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Induction Motor Drives-A Literature Review

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ABSTRACT

A review of literature for Electrical machines and power electronics over the past 40 years shows a pattern of circuit invention, loss and reinvention, often times repeated. This has ensued in a great waste of time and effort as well as perpetual legal wrangling and the loss of useful ideas for long periods of time and there is a need to overcome the shortcomings. This paper gives an overview of the induction motor (IM) drives. It also examines various control methodologies, using voltage and current control. The literature survey for industrial controls and power electronics over last three decades shows design of Multi converters in high power applications is often repeated. It, therefore, analyse the progress made in induction machine drive research and development since its inception. Efforts are made to highlight the current and future issues involved for the development of induction machine drive technology for future applications. Important inventions from overseas and their impact are also discussed. Authors strongly believe that this article shall be very much helpful to the researchers working in the field IM drives for finding out the relevant references.

Keywords: Induction motor drives, Power electronics, Multi converters.

1. INTRODUCTION

Hitherto, in the most of the applications, AC machines are preferable over DC machines due to their simple and most robust construction. Earlier only dc motors were employed for drives requiring variable speeds due to facilitate of their speed control methods [1]. The conventional methods of speed control of an induction motor were either too extravagant or too inefficient thus limiting their application to only constant speed drives. Today, with advancements in power electronics, microcontrollers, and digital signal processors (DSPs), electric drive systems have improved drastically. Power electronic drives are more reliable, more efficient, and less expensive. Indeed, a power electronic drive on average consumes 25% less energy than a typical motor drive system. Approximately, 60% of loads in all over the world are motor loads. More than 90% of these loads are consumed by three phase induction motors with a big utility factor between 0/7-0.9 in a day and most of them are utilized in industrial factories. The advancements in solid-state technology is making it possible to build the essential power electronic converters for electric drive systems. A brief classification of the available drive types [2] is given in Figure 1.

Induction motors are the most widely used motors in industry. About 60% of the industrial electric energy is converted into mechanical energy by means of pumps, fans, adjustable speed drives and machine tools equipped with induction motors. However, modern trends and development of speed control methods of an induction motor have increased the use of induction motors in electrical drives extensively. Thus, considerable research efforts have been focused on topics like modeling and parameter estimation of induction motors.

It has been suggested that Electrical machines is a mature field with limited further scope, while recent work has explored speed control of machines as they approach their limits in terms of technical measures. These are valuable studies, and we will discuss to these thoughts later.

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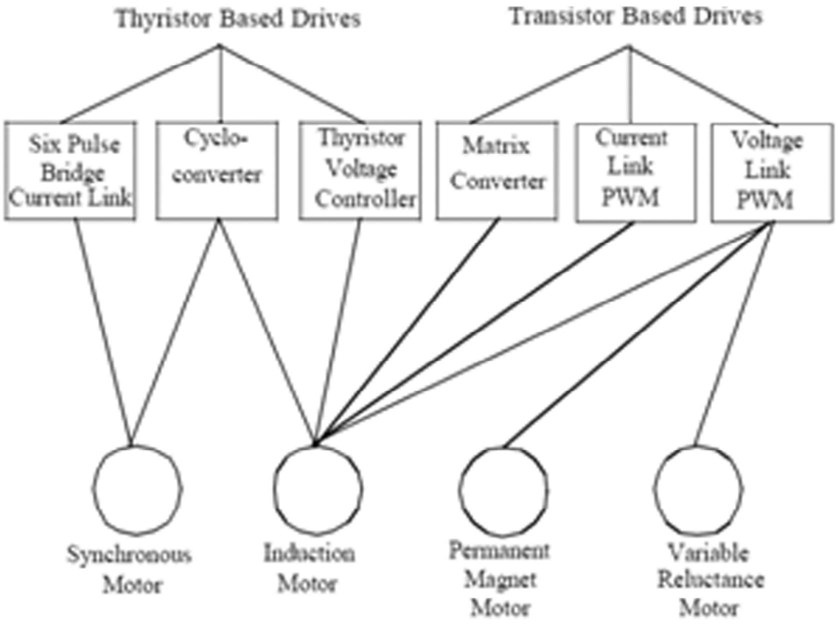

Figure 1: Major drive type categories

2. INDUCTION MOTOR DRIVES

An electrical machine has gone through slow but sustained evolution during the past century. The advent of powerful digital computers, incipient and ameliorated materials, coupled with extensive R&D, has resulted in higher power density, higher efficiency, and many performance enhancements of machines. The dramatic improvements that are required in the performance, reliability, and cost-effectiveness of electric drives can only be achieved by developing an integrated system approach based on the advanced packaging of semiconductor devices, and innovative circuits with integrated functionality, suitability for control, and application versatility. Three- phase induction motor outshines in terms of machine efficiency, robustness, reliability, durability, power factor, ripples, stable output voltage and torque [3]. When operated directly from the line voltages, they operate at a nearly constant speed. However, with the help of power electronic converter it is possible to vary the speed of an induction motor.

The fundamental elements needed in an Electric motor drive system (as shown in Figure 2) include:

- Power electronic Converter
- Electric Motor
- Controller(Analog/Digital)

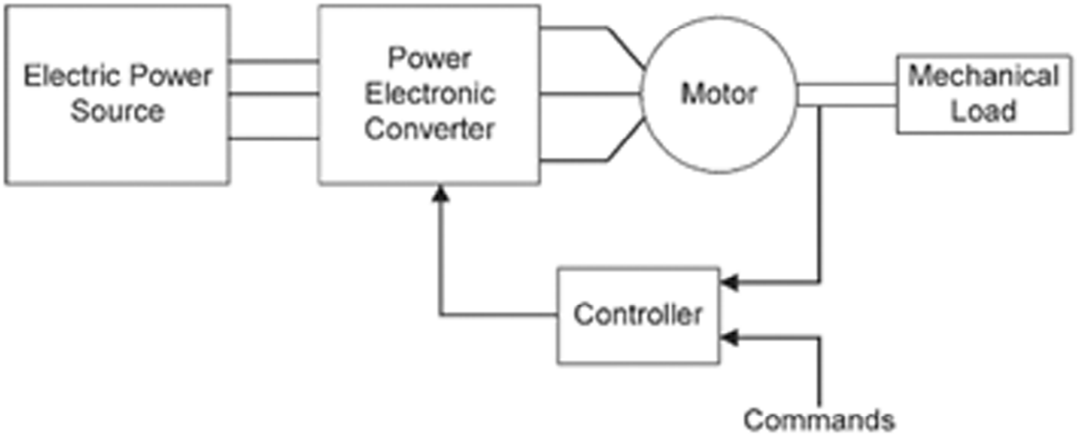

Figure 2: Electric motor drive

Digital control of induction motors results in more efficient operation of the motor thereby resulting in longer life and lower power dissipation. Although various induction motor control techniques are in practice today. During starting of an induction motor, the stator resistance and the motor inductance of both rotor and stator must be kept low to reduce the steady state time and also to reduce the jerks during starting. On the other hand, higher value of rotor resistance leads to lesser jerks while having no effect on the steady state time.

To analyze the effect of transients on performance of induction motor, dynamic modeling is performed. For dynamic modeling of three phase induction motor three phase motor is transformed to two phase machine and input power [3,4] is given by:

$$p_i = \frac{3}{2}R_s i_s{}^2 + \frac{2}{P}\omega_s \,\mathrm{Im}[i_s\lambda_s] + \frac{3}{2}\mathrm{Re}[i_s \frac{d}{dt}\lambda_s]$$

where R_s is stator resistance per phase, i_s is stator current, λ_s is complex conjugate of stator flux linkage phasor, ω_s is stator frequency at which reference frames are rotating.

There are 3 different components of input power in above equation. First term represents stator resistance loss, second term represents sum of rotor slip power and mechanical power whereas third term represents the rate of change of magnetic energy.

In induction machine, flux linkage can be controlled by stator current phasor which furthermore control electromagnetic torque.

In steady state, rate of change of magnetic energy is zero, but has a finite value during transients. For control of induction machine, this must be zero at all times of operation. This can be made zero under following conditions:

1. When stator flux linkages phasor remain constant in magnitude, from synchronous reference frames thereby giving derivative of flux linkage as zero. Withal Torque angle has to be constant.
2. By adjusting current phasor, such that resulting flux linkage varies whereas derivative of flux linkage phasors becomes zero.

To attain these conditions, stator flux linkages must be known in magnitude as well as in position, along with current phasors.

3. PHASE CONTROLLED INDUCTION MOTOR DRIVES

The most mundane method of electronic ac power control is called phase control. Figure 3, illustrates this concept. During the first portion of half-cycle of the ac sine wave, an electronic switch is opened to obviate the current flow. At some particular phase angle α, this switch is closed to allow the full line voltage to be applied to the load for the remnant of that half-cycle. Varying α will control the portion of the total sine wave that is applied to the load, and thereby regulate the power flow to the load. Triggering angle can be delayed up to a maximum of 180 degrees. Triggering angle, α is delayed to engender zero torque and hence load slows down the motor. By changing phase sequence of supply, faster speed reversal of the motor is obtained. Also; motor is running opposite to rotating magnetic field. This results in slip greater than one hence resulting in braking region operation of motor. This would slow down the motor much faster [5]. To maintain stator current within safe limits, triggering angle is increased. Exorbitant currents at the beginning will last for a very short time.

Triggering angle α will control the input. For a specified triggering angle α, it is intricate to calculate conduction angle β. The conduction angle can be calculated from machine equivalent circuit. High Triggering angle engenders high losses in the machine.

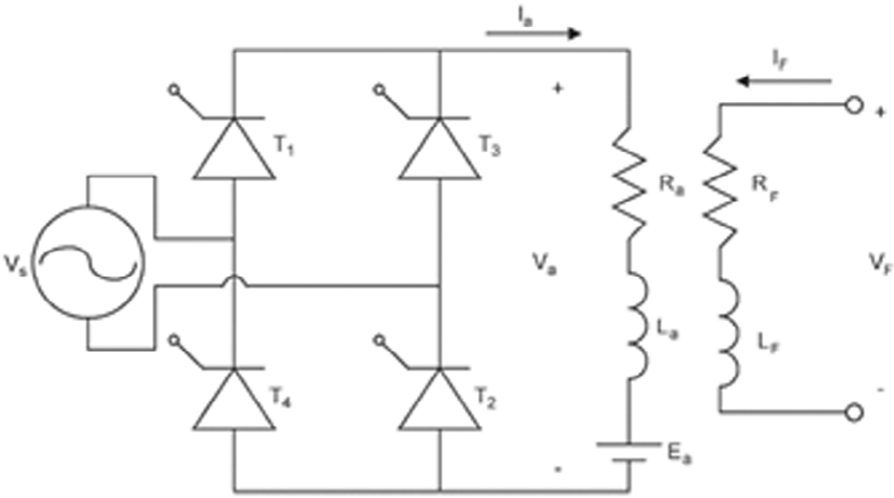

Figure 3: Single phase full wave controlled rectifier

4. FREQUENCY CONTROLLED INDUCTION MOTOR DRIVES

Variable-frequency AC drives are now available from fractional kilowatts to very large sizes for use in electric generating stations. In immensely colossal sizes, naturally commutated converters are more mundane, usually driving synchronous motors. However, in low to medium sizes (up to 750kW) transistor based PWM voltage source converters driving induction motors are almost exclusively utilized. The modern strategy for controlling the AC output of such a power electronic converters is the technique known as Pulse-Width Modulation (PWM) [6, 7]. PWM varies the duty cycle of the converter at a high switching frequency to achieve a target average low frequency output voltage or current. PWM-based drives [8, 9] are used to control both the frequency and the magnitude of the voltages applied to motors.

Frequency controlled induction motor drives perform speed control on the basis of change in frequency and are classified as per the hierarchy shown in figure 4 [5].Direct frequency changers employ cycloconverters single phase or three phases i.e. convert ac supply of fixed frequency to variable frequency. The output frequency falls in range from 0 to 0.5fs (supply frequency).For wide frequency range, indirect frequency changers are used. Indirect frequency changers consist of rectification and inversion. These indirect frequency changers are classified according to the source used-Voltage source or current source.

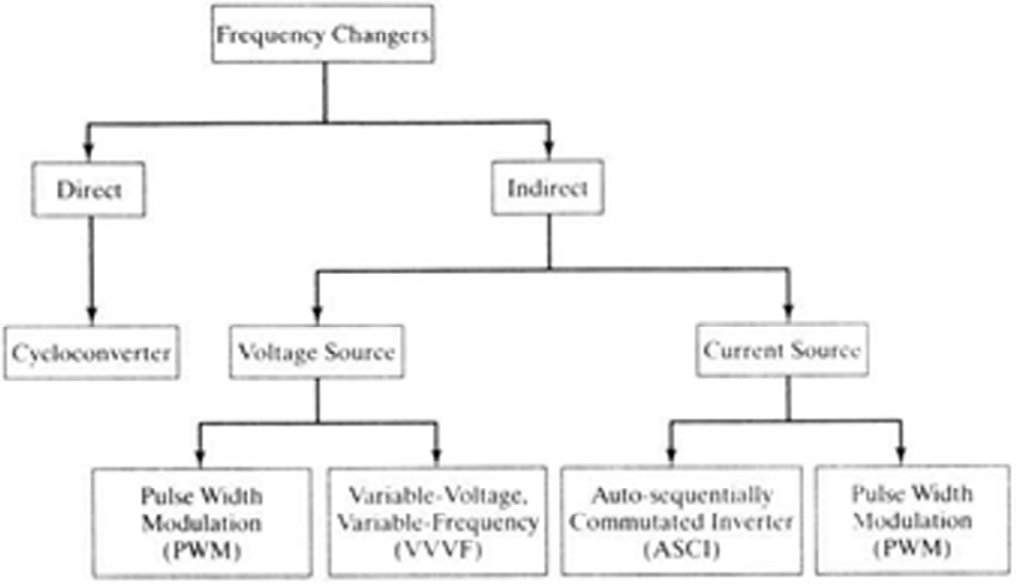

Figure 4: Classification of frequency changers

4.1. Voltage source drive

In Voltage source drive, rectification is uncontrolled and inversion control magnitude and frequency. A DC link filter (Capacitor) is used for constant dc input to inverter. It also smoothens ripples from dc output of rectifier. Uncontrolled rectification gives advantage of nearly unity power factor with disadvantage, that power cannot be recovered from dc link.

Many variable speed drives require a constant torque output and this can be achieved if the air-gap flux in the motor is maintained constant. From the classical law of Faraday, the E.M.F induced in winding is proportional to the rate of change of the magnetic flux. Therefore, as the operation frequency is reduced or increased the rate of change of flux is also reduced or increased accordingly. Speed control in Inverter driven induction motor can be done by varying frequency.

E.M.F induced in an a.c. machine is given as:

$$E = 4.44 k \phi f_s N$$

Where ϕ is air gap flux, f_s is supply frequency, N is number of turns per phase, k is stator winding factor.

If k, N is constant, then flux is proportional to ratio between supply voltage and frequency $\phi \propto \frac{E}{f}$.

Various control techniques are used to control speed of induction motor drive

- Constant volt/Hz control
- Constant slip speed control
- Constant air gap flux control

4.1.1. Constant Volt/Hz control

A very simple induction motor drive is explored in figure 5.

The quality of the output voltage is not good. To obtain the optimal flux operation *V/f* should be kept constant [10] but an AC to AC converter does not keep it constant. An induction motor drive (as shown in figure 5) with constant voltage and frequency, three-phase source is the input. With the AC to DC rectifier, DC to AC inverter, and controller, the voltage and frequency can be varied. This control can be used to keep

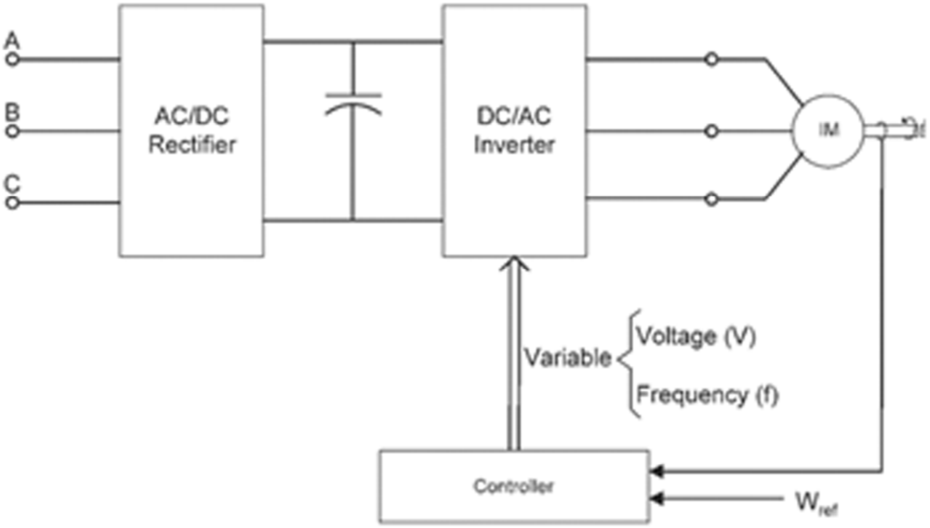

Figure 5: Block diagram of an induction motor drive

V/f constant and provide optimal flux operation. So when the operation frequency is reduced, the EMF, and therefore the applied voltage (if the stator impedance is negligible) must be reduced proportionately or the saturation flux density is exceeded, resulting in excessive iron loss and magnetizing current. When the operating frequency is increased, the applied voltage should be increased proportionately in order to maintain the magnetic flux density. It can be therefore concluded that in order to keep the air-gap flux constant, the applied voltage/frequency ratio must be held constant.

This mode of operation is known as constant V/f operation and has been widely used for induction motor drives as a general purpose inverter, particularly in cases where precise speed control is not necessary. This is the simplest method, which does not provide a high performance. For continuously variable speed control, the output frequency of inverter must be varied. The applied voltage to the motor must withal be varied in linear proportion to the supply frequency to maintain constant motor flux.

4.1.2. Pulse Width Modulation (PWM)

PWM is employed in a wide variety of applications, ranging from measurement and communications to power control and conversion. In ac motor drives, PWM inverters make it possible to control both frequency and magnitude of the voltage and current applied to a motor. As a result, PWM inverter based motor drives are more variable and offer in a wide range better efficiency and higher performance when compared to fixed frequency motor drives.

PWM is used to control the voltage and reduce the harmonic contents [11, 12] in the inverter output. In particular, sinusoidal PWM give minimum harmonic contents in the inverter output voltage, thereby reducing THD [13-15]. However, the relative complexity involution of control makes this modulation strategy onerous to implement.

One of the earliest modulation signals for carrier-based PWM is sinusoidal PWM (SPWM). The SPWM technique is based on the comparison of a high frequency carrier signal and a low frequency pure sinusoidal modulation signal. The switching state is transmuted when the sine wave intersect the triangular wave. The crossing positions determine the variable switching times between states. In three-phase SPWM(as shown in Figure 6), a triangular voltage waveform (VT) is compared with three sinusoidal control voltages (Va, Vb, and Vc), which are 120^o out of phase with each other and the relative levels of the waveforms are used to control the switching of the devices in each phase leg of the inverter.

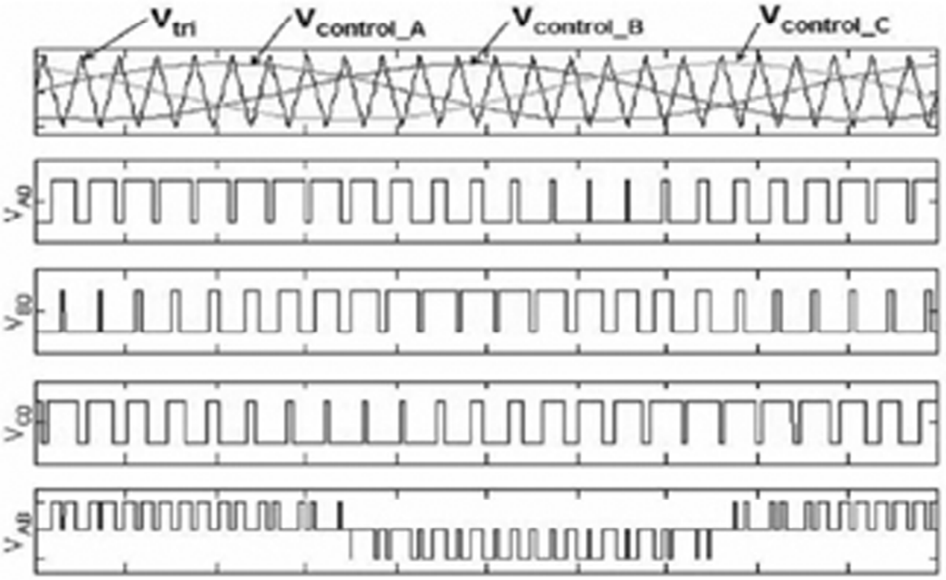

Figure 6: Three phase sinusoidal pulse width modulation

The desired output voltage is achieved by varying the frequency and amplitude of a reference or modulating voltage. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation.

The ratio of the peak magnitudes of modulating wave (M) and the carrier wave (C) is defined as modulation index. Normally the magnitude of modulation index is circumscribed below one (i.e., 0<m<1). Variation of modulation index varies fundamental amplitude. The ratio between carrier frequency, f_c and reference frequency, f_r changes harmonics. Carrier frequency must have high value to eliminate lower harmonics [14]. This will increase switching thereby giving high switching losses [16-18].

4.1.3. Constant slip speed control

The slip, s is given as

$$s = \frac{Ns - Nr}{Ns}$$

For speed variation of rotor, slip must be varying as slip speed (Ns) is maintained constant.

4.1.4. Constant air gap flux control

Electromagnetic Torque of induction motor is dependent on slip speed

$$T = \frac{KsE_2{}^2R_2}{\sqrt{R_2{}^2 + (sX_2)^2}}$$

Where $$K = \frac{3}{2\pi n_s}$$

Where n_s is synchronous speed in r. p. s, $n_s = N_s / 60$.

Constant air gap flux [10] requires magnetizing current to be controlled which is possible with control of stator current of induction motor. By maintaining constant air gap flux, torque can be varied thus controlling speed of induction machine.

4.2. Current source drive

Electrical devices are current sensitive, also torque is directly related to current. Therefore, Current source drives [19-22] gives precise and direct control of electromagnetic torque and drive dynamics.

In Current source drive, rectification and inversion control magnitude and frequency. A DC link filter (inductor with commutating capacitor) is used for constant dc input to inverter. This drive is suitable for four quadrant operation but uncontrolled rectification gives advantage of nearly unity power factor with disadvantage, that power cannot be recovered from dc link. Current source drives are realized with Auto-Sequential Commutated Inverter (ASCI).

A constant current source is taken, which may be realized by using an inductance of appropriate value. This must be high, in series with the current limited dc voltage source. The thyristor pairs, Th_1 & Th_3, and Th_2 & Th_4, are alternatively turned ON to obtain a nearly square wave current waveform. Two commutating capacitors – C_1 in the upper half, and C_2 in the lower half, are used. Four diodes, D_1–D_4 are connected in series with each thyristor to obviate the commutating capacitors from discharging into the load. The output frequency of the inverter is controlled in the usual way, i.e., by varying the half time period, (T/2), at which the thyristors in pair are triggered by pulses being fed to the respective gates by the control circuit, to turn them ON.

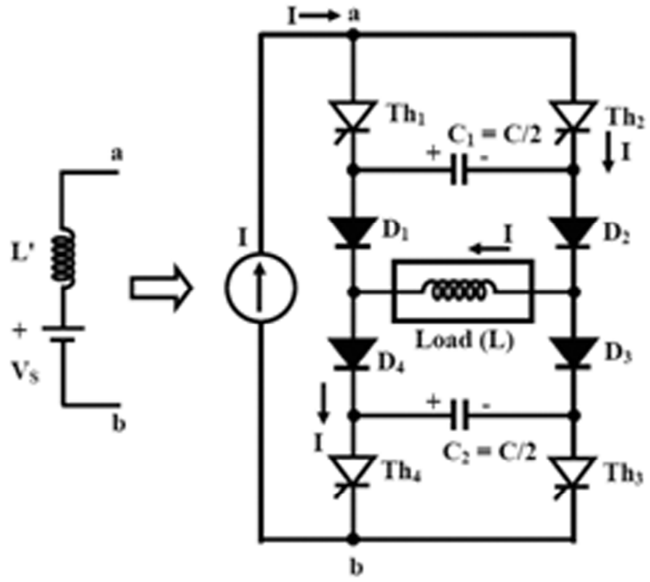

Figure 7: Single phase current source inverter of ASCI Type.

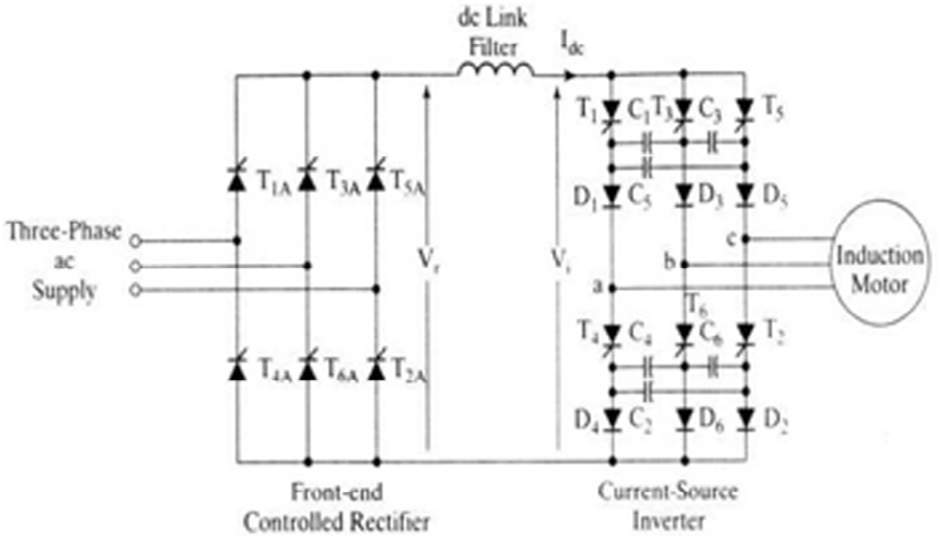

Figure 8: Current source induction motor drive

Current source drives are realized with Auto-Sequential Commutated Inverter (ASCI). Controlled rectifier supply dc output to Auto-Sequential Commutated Inverter through a filter inductor. The function of inductor is to maintain dc link current at a steady state value. The type of operation is termed as Auto-Sequential Commutated Inverter (ASCI).

At any time, two SCR’s are conducting (one from positive group and other from negative group) and commutation takes place after every 60 degrees. The current commutation is slow and hence SCR’s with large turn off time are required. This reduces cost of ac drive. A comparison [23, 24] between current source drive and voltage source drive is performed briefing few points as enlisted below.

Current source drives are more economical than voltage source drives for high ratings (more than 100 hp). Current source induction motor drives are used for high power applications like paper mills, rubber industry, sugar industry etc.

Voltage source induction motor drives are used in applications where precise torque control is not vital in frequency range 0-50 Hz like fans, conveyor, hand tools etc.

5. VECTOR CONTROLLED INDUCTION MOTOR DRIVES

Vector control refers to the manipulation of terminal currents, flux linkages and voltages to affect the motor torque while field orientation [25] refers to the manipulation of the field quantities within the motor itself. The control of frequency, magnitude of current, flux phasor is possible by inverter control and is known as vector control because it relate phase control of rotor flux linkages. Depending upon how field angle is calculated, different vector control methods are classified:

5.1. Direct vector control

If field angle is calculated from terminal voltages and current, then it is termed as direct vector control.DTC (Direct torque control) is based on limit cycle control. It enables both quick torque response in the transient operation and reduction of the harmonic losses.

DTC is an alternative to the field-oriented control technique (FOC). The DTC is very simple. Its basic configuration consists of a pair of hysteresis comparators, torque and flux calculator, and a lookup table to find out the switching vector from the torque and flux stators, and a voltage-source inverter (VSI). In the direct torque control, the torque and flux are compared into hysteresis comparator, and the torque and flux stators are generated, which are used to switch the VSI thereby changing speed of induction motor. For VSI, we have eight possible switching states and out of the eight possible switching states, six are non zero switching vectors and two are zero switching vectors

Two of the major issues which are referred normally in DTC drives are the variation of the switching frequency of the inverter used in the DTC drives with operating conditions and the high torque ripple. It is well known that the underlying to the variable switching frequency problem is the use of hysteresis comparators. Switching frequency is highly influenced by the motor speed, which is mainly due to the torque slope [26].

5.2. Indirect vector control

If field angle is calculated from rotor position measurement and machine parameters, then it is termed as indirect vector control [27].

Indirect vector control scheme:

Step 1: Measure flux, torque, rotor resistance, rotor inductance, mutual inductance

Step 2: Calculate Field current (stator d-axis current), torque current (stator q-axis current), slip speed.

Step 3: Calculate stator current from d-axis and q-axis current, command torque angle θ_t, command slip angle θ_{sl}, d-axis angle θ_f, θ_s. Where $\theta_s = \theta_f + \theta_t$ and $\theta_f = \theta_r + \theta_{sl}$

Step 4: Calculate stator d-axis and q-axis current.

Step 5: Calculate stator current

Vector controlled induction motor drives give high performance as machine operation goes from the motoring mode to the generating mode by reversal of currents in the rotor bars. Hence, Fast Torque and speed reversal is possible.

6. SUMMARY

The goal of this paper has been to highlight a problem which afflicts our discipline, to illustrate its pervasiveness and to make suggestions on what to do about it. The problem will never be totally overcome but there is a lot we can do, especially in this age of computer access to information. The progress of Electric drives in the last few years with increasing use of a standard, modular, integrated approach have led to increased penetration of power conversion equipment. The observation that power electronics technology may be becoming a mature field for Electrical machines after a lifetime of at least a century as many other technologies before it was an important motivation to critically examine the present state of the art and possible future development. In this process it is important to understand historically how and when the original driving philosophy for the spectacular development of power electronics technology has come about.

On the evaluation of the state of the art, it can indeed be concluded that the historical development of Induction motor drives is approaching the limits of the most important internal metrics of the technology in its present form. This is a definite indication of maturity in the internal development process. It is also clear, however, that upcoming maturity only applies to the internal constituent technologies of power semiconductor switch technology and power electronic switching network technology. It is expected that converter, control, and machine will eventually be integrated as an intelligent machine of the future, particularly in the lower end of power rating.

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