Induction Motor Control Strategies: Past and Present.

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ABSTRACT

The DC motor, the synchronous motor, and the induction motor have been the workhorses of industry for many years. The synchronous motor compares favorably with the induction motor due to its natural ability to supply reactive current as well as its ability to eliminate rotor slip power loss. The control of DC motors is relatively simple. In the case of the induction motor, advancements in semiconductor power electronics, micro-controllers, and micro-computers have made it possible to reduce minimally the complexity inherent in its speed control.

This paper brings up to date the present and the past control strategies of the induction motor. The inherent problems encountered and the associated improvements in the control and application of the induction motor are highlighted. The industrial applications of adjustable-speed induction motor drives are also presented.

(Key words: induction motor, control strategies, adjustable speed-drives, open loop, closed loop).

INTRODUCTION

The DC motor, the synchronous motor, and the induction motor are the basic electric machines that have been in use in industry for nearly a century (Sen 1988). Due to sustained research efforts in drive technology, other types of electric machines, such as Brushless DC Machines, Permanent Magnet Machines, and Switched Reluctance Machines, have recently become viable alternatives in many industrial applications. The induction motor is superior to the DC motor with respect to smaller size, weight and motor inertia, maximum speed capability, efficiency, and lower cost (Murphy and Turnbull 1988; McDonald and Sen 1978; Nasar and Boldea 1990; King 1963). However, the simplicity of control of the DC motor is much higher because the induction motor inherently has a complex, non-linear, and highly interacting multi-variable control structure, whereas the separately excited DC motor has a decoupled control structure with independent control of flux and torque.

Comparable control performance of induction motor drives generally requires more convoluted control algorithms (implemented by fast real time signal processing) that control modern power semiconductor circuits, which drive the motor. However, the availability of adequate power semi-conductor devices, microelectronics, and microcomputers has sustained wide spread interest in variable speed induction motor drives and has consequently opened new possibilities in the control of induction motors.

Conventionally, electric motors were controlled manually (Ramamoorty and Arunachalam 1978; Sen and Ma 1975). Resistance control of DC motors and variac control of induction motors are typical examples. Electronic control started with the advent of gas tubes such as thyratrons and Ignitrons in the 1930's (Sen 1990). The modern era of control began with the advent of power semiconductors in the 1950's. Subsequent progress in power electronics and microcomputers has amply influenced the operation and performance of drive systems, especially AC variable-speed drives.

Traditionally, linear controllers such as proportional (P), proportional plus integral (PI), and proportional plus integral plus derivative (PID) controllers have been used extensively in the past to achieve speed control in electric motor drives. Unfortunately, these conventional linear controllers cannot provide fast dynamic response, parameter-insensitive control characteristics, and rapid recovery from speed drop caused by impact loads as are needed in the high performance drive applications. In recent years, much research interest has been directed to the use of modern controllers (micro-controllers) in drive systems. Such modern control techniques have been seen to present a better promise in realizing the needs of high-performance drive.

This paper presents a comprehensive review of the work done in induction motor drives and controls as well as industrial applications of adjustable-speed induction motor drives.

CONVENTIONAL METHODS OF SPEED CONTROL

Induction motors are practically a constant-speed machine which account for 90 percent of the electrical drives used in industry (Edwards 1991). Induction machines are usually constructed to work with a small value of slip, normally less than 5% at full load. Therefore, the deviation of the motor speed from the synchronous speed is practically very small. However, there are certain applications that require enormous variation of the motor speed.

DC motors form an obvious choice for this kind of drive because of the ease of speed control, but they are relatively expensive. The induction motor has the advantages of low cost and high reliability. The possible methods of speed control may be deduced from the fractional slip definition (Ramshaw 1973), which shows that the motor speed may be controlled by:

(a) Varying the slip (s)
(b) The number of pole-pairs (P) or
(c) The supply angular frequency (ω)

Also, from the general torque equation of the induction machine, it can be seen that the load torque depends on the rotor resistance. This implies that the speed control of the motor may be achieved by varying the rotor resistance (invariably varying the slip). A brief description of these methods of control is given below.

VARIATION OF ROTOR SLIP

The torque depends on motor resistance. Therefore, increasing the rotor resistance (R_2) will at constant torque cause a proportionate increase in the slip (s) with a resultant decrease in the rotor speed. Thus, the speed for a given load torque may be varied by varying the rotor resistance. Figure 1 shows the family of torque/speed characteristics for a number of values of rotor resistance. To achieve this method of control, balanced three-phase external resistance is introduced into the rotor circuit of a wound-rotor induction motor (Dewan and Straughen 1975; Slemon 1966).

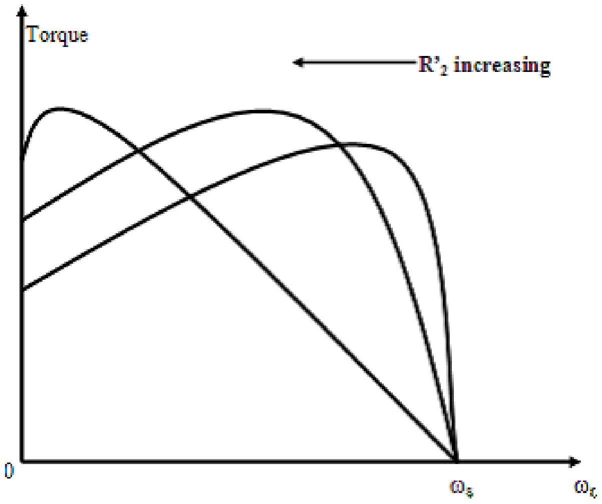

Figure 1: Control by Variation of Rotor Resistance.

The function of these resistances is to introduce voltages at rotor frequency, which oppose the voltages induced in the rotor windings. The main demerit of this method of control is that energy is dissipated in the rotor-circuit resistance, internal and external, and this energy is wasted in the form of heat. Because of the wastefulness of this method, it is used where speed changes are needed for short durations only.

An alternative method of varying slip, which may be applied to cage rotor machines, is to vary the magnitude of the stator voltage (V_1). Figure 2 shows the family of Torque/Speed characteristics for a number of values of V_1

As with rotor resistance variation, the operating efficiency is poor and the motor derating is necessary at low speeds to avoid overheating due to excessive current and reduced ventilation. This method is rarely used since a large change in voltage is required for a relatively small change in speed. Also, this large change in voltage will result in a large change in the flux density, which seriously disturbs the magnetic conditions of the motor. However, it has the merit of cheapness, simplicity, and it is sometimes used with small machines when efficiency is not particularly useful.

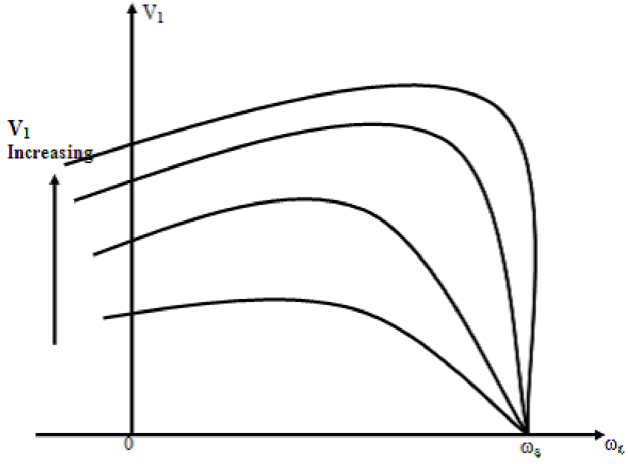

Figure 2: Speed Control by Variation of Supply Voltage.

NUMBER OF STATOR POLES VARIATION

This method is easily applicable to squirrel-cage motors because the squirrel-cage rotor adopts itself to any reasonable number of stator poles (P). This method of speed control can only give discrete changes of speed, since P must be an integer. An obvious way of varying P is to have an independent winding for each pole number, with a selector switch to connect the appropriate winding to the supply.

A better solution is to design a single winding in such a way that the number of poles can be changed merely by altering the interconnection of the coils. The technique of pole-amplitude modulation (PAM) permits values of P such as 4, 5, 6 to be obtained from a single stator winding, which gives a useful degree of speed control. This method of speed control is highly restricted to motor type and to the reasonable number of stator poles (Edwards 1991; Slemon 1966). Although it does not provide continuous control of speed, it is simple, efficient, and adequate for elevator motors, traction motors, and also for small motors driving machine tools.

FREQUENCY VARIATION CONTROL

The most efficient method of speed control for induction motors is to vary the stator frequency. Since the speed is close to synchronous speed, the operating slip is small, and slip power loss in the rotor circuit is small. Variable frequency supply can be obtained from variable-speed synchronous generators, commutator frequency changers, electronic inverters, or cycloconverters. This type of control strategy provides the desirable high starting torque (at low frequencies) with its associated rapid acceleration and reduced starting losses. But it is a necessary economic measure to run it at the highest possible frequency because of increased efficiency. The inherent demerit of this method of control scheme is that the motor performance deteriorates at low frequency when the air-gap flux decreases, because of the voltage drop across the stator leakage impedance (Dewan, Slemon, and Straughen 1984; Bose 1986). The Torque/Speed characteristics for different supply frequencies take the form shown in Figure 3.

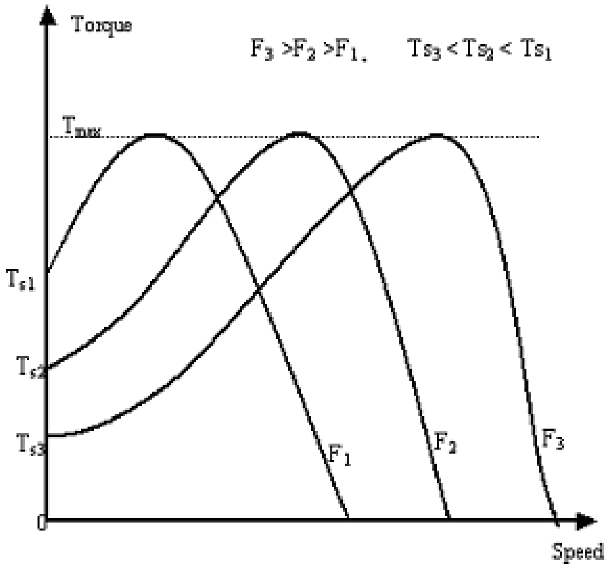

Figure 3: Induction Motor Torque/Speed Characteristic for Constant V/F.

SOLID-STATE SPEED CONTROL STRATEGIES

The inherent inadequacies of the conventional speed control strategies call for a suitable, efficient, and wasteless control method via electronic means. Therefore, induction motor speed control through solid-state switching becomes highly imperative. Through these means, the speed of the induction motor could be controlled by inserting an inverter in the rotor chopper-controlled external resistor (Ramamoorty and Arunachalam 1978) or by controlling the stator voltage (Stefanovic 1977, Miles 1979) by means of solid-state switching devices such as power transistors or silicon-controlled rectifiers. Induction motor drives (IMD) are always of the adjustable-frequency type, because the rotor magnetic field does not have an independent existence but is caused by currents induced from the stator by transformer action (Edwards 1991).

An induction motor must always run with a speed difference. The change in slip between no-load and full-load will result in a small speed variation if the inverter frequency is held constant. In many applications this is unimportant; open-loop control with an adjustable-frequency inverter is then a popular and economical choice for a variable-speed drive.

Open-loop speed control of an induction motor provides a satisfactory adjustable speed drive when the transient performance characteristics are undemanding and when the motor operates at steady speeds for long periods. The demerit of this system is that it cannot be used in the presence of supply voltage fluctuations and loads disturbances. Also, when the drive requirements include rapid acceleration and deceleration, an open-loop system is unsatisfactory because the supply frequency cannot be varied quickly without exceeding the rotor breakdown frequency. However, when fast dynamic response and greater speed accuracy are needed, closed-loop control methods are essential, but a precise feedback system must be used to sense the rotor speed and adjust the inverter frequency accordingly. These control methods are therefore usually applied in solid-state control of induction motor drive.

As is evident from the literature (Slemon and Dewan 1974, Lipo and Cornell 1975, Amato 1965, Salihi 1969, Campion 1991, Gosbell and Dalton 1992, Tungpimolrut 1994), numerous solid-state speed control schemes have been devised and investigated in the analysis and control of variable speed induction motor drives.

Some of these methods are: Terminal Volts/Hertz Control, Air-gap Flux Control, Stator Current Control, Field-Oriented Control, and Static Control of Rotor Resistance. The above control schemes are now discussed according to motor types: Squirrel-Cage Induction Machine (SCIM) and Wound Rotor Induction Machine (WRIM).

SPEED CONTROL OF THE SCIM

The induction motor with a squirrel-cage rotor is one of the lowest cost machines to manufacture and it eliminates all brushes, resulting in an exceedingly simple and rugged construction (Moghbelli 1991). It is robust and has been extensively used in a wide range of power ratings (Sen 1990).

STATOR VOLTAGE CONTROL

A simple and economic method of control is to vary the stator voltage at supply frequency using thyristors or triacs. The rotor slip is determined by the load torque and the applied voltage, therefore, continuous speed control may be obtained by stepless adjustment of the stator voltage without any alteration in the stator frequency.

Stator voltage control eliminates the complex circuitry of the adjustable-frequency schemes, and consequently, is cheaper to install. However, the operating efficiency is poor, and motor derating is necessary at low speeds to avoid over-heating due to excessive current and reduced ventilation (Shepherd and Stanway 1964, Paice 1968). Stator voltage control is widely used for fractional horsepower drives and also for AC-powered cranes and hoists where large torque at high slip is only demanded for intermittent portions of the duty cycle.

Adjustable-speed drives using stator voltage control are normally closed-loop systems. Figure 4 shows such a scheme. The DC tachometer delivers a voltage proportional to the motor speed (n) and this is compared with the DC reference voltage representing the desired speed (n*). The difference between the two signals is the error voltage, which is amplified in the speed controller (Lipo 1971, Bedford and Nene 1970). The resulting signal controls the thyristor firing angles and thereby alters the terminal voltage and the motor speed so that the error is reduced.

OPEN-LOOP SPEED CONTROL BY STATOR VOLTAGE AND FREQUENCY

Variable-frequency drives originally used open-loop, Volt/Hertz control to regulate machine flux. They were found to be satisfactory for low-performance, cost-effective industrial drives

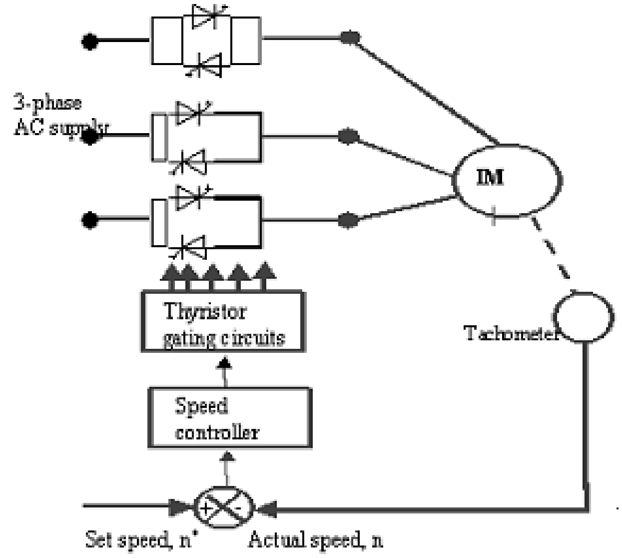

Figure 4: Closed-Loop System for Induction Motor Speed Control by Stator Voltage Control.

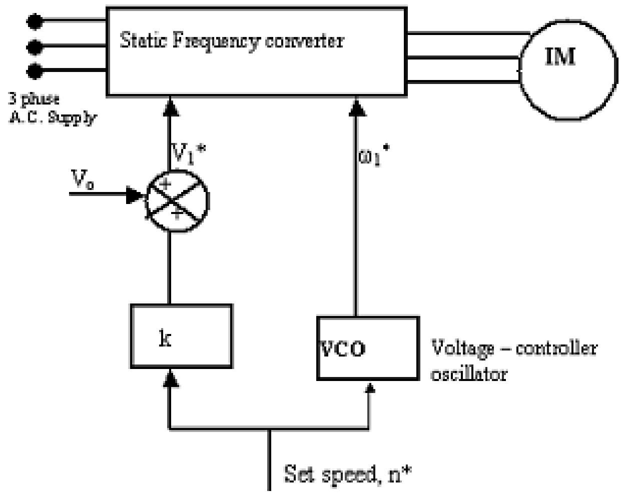

Figure 5: Open-Loop Adjustable Induction Motor Drive with Terminal Volts/Hertz Control.

where high dynamic performance is not required. Figure 5 shows a block diagram of an open-loop adjustable drive with terminal Volts/Hertz control. The set point or reference signal is the speed command (n*) that generates the inverter frequency command (ω^*_1) via a voltage-controlled oscillator (VCO). The voltage command (V^*_1) is also determined directly from the set speed signal, as show. The static frequency converter (SFC) may be either a cycloconverter or a DC link converter employing a six-step or PWM voltage-source inverter (Abbondani 1977). The excessive current generated by this type of control scheme can be rectified by passing the speed reference through a ramping circuit that gives a timed rate of change of frequency. Alternatively, a current limit control can be introduced.

CLOSED-LOOP SPEED CONTROL BY STATOR VOLTAGE AND FREQUENCY

In open-loop speed control, the rotor slip increases and the induction motor shows down slightly when load torque is applied. This invariably calls for closed-loop speed control with slip regulation for improved drive performance. Figure 6 shows such closed-loop speed control scheme. The speed error is compensated in the speed controller and is used to generate the slip frequency command (ω^*_2).

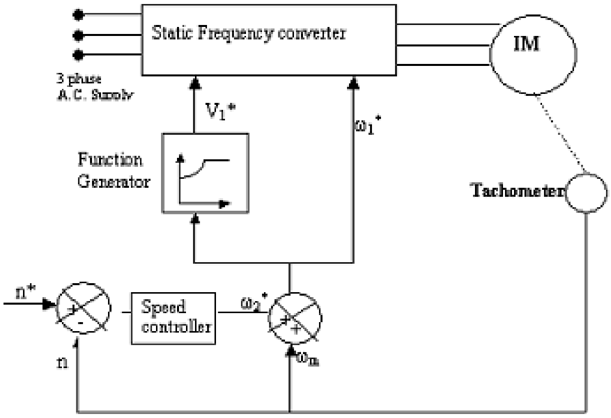

Figure 6: Closed-Loop Volts/Hertz Control and Slip Regulation.

This signal is added to the tachometer signal, in the usual manner, to determine the inverter frequency command (ω^*_1). The latter signal is also supplied to a function generator that develops the voltage command (V^*_1). The function generator implements a voltage boost at low frequencies so that the air-gap flux is approximately constant. The induction motor torque is therefore proportional to the slip frequency. Figure 7 shows an alternative Volts/Hertz control scheme based on a co-ordination of stator current and slip frequency (Stefanovic 1977). The set speed (n*) is compared with the actual speed (n) to determine the speed error, which is then passed through the speed controller and defines the inverter frequency and voltage.

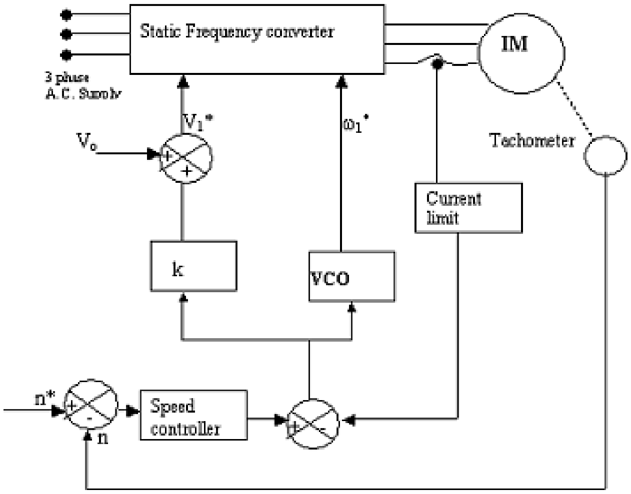

Figure 7: Closed-Loop Volts/Hertz Control and Current Limiting.

The current-limit signal comes into effect when the motor current rises to a pre-set maximum level. This signal then controls the rate at which the inverter frequency and voltage are ramped.

AIR-GAP FLUX CONTROL

High torque throughout the speed range of an induction motor is obtained through air-gap flux control operation. This genuine constant-torque capability over the full speed-range makes deterioration at low-speed performance difficult.

One of the demerits of this method is that direct measurement of air gap flux is difficult. Also, the flux signal from the flux sensor is disturbed by large slot harmonics that cannot be filtered effectively because their frequency varies with motor speed. Also the scheme is expensive to install, as a special machine is required with built-in Hall sensors. Plunkett (Plunkett 1977) and Lipo (Lipo 1977) noted that it is possible to sense the rate of change of air gap flux by placing search coils in the wedges closing the stator slots. The closed-loop control scheme is shown in Figure 8.

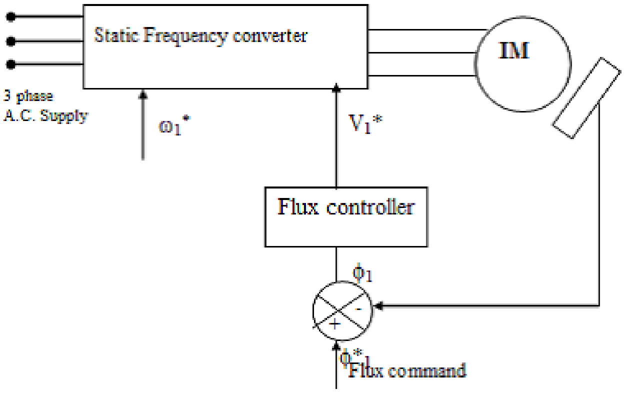

Figure 8: Closed-Loop Control of Air-Gap Flux.

Indirect control of air gap flux is possible by directly controlling the stator current and slip frequency.

STATOR CURRENT CONTROL

The current source inverter (CSI) induction motor drive offers some advantages over the voltage source case. The CSI can withstand short circuits and commutation failures. It offers inherent over-current protection when current feedback is used. The drive scheme has a simple circuit and gives high quality torque control and rapid dynamic response (Krishran 1980). These advantages have resulted to the increasing use of CSI drive applications (Cornell and Lipo 1977; Krishran 1980).

The main disadvantages are the presence of high voltage stresses and low-speed torque pulsations. There are merits in controlling stator current rather than stator voltage when it comes to induction motor drive. Direct control of the stator phase currents gives fast, effective control of the amplitude and spatial phase angle of the stator mmf wave, thereby facilitating high quality torque control and rapid dynamic response. The controlled stator current can be delivered by a current-controlled PWM inverter or by a current-source inverter (CSI). Unlike the Volt/Hertz control, the stator current control strategy is independent of stator parameters, resistance, and leakage inductance. Hence, speed regulation can be achieved even at low speeds. The control scheme is shown in Figure 9.

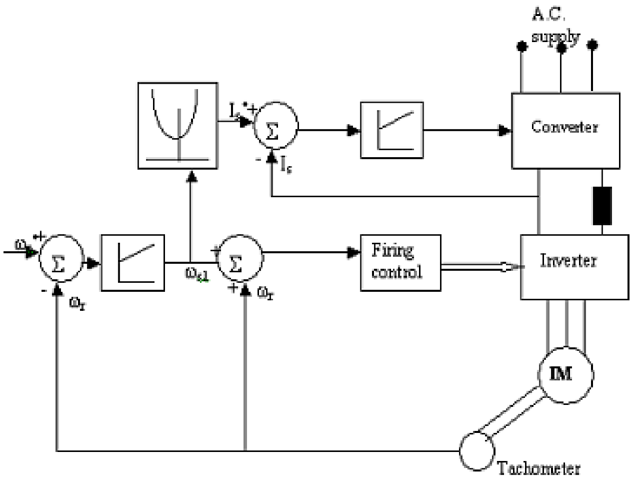

Figure 9: CSI Drive with Slip Frequency Control.

FIELD-ORIENTED CONTROL

The control strategies considered so far provide satisfactory steady-state performance. Unfortunately, they fail to provide satisfactory transient performance. High-performance drives, such as robotics, rolling mills, and machine tools require fast and precise torque response. To achieve this, the dynamic structure of the machine has to be considered. Several control strategies have been devised to obtain fast torque response but much optimism goes to Field-Oriented Control (FOC).

Field orientation is a technique that provides a method of decoupling the two components of stator current: one producing the air-gap flux and the other producing the torque. The principle of field orientation originated in the former West Germany through the work of Blaschke and Hasse (Blaschke 1972; Hasse 1969). A variety of implementation methods have now been developed but these techniques can be broadly classified into two groups: direct control and indirect control.

The classification is based on the method used to determine the rotor flux vector. Indirect Field-Oriented Control, as proposed by (Hasse 1969), requires a high-resolution rotor position sensor, such as an encoder or resolver, to determine the rotor flux position. Direct Field-Oriented Control, as suggested by (Blaschke 1972), determines the magnitude and position of the rotor flux vector by direct flux measurement or by a computation based on machine terminal conditions. The two methods of FOC are shown in Figures 10 and 11. It is important to note that through this method, the induction motor dynamics lose most of their complexity and a high performance drive can be achieved. Through this control method, the induction motor drive can achieve four-quadrant operation with a fast torque response and good performance down to zero speed (Gabriel 1980). However, this method is an unduly complicated approach requiring sophisticated signal processing and complex transformation. These inadequacies have been made increasingly irrelevant due to the spectacular advances in the speed and processing power of modern digital processors and the significant reductions in processor size and cost. Also, to solve the problem of performance degradation due to parameter variations in an Indirect Field-Oriented Control, a novel and simple estimation method for the rotor circuit time constant has been carried out successfully by (Tungpimolrut 1994).

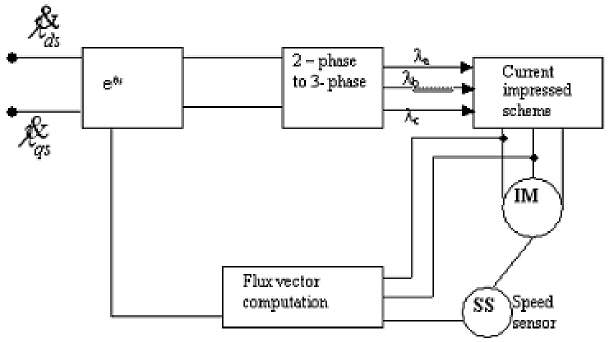

Figure 10: Direct Field-Oriented Control Scheme.

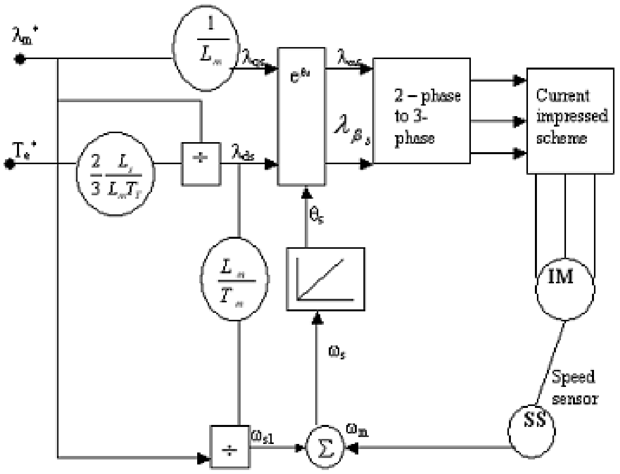

Figure 11: Indirect Field-Oriented Control Scheme.

SPEED CONTROL OF THE WRIM

The WRIM offers a lot of flexibilities for wide range of speed control compared to the squirrel-cage motor. This is made possible due to the availability of rotor terminals in the former. However, the WRIM is not as rugged as the SCIM and cannot operate at high speeds. The most important method of speed control involves the removal of rotor slip power by a converter cascade circuit. Conventionally, the speed of the WRIM is changed by manually varying the rotor resistance in discrete steps (Ramamoorty 1978). With the advent of power semiconductors, the conventional resistance control scheme can be eliminated by employing a three-phase rectifier bridge and a chopper-controlled external resistance (Lesan 1996, Ramamoorty 1978). The scheme is shown in Figure 12.

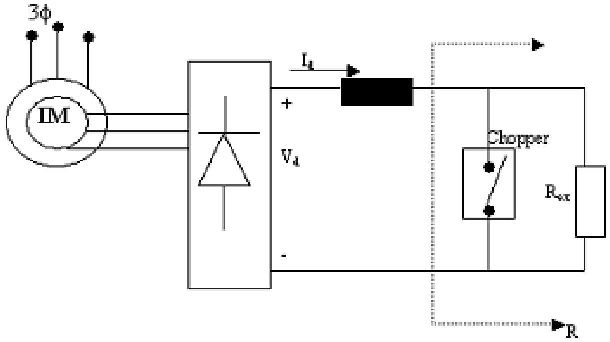

Figure 12: Speed Control by Static Variation of External Rotor Resistance.

Figure 13 and Figure 14 show the static Kramer and static Scherbius systems, respectively. The systems allow recovery of slip power and have been applied extensively for pump and blower drives. The Kramer system provides sub-synchronous speed control while the cycloconverter in the Scherbius system allows for bi-directional power flow. Therefore, the Scherbius system can operate in both sub-synchronous and super-synchronous modes (Smith 1977). However, the provision of super-synchronous speed control complicates the static converter cascade system and nullifies the merits of simplicity and cost, which are inherent in a purely sub-synchronous drive (Reinert and Parsley 1995). Also, the cycloconverter cascade is expensive and it introduces additional control complexity, but the near-sinusoidal rotor currents minimize harmonic heating effects and low-frequency torque pulsations. Field-oriented control can also be applied in wound rotor induction motors to provide decoupled control of real power and reactive power. These features are very beneficial in high-power applications. Figure 15 clearly depicts the field-oriented control of a WRIM.

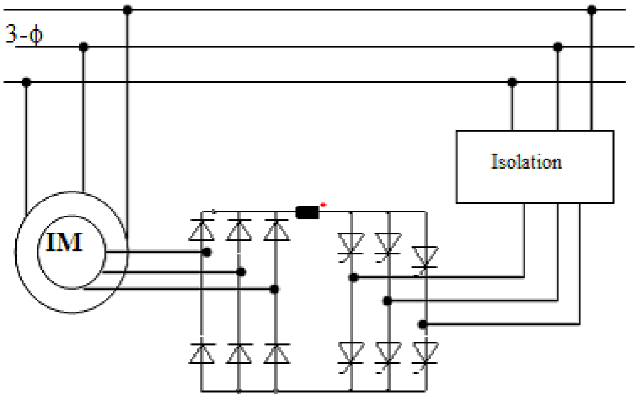

Figure 13: Static Kramer Drive.

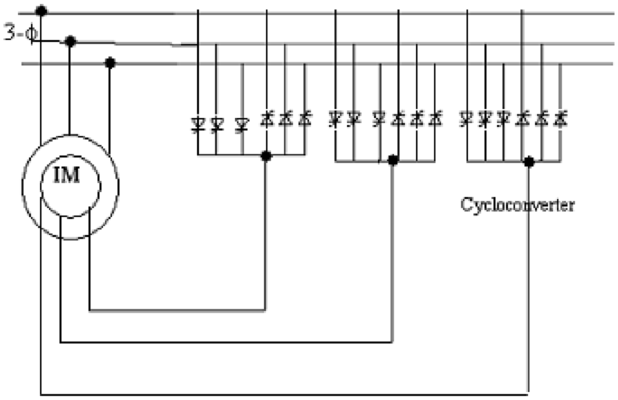

Figure 14: Static Scherbius Drive.

INDUSTRIAL APPLICATIONS OF VARIABLE-SPEED INDUCTION MOTOR DRIVE

The requirements for electric motors in industry are many and varied, and it is impossible to devise hard and fast rules for using a particular type of machine (Sharpe 1991). For medium and large power drives requiring a fairly constant speed, the first choice is always the squirrel-cage induction motor because of its simplicity, low cost, robustness and relatively low maintenance. Drives such as ventilation fans, hydraulic pumps, compressors, extruders, etc.,

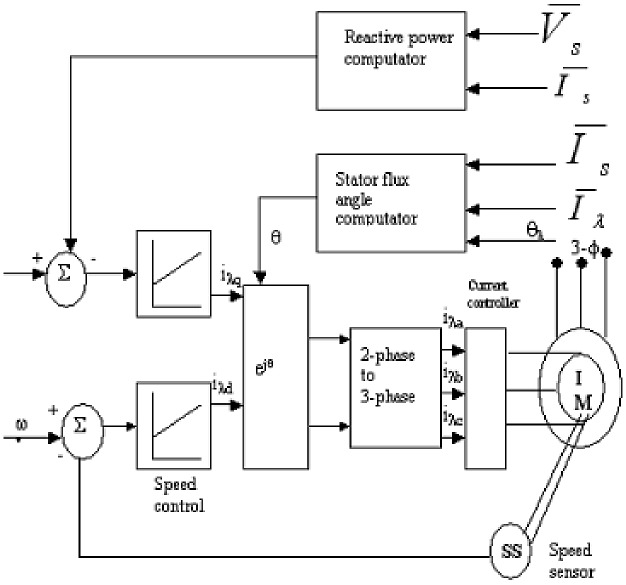

Figure 15: Field – Oriented Control of a Wound-Rotor Induction Motor.

are suitable applications for the squirrel cage motor.

Wound rotor induction motor may be used for the applications where:

(i) the starting current cannot be permitted to exceed a specific value
(ii) a high starting torque is required
(iii) the average accelerating torque is to be large and
(iv) the motor is to have a fixed preset full-load regulation.

Because of the lightness, ruggedness, and reliability of induction motor over the DC motor, it therefore has advantages in traction applications that use axle-mounted traction motors where space is limited, un-sprung weight must be reduced, and maintenance requirements minimized. It has been noted, generally, that the speed of an AC motor increases linearly with supply frequency. Therefore, a high frequency inverter and brushless AC motor can be used to give a reliably high-speed drive. Consequently, the induction motor has significant advantages for high-speed applications in the machine tool industry. Cycloconverter-fed induction motors are also used in very high power drives. Typical applications include gearless cement or ball mill drives, which use a directly coupled, slow-running induction motor (Sen 1990). The wound-rotor induction motor with a sub-synchronous converter cascade has the natural ability for slip energy recovery and can therefore be used in fan and pump drives.

CONCLUSION

We have presented the comprehensive review of the state of the art in the field of induction motor drives and control strategies. Generally, research in drive technology has witnessed an unprecedented growth during the last three decades. Interest in induction motor drives is gathering momentum and will likely surpass DC drive technology in many industrial applications. It is anticipated that the impressive growth in the area of induction motor drive, control and application, will continue to rise unabatedly because of the advent of high-speed micro-controllers, high-efficient semi-conductor devices, high-speed microprocessors, and microcomputers and efficient control methods.

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