
2. Higher torque
3. Flux ripple exist.

Fig. 4 shows a block diagram of the overall system.

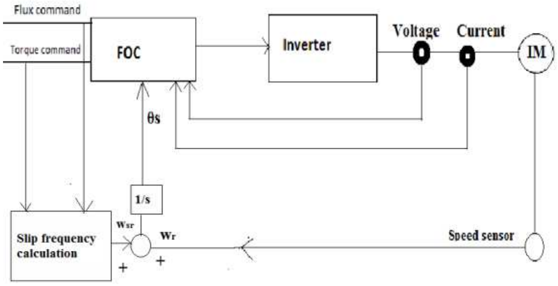

Fig. 4: Direct torque control [14]

Steps followed in DTL:
1. Speed and torque are estimated
2. Estimated speed is compared with the desired value
3. Error signal acts on PI controller to generate reference torque signal.
4. Estimated speed generates a reference signal for the stator flux linkage.
5. Error in torque and stator flux, combined with the angular position of the stator linkage space vector, determines the stator voltage space vector.

Application: Variable speed control.

3.4 Proportional Integral Derivative controller (PID controller)

A PID controller is a feedback control system, which calculates an error value $e(t)$ as the difference between the reference value and a measured variable and applies a correction based on proportional, integral, and derivative terms continuously [17,18,19]. The controller attempts to minimize the error signal by adjustment of a control variable $u(t)$ to a new value determined by a weighted sum:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt}$$

Where K_p, K_i and K_d denote the coefficients for the proportional, integral, and derivative terms respectively [19].

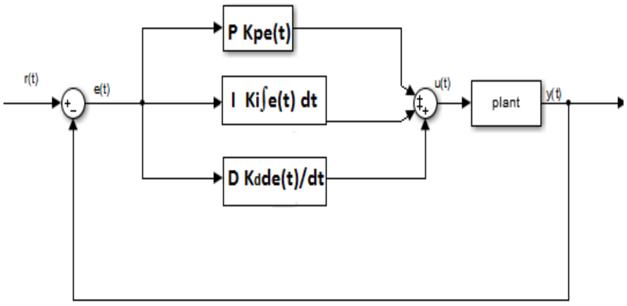

Fig. 5: A block diagram of a PID controller in a feedback loop [17]

In this model,
P - works for present values of the error.
I - works for past values of the error.
D - works for possible future trends of the error.

Increasing the Proportional gain (K_p) will reduce the rise time but never eliminates the steady-state error. Introducing the Integral gain (K_i) will help to reduce the steady state error, but it makes the system very sluggish (and oscillatory), thereby making the transient response very poor. The effect of adding a Derivative gain (K_d) is increase in the stability of the system, reduction in the overshoot, and improvement in the transient response (but no effect on the steady-state error). The general effect of each controller parameter (K_p, K_i, K_d) independently on a closed loop feedback system have been summarized in Table 1.

Table 1: Effects of the parameters K_p, K_i, K_d on closed loop system [19]

Parameter	Rise Time	Overshoot	Settling Time	S-S Error
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Decrease
K_d	Small Change	Decrease	Decrease	No Change

This table should be used for only reference, because this correlation may not be exactly accurate and K_p, K_i & K_d are dependent on each other. In fact, changing one of these variables can change the effect of the other two [19].

3.4.1 PID in Induction Motor Control

Mostly, induction motors are controlled by PI controller [20]. Measured speed is compared with the pre-set value, and the error signal is sent to the PI controller. Based on the error signal, PWM signals are generated and fed to the inverter. From the inverter, enough amount of current and voltage are generated for the correction of speed or torque as shown in Fig. 6. Thus, the desired speed is obtained.

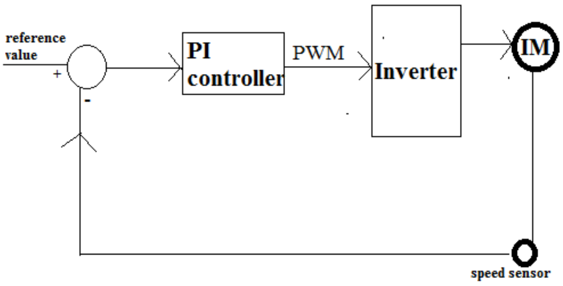

Fig. 6: PI control of Induction Motor

3.5 Sliding Mode Control (SMC)

Sliding mode control is a nonlinear variable control method that a nonlinear system is controlled by a discontinuous control signal. The feedback control law is not a continuous function of time. It can switch from one condition structure to another condition structure according to the current position state. Multiple control laws are designed for a system against different dynamics conditions in order to bring the system in the desired trajectory. The motion of the system, as it slides within the boundaries, is called sliding mode and the surface, where the set of points are defined within the boundaries is called sliding surface [21,22,23].

Advantages:
1. It takes a finite time to reach sliding surface
2. It's Robustness

Applications:
1. Robotics
2. Electric drives

3.5.1 SMC in induction motor control

Sliding mode control is an advanced control method used in many of the applications, like control of induction motor. Here, the trajectory to be followed by the rotor is defined with the control law. A motor can experience different unwanted disturbances, but by ignoring it, the motor must follow the trajectory. Here in Fig. 7, measured speed is compared with the reference; and with this information, fast switching action will be performed in order to bring the motor in the desired condition within a finite time.

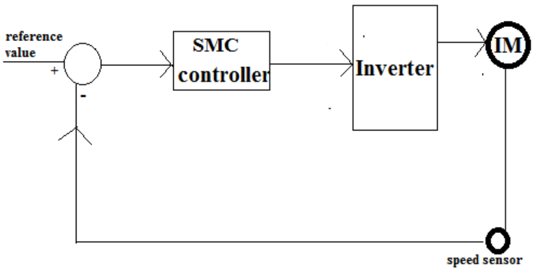

Fig. 7: SMC control of induction motor

4. Comparision of Different Controllers

Table 2 shows the comparision between Scalar and Vector Control. Table 3 shows the comparision between Vector Control and Direct Torque Control (DTC). Table 4 depicts the comparision between PID control and SMC methods. Lastly, Table 5 compares the performances of PID and Sliding Mode Controllers for a change in load at 1.5 sec (after simulation begins), has been shown in Table 5.

Table 2: Comparison between Scalar and Vector Controls [8,24]

Comparison Aspects	**Scalar V/F control**	**Vector control IM**
Speed response	Speed varies at all load conditions	Good speed response with some overshoot
Torque response	In low speed ranges large torques are obtained	Ripples are less
Transient response	Slow	Fast
Difficulty level	Easy	Tough

Table 3: Comparison between Vector Control and Direct Torque Control (DTC) [26]

Comparison Aspects	**Vector Control**	**Direct Torque Control**
Speed Response	Fast and robust	Fastest
Torque response	Faster but spiky	Better torque response
Flux response	Slower and it is affected by the load	Faster and stable
Ease of implementation	Complicated because of the transformation	Easy
V-sag / Interruptions	Speed deviates gradually Current increases gradually	Speed reaches zero at certain points, Current doesn't increase and it falls suddenly

Table 4: Comparative results of PID and SMC [28]

Controller	%max. overshoot (M_p)	Rise Time (T_r)	Settling Time (T_s)
PI Controller	11.89	38.7 msec	0.8021 sec
Sliding Mode Controller	-	22.2 msec	0.0362 sec

Table 5: Performances of PI and SMC Controllers for a change in load at 1.5 sec after simulation begins [28]

Controller	%drop rotor speed for Load of 10 N-m	%drop rotor speed for Load of 15 N-m
PI Controller	14.11	21.31
Sliding Mode Controller	0.036	0.071

5. Conclusion and Feature Scope

All the controller schemes, which have been mentioned in this paper, have advantages as well as disadvantages according to the area of application. Indeed, the most error-free, more accurate control scheme is preferable. All the conventional methods cannot be forgotten; because of the development of them, it has been possible to come up to this advanced stage. Among the above controlling schemes, newly implemented in most advanced systems is the Sliding Mode Control (SMC). In SMC, there are still problems yet to solve. Finding a new strategy to solve the problems is required. Advanced control design can lead to advanced systems.

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