

A Ph.D. SYNOPSIS

in the area of

Electrical Machines

on the topic

**“Parameter Estimation of Three Phase Induction Motor:
An Innovative Approach”**

Submitted by

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FACULTY OF ENGINEERING
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DAYALBAGH AGRA-282005
(2013)

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1.1 Introduction

Three-phase induction motors are the most commonly used and frequently encountered machines in industries due to following advantages [LOR 97]:

- Simple design, rugged in construction, cheap
- almost no maintenance
- wide range of power ratings: fractional horsepower to several hundreds of hp.

In spite of these advantages, the induction motor has two inherent limitations:

- the simple induction motor is not a true constant-speed machine, its full-load slip is around 1-5% and
- Frequency of the power source regulate its speed
 - difficult to have variable speed control
 - for optimal speed control
 - for optimal speed control, a variable-frequency power-electronic drive is required

In spite of these limitations about 80% motors in the industries are induction motors. Hence, there is great importance to improve the reliability of induction motors under different operating conditions. For this purpose induction motor parameters play an important role. The three phase induction motor schematic diagram is shown in Fig. 1.



Fig. 1 Induction motor

1.2 Constructional Features of Induction Motor

An induction motor has mainly the following parts

- i. A stationary stator

It is consisting of a steel frame, stator core, stator windings and a connection box as shown in Fig. 2. The steel frame of stator that supports a hollow, cylindrical core known as yoke. The stator core constructed from stacked laminations and having a number of evenly spaced slots which provide the space for the stator winding.



Fig. 2 Stator of Induction Motor

ii. A revolving rotor

The induction motor rotor is consisting of laminated core, rotor windings, shaft, slip rings in case of wound rotor induction motors as shown in Fig. 3. The rotor core is composed of punched laminations which are stacked to create a series of rotor slots and provide space for the rotor winding.

There are two types of rotor windings, namely:

- a. Conventional 3-phase windings made of insulated wire (wound-rotor) similar to the winding on the stator. Usually Y-connected, the ends of the three rotor wires are connected to 3 slip rings on the rotor shaft. Hence, the rotor circuit is accessible.
- b. Aluminum rotor bars shorted together at the ends by two aluminum end rings, forming a squirrel-cage shaped rotor (squirrel-cage)



(a) Squirrel cage rotor (b) Slip ring induction motor

Fig. 3 Different types of rotor of induction motor.

iii. Bearings- A bearing is a mechanical element that permits relative motion between the parts, such as the shaft and the housing having minimum friction.

iv. Cooling Fan- All rotating electrical machines generate heat as a result of the electrical and mechanical losses inside the machine. Losses are high during starting, overload or dynamic braking. Cooling is necessary to continuously transfer the heat to a cooling medium, such as the air. For AC induction motors, cooling air is usually internally circulated and externally by one or more fans mounted on the rotor shaft. The most common type of AC motor is the totally enclosed fan cooled motor which is provided with a forced external cooling fan mounted on the non-drive end (NDE) of the shaft with cooling ribs that run axially along the outer surface of the motor frame. The fans are designed that keep the air flow close to the surface of the motor along entire length and improve self-cleaning and cooling of the ribs. An air-gap is left between the fan cover and the ribs usually.

1.3 Principle of operation of Induction Motor

The induction motor works on the principle of induction. When a three phase supply is given to a balanced three phase stator windings, which are uniformly distributed in space and mechanically displaced by 120° , produces a constant amplitude rotating magnetic field known as stator rotating MMF(F_s) as shown in Fig. 4. This rotating magnetic field rotates with the speed known as synchronous speed (N_s), mathematically written in terms of frequency and number of stator poles as:

$$n_s = \frac{120f}{P} \text{ rpm}$$

This rotating magnetic field cuts the rotor windings and produces an induced voltage in the windings of rotor. As the rotor windings are short circuited, for both wound-rotor and squirrel cage, and induced current flows in the windings of rotor. Another magnetic field is produced by the rotor current called rotor MMF (F_r). A torque is produced as a result of the interaction of those two magnetic fields (i.e. stator MMF and Rotor MMF):

$$Tm = K F_s \times F_r$$

Where Tm is the motor torque and

F_r and F_s are the MMFs of the rotor and the stator respectively.

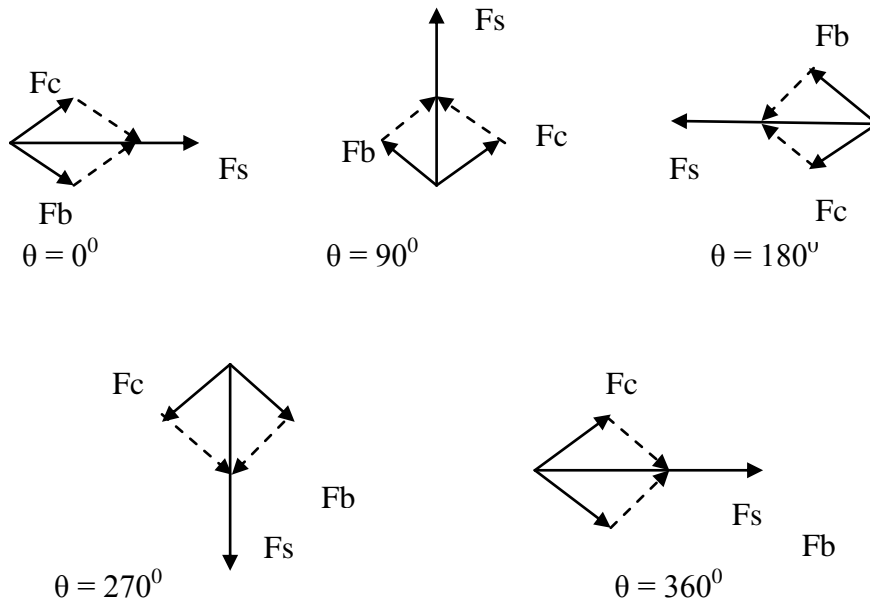
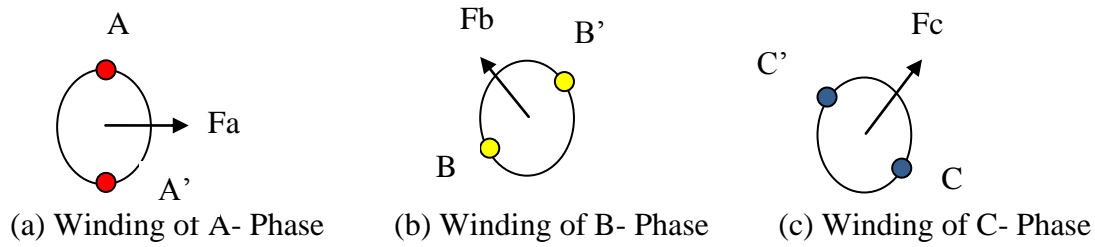


Fig. 4 Stator rotating MMF at different angles

Torque Production

In an induction motor the conventional 3-phase winding sets up the rotating magnetic field (F_s) and the rotor carries the current carrying conductors. An EMF and hence current is induced in the rotor due to the slip speed (i.e. difference between the F_s and the rotor). This induced rotor current produces a torque. As the slip speed reduced the torque produced also reduced. However, this slip speed cannot become zero because that would stop generation of the torque producing current itself. Therefore, induction motor can never run at synchronous speed and hence, it is called asynchronous motor.

The parameter slip 's' is a measure of this relative speed difference (slip speed)

$$s = \frac{n_s - n}{n_s} = \frac{\omega_s - \omega}{\omega_s} \quad \Rightarrow \quad n_s = \frac{120f_1}{p}; p = \text{Number of poles}$$

where n_s, ω_s, f_1 are the speeds of the F_s in rad/sec and RPM and n, ω are the speeds of the rotor in RPM and rad./sec respectively.

The slip frequency and the angular slip frequency at which voltage is induced in the rotor is given by

$$\omega_2 = s\omega, f_2 = sf_1, E_{2s} = s \frac{N_2}{N_1} E_1 \quad \text{where } N_1 = \text{Stator turns}, \quad N_2 = \text{Rotor turns}$$

$$n_{slip} = n_s - n$$

Where n_{slip} = slip speed

n_s = speed of the magnetic field

n = rotor speed of the motor

1.4 Equivalent Circuit of Induction motor

The induction motor acts like the transformer with the exception that its secondary windings are free to rotate.

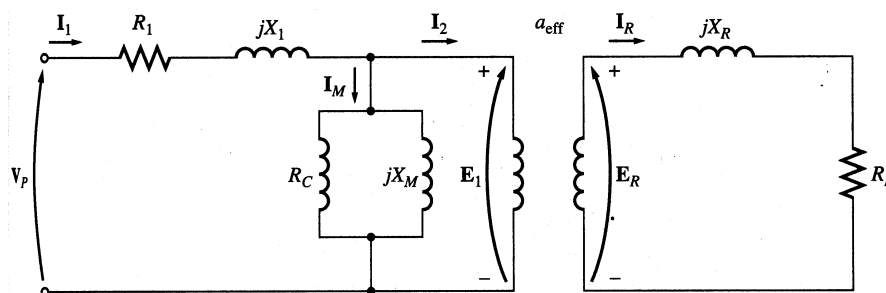


Fig. 5 Equivalent Circuit of Induction Motor

Where X_R & R_R are rotor reactance & rotor resistance.

The same is true for the frequency, i.e. $f_r = s * f_s$

It is known that $X = \omega L = 2\pi f L$ so, as the frequency of the induced voltage in the rotor changes, the rotor circuit reactance also changes $X_R = 2\pi f_r L_r = 2\pi s f_s L_r = s * X_{R0}$

Where X_{R0} is rotor reactance at the supply frequency (at blocked rotor)

Then, we can draw the rotor equivalent circuit as follows

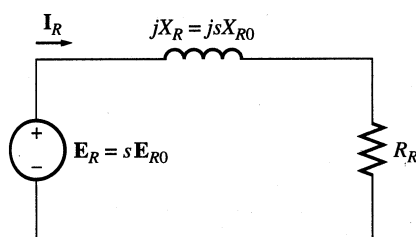


Fig. 6 Rotor Equivalent circuit

Where E_R is the rotor induced voltage and R_R is the rotor resistance

Now the rotor current can be calculated

$$I_R = \frac{E_R}{(R_R + jX_R)}$$

$$= \frac{sE_{R0}}{(R_R + jsX_{R0})}$$

The numerator and denominator are divided by s so nothing changes we get

$$I_R = \frac{E_{R0}}{\left(\frac{R_R}{s} + jX_{R0}\right)}$$

Where E_{R0} is the induced voltage and

X_{R0} is reactance of rotor at blocked rotor condition ($s = 1$)

Now the rotor equivalent circuit may be redrawn as shown in Fig. 7.

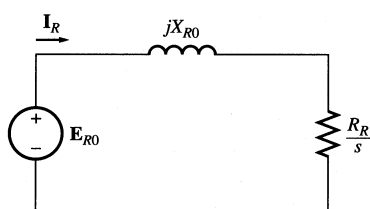


Fig. 7 Modified rotor equivalent circuit

If we can combine the stator and rotor equivalent circuits in one equivalent circuit as shown in Fig. 8.

Where

$$X_2 = a_{eff}^2 X_{R0}$$

$$R_2 = a_{eff}^2 R_R$$

$$I_2 = \frac{I_R}{a_{eff}}$$

$$E_1 = a_{eff} E_{R0}$$

$$a_{eff} = \frac{N_S}{N_R}$$

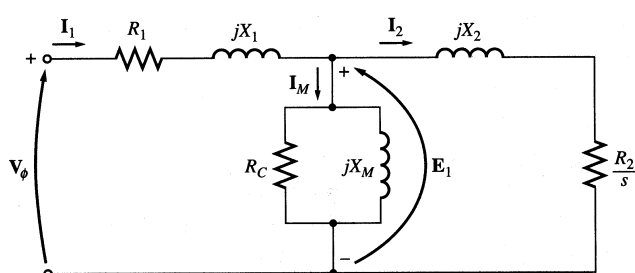


Fig. 8

1.5 Determination of Induction-Motor Parameters

i. DC Test of determination of stator resistance

Connect any two stator leads to a variable-voltage DC power supply. Power supply is adjusted to provide rated stator current. Then determine the resistance from the applied voltage V_{DC} and stator current I_{DC} as follows.

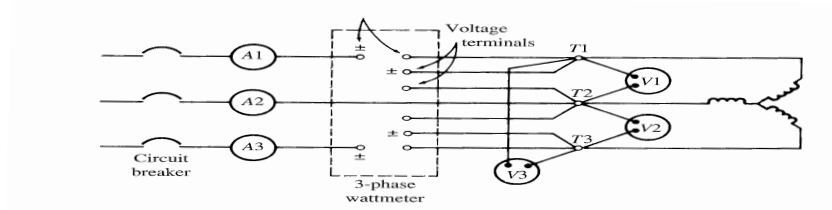
- a. For a Y-Connected Stator $R_{DC} = \frac{V_{DC}}{I_{DC}}$
 Stator resistance of each phase $R_{1Y} = R_{DC}/2$

- b. For a Delta-Connected Stator

$$R_{DC} = \frac{V_{DC}}{I_{DC}}$$

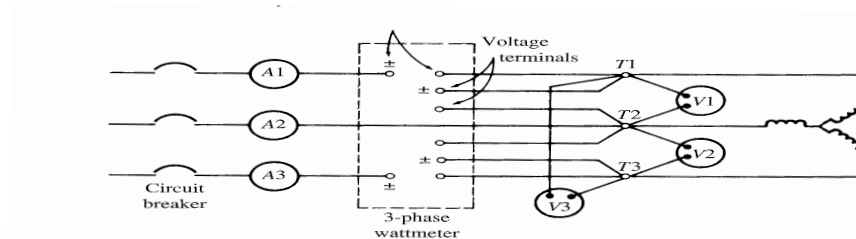
$$R_{DC} = \frac{R_{1\Delta} \cdot 2R_{1\Delta}}{R_{1\Delta} + 2R_{1\Delta}} = \frac{2}{3} R_{1\Delta} \text{ \& } R_{1\Delta} = 1.5R_{DC}$$

ii. Blocked-Rotor Test



From the DC test, determine R_2 when combined with data. The rotor is blocked so that it will not turn. A variable-voltage AC supply is connected and adjust the supply voltage until the blocked-rotor current is equal to the rated current. Neglect the exciting current under blocked-rotor conditions to remove the shunt parameters of equivalent circuit. Finally determine X_1 and X_2 .

iii. No-Load Test



The rotor is allowed to run freely under no-load condition at rated voltage and rated frequency. At no-load condition, the speed is very close to synchronous speed and the slip =0, causing the current in R_2/s to be very small, and will be ignored in the calculations. Determine the magnetizing reactance, X_M and friction, combined core and windage losses.

All the above mentioned parameters of induction motor is calculated under static conditions, but when motor operates these parameters changes dynamically predicting the motor condition.

1.6 Literature Review

The induction motors are exposed to a wide variety of environments and conditions. These factors, coupled with the aging process of any machine, make the motor subject to faults. These faults, if undetected is left, contribute to the degradation and eventual failure of the motors. Many methods and schemes are developed for parameter estimation of large induction motors, but these are generally not applied in smaller machines due to limitations related to sensing-device size and economic considerations.

The induction motor parameter estimation is the art and science of building mathematical models of dynamic systems from observed input-output data. It can be seen as the interface between the real world of applications and the mathematical world of control theory and model abstractions [LJU 08].

The knowledge of all the machine parameters is very important to tune the controllers of a high performance motor drive system [VEL 89, HOL 91, STE 94, BOR 94, RIB 97]. The accurate knowledge of the induction motor parameters is critical for the sensorless drive strategies based on the stator flux estimation [HOL 01]. This fact has stimulated the development of specific techniques to determine the induction motor parameter [RIB 97], [HAB 93, BLA 95, KER 96, UMA 95, JAC 00].

The problems of estimating the parameters and states of a motor have been attacked from a variety of different perspectives summarised by various researchers [LAN 86, VEL 88, LN 89]. A variety of online and off-line methods have been proposed for determining the parameters of an induction motor rotor [HIL 84].

There are various techniques to estimate the induction motor parameters, such as:

1. Conventional techniques
2. Soft computing techniques
 - a. Fuzzy system
 - b. Artificial neural network
 - c. Genetic Algorithms
 - d. PSO
 - e. Integration of above techniques

1.6.1 Conventional methods

There are various conventional methods available with their merits and demerits [PON 07, SIN03, BEL 08, ILO 05, TAL 07, BEN 00]. There are many ways to detect mechanical and electrical problems in induction motors, either directly or indirectly, such as motor current signature analysis [JUN 06, THO 01], line neutral voltage signature [KHE 09], instantaneous reactive power signature [DRI 09], stator current and motor efficiency [FRO 10], electromagnetic field monitoring [THO 93, ROM 10], chemical analysis, temperature measurement [FIL 94], infrared measurement, acoustic noise analysis [LEE 94], partial discharge measurement [OKU 07] and vibration monitoring [SCH 04, BEL 06, SAD 07], and fault detection based on parameter adaptation [BAR 09].

Dynamic performance of induction motor field-oriented controllers strongly depends on model parameter accuracy. A parameter mismatch produces an error in field orientation and undesirable coupling between the flux and torque controllers. Although it is possible to determine in advance the model parameters, significant changes may take place during the normal operation which has to be compensated online. In addition, several algorithms have been proposed to estimate the rotor speed (direct field-oriented control) [ZAM 98, SCH 92, KIM 94] or the rotor resistance (indirect field-oriented control) [GAR 97, ATK 96, STE 94] from an electromagnetic model and using only stator voltage and current measurements. Since the motor models used for estimation contain other machine parameters, the robustness of these algorithms can be improved if the errors or changes in model parameters are compensated online. Clearly, these parameters must be estimated independently of rotor speed and rotor resistance.

The Knowledge of all the machine parameters is very important to tune the controllers of a high performance motor drive system [VEL 89, HOL 91, STE 94, BOR 94, RIB 97]. In particular, the value of the stator resistance is very important for some induction motor drive control strategies [DON 88, ROW 91, BOS 95]. The accurate knowledge of the stator resistance is critical for the sensorless drive strategies based on the stator flux estimation [HOL 01]. This fact has stimulated the development of specific techniques to determine the stator resistance [RIB 97] & [HAB 93, BLA 95, KER 96, UMA 95, JAC 00].

For several decades, the Kalman filter has proved to be a powerful tool for state and parameter estimation of linear and nonlinear systems and has been applied in various fields such as robotics [MAR 05], thermodynamics [CHA 04], medicine [BOR 04] or electrical engineering [BOL 03, MAC 06]. Applied to induction motors, it was proposed for estimation

of flux [CAV 89, ATK 91, SAL 93] and parameters [WAN 07, CAV 89, ATK 91, ZAI 92, WAD 97]. In addition, many studies have focused on diagnosis; among the proposed methods, some are based on state or parameter estimation [SED 98, DUR 99, SAI 00].

Induction-Motor Parameters vary significantly with operating conditions. Besides, the load torque can vary from no load to full load and stator (R_s) and rotor (R_r) resistances change with temperature and frequency, while inductances tend to saturate at high current levels. The effects of parameter and model uncertainties become even more relevant with speed sensorless control, calling for sophisticated methods for the estimation of flux and velocity. The benefits of sensorless control are the increased reliability of the overall system with the removal of mechanical sensors, thereby reducing sensor noise and drift effects as well as cost and size. However, to exploit the benefits of sensorless control, the developed estimation methods must achieve robustness against parameter and model uncertainties over a wide speed range. Parameters of particular concern in the sensorless control literature are the frequency-dependent R_r , temperature-dependent R_s , and the estimation of flux and velocity [BAR 08].

Nowadays, field-oriented control of induction motor electrical drives is widely used when high motor performances are required. However, performance is greatly affected by parameter uncertainty so as the behaviour of both controller and estimator, designed using a model-based approach, rapidly deteriorates in the presence of these uncertainties. Obviously, the behaviour of the whole control system is particularly sensitive to that of the state estimator. To cope with these uncertainties, on-line parameter identification, adaptive or robust design techniques, can be employed for designing either the estimator or the controller, or both [ALO 13].

Induction motor parameters change with temperature, frequency and saturation. The consequence of any mismatch between the parameter values used in the controller and those in the motor is that the actual rotor flux position does not coincide with the position assumed by the controller. The situation is illustrated in Fig. 9 given below [LEV 99]. This means that the actual rotor flux contains both d – and q -axis component, leading to a loss of decoupled flux and torque control. Performance of the drive therefore deteriorates from the desired. In order to avoid such a situation, it is necessary to provide the vector controller with accurate induction motor parameter values. These parameters have to be obtained somehow from measurements, during initialization of the drive. Since any vector controlled induction motor drive is inverter fed, numerous tests based on an inverter supply have been developed in recent past for determination of the required parameter values [LEV 99, VAS 98, LOR 97] Such methods are called “offline parameter identification methods.” In addition, numerous

example, procedures described in [CHR 96, MOO 94, RUF 93] are all based on some tests with single-phase supply to the machine. However, the method described in [CHR 96] involves application of pseudo-random binary-sequence voltage excitation and requires an adaptive observer. The procedure of [MOO 94] relies on maximum likelihood method to obtain transfer function parameters. A step voltage is applied at the stator terminals and the stator voltage and stator current responses are recorded. The Laplace transformation is used to get the transfer function along with the maximum likelihood estimation. The method of [RUF 93] requires application of the recursive least squares algorithm, this being the same as for the procedure of [CON 87]. The second possible excitation for parameter identification at standstill is single-phase ac. Standstill frequency response test forms in this case the basis for the parameter identification [BUN 93, KLA 91, BUN 95, KER 95]. A particularly interesting procedure based on single-phase ac excitation is the rotor time constant identification method of [WAN 88]. It is based on trial- error and essentially does not require any computations. Some of the offline identification procedures surveyed so far enables identification of the machine's magnetizing curve in addition to other rated parameter values. Such is the case for the methods described in [RUF 94, KWO 94, BUN 93, KLA 91, BUN 95]. It should be noted that the requirement for magnetizing curve identification often adds to the complexity of the commissioning procedure since more than one test needs to be performed. A significant step forward in this sense is the method of [BER 01], where magnetizing curve is identified at standstill using only one test with single phase ac supply. Other possibilities of the magnetizing curve identification for self-commissioning purposes have been explored in [RUF 96, RAS 96, BER 97]. If the conditions of the commissioning are less stringent, the drive may be allowed to rotate for the purposes of parameter identification. A whole array of additional parameter determination methods opens up in this case. For example, an extremely simple procedure for rotor time constant tuning [LOR 85] is based on the tests performed while the machine is rotating. The drive is operated in the torque mode for the purposes of the rotor time constant tuning, with rated rotor flux reference. An alternating square-wave torque reference is applied at certain speed of rotation. If the rotor time constant value used in the controller is correct, the actual torque is an alternating square-wave as well, so that the speed response follows a triangular function. If the rotor time constant setting is not correct, then the actual torque response is not the same as the torque reference. Speed response then deviates from triangular.

Standard no-load test and locked rotor test may be performed with a PWM inverter supply if the commissioning situation allows for such testing. Parameters that are calculated are the same as those obtained with sinusoidal supply, provided that the calculations are

based on the fundamental components [BOG 93]. This feature is exploited in [LIN 96], where the parameters are identified using the dc, no-load and the pseudo-locked rotor tests. A method for pseudo-locked rotor test is presented since the mechanical locking of the rotor is undesirable in any onsite commissioning scenario. Identification of the machine's magnetizing curve becomes a simple and straightforward task if the machine is allowed to rotate under no-load conditions during the onsite commissioning. By defining the magnetizing curve's analytical approximation in a suitable functional form and by performing a series of steady state fundamental harmonic voltage measurements in the field weakening region, it becomes possible to determine the correct magnetizing curve approximation purely by visual inspection of the measurement results [LEV 00]. An experimental illustration of this method is given, where measured line-to-line fundamental voltage component is shown, together with the reconstructed magnetizing curve. Another magnetizing curve identification procedure is described in [LEV 99]. It relies on the signals that are already present within the drive controller (stator currents and the dc link voltage), so that additional measurements are not required. A special identification function, proposed in [LEV 99], ensures precise acquisition of the magnetizing curve, robust against the stator resistance variation, and the inverter lock-out time. The algorithm does not require any test signals. It is sufficient to perform the measurements during running of the unloaded motor at around 100 r/min. Performing measurements at such a low speed enables the impact of iron and mechanical losses on identification accuracy to be minimized. This, in turn, enables accurate identification down to 10% of the rated magnetizing flux, including the point of inflection. An illustration of the results of the procedure of [LEV 99] is given. Some other approaches to the magnetizing curve identification, described in [LEV 92, GAN 98, STA 97] are more involved and therefore less suitable for onsite commissioning of the drive. Method of [LEV 92] performs identification at standstill and only current measurements are needed. However, all the three phases of the machine are energized and standstill condition is achieved by means of closed loop speed control. The method requires that the vector controlled induction motor is coupled to a controllable load and is therefore not suitable for onsite commissioning. Similar conclusion applies to the broad-band excitation method [GAN 98], which requires injection of multiple frequency supply into the machine's stator terminals. Method of [STA 97], although apparently very accurate, is rarely applicable in practice since it requires that the neutral point of the stator star connected winding is accessible.

It is worth noting that offline magnetizing curve (or magnetizing inductance) identification suffices for saturation compensation schemes and that identification of dynamic

(differential) inductance is usually not required. However, there are methods that enable identification of the dynamic inductance as well, for example [GAN 98] and [STA 94]. Compensation of iron losses in vector controlled induction machines usually requires knowledge of the equivalent iron loss resistance for the fundamental harmonic, which is a function of the fundamental frequency [LEV 95]. The equivalent iron loss resistance can be identified during the drive commissioning using the procedure outlined in [LEV 96]. A series of no-load tests are performed at various fundamental frequencies, using the same PWM voltage source inverter that will be subsequently used for the normal drive operation. Fundamental harmonic input power needs to be measured, mechanical losses are separated from the fundamental iron losses using the customary no-load test procedure, and equivalent iron loss resistance is eventually calculated. The procedure requires that rotation is permitted and that no-load condition is available. An illustration of the experimental results related to fundamental iron loss component and the corresponding equivalent iron loss resistance is given. Tests at standstill, which would enable identification of the equivalent iron loss resistance, do not seem to exist at present. It should be noted that accuracy of parameter determination in all offline identification techniques depends on the sample rate selection, quantization errors, resolution and accuracy of sensors, etc. [BOR 95]. Identified parameter values will therefore always be characterized with certain error margin. The major problem encountered in offline parameter identification at standstill is undoubtedly the inverter lock-out time and nonlinearity, which make the accurate parameter determination on the basis of reconstructed voltages very difficult without prior knowledge of the inverter voltage drop characteristics [BUJ 95]. A technique for overcoming this problem has recently been proposed, based on recursive least squares [BER 97]. Further important works describing various approaches to self-commissioning and commissioning are those of [GAS 99, KUD 97, CHO 99, GOD 99, BAR 99, KAR 97, RIB 00, SEO 01].

1.6.1.2 Online Rotor Time Constant Estimation Techniques

The major effort has been put into development of rotor time constant (rotor resistance) online estimation methods. Due to a huge number of proposed solutions of very different nature, these are further classified into four subgroups.

A. Spectral Analysis Techniques

This group of methods encompasses all of the cases where online identification is based on the measured response to a deliberately injected test signal or an existing characteristic harmonic in the voltage/current spectrum [MAT 85, TOL 93, CHA 92, GAB 82, SUG 87, SAI 89, CER 95, TUN 94]. Stator currents and/or voltages of the motor are

sampled and the parameters are derived from the spectral analysis of these samples. In spectral analysis, a perturbation signal is used because under no-load conditions of the induction motor, the rotor induced currents and voltages become zero, so slip frequency becomes zero, and hence, the rotor parameters cannot be estimated. In [MAT 85] and [TOL 93], the disturbance to the system is provided by injecting negative sequence components. An online technique for determining value of the rotor resistance by detecting the negative sequence voltage is proposed in [MAT 85]. Special precautions need to be taken to circumvent the torque-producing action when an induction motor, equipped with this system, is used as a torque drive; otherwise, the outer loop might prevent the perturbation from being injected into the system. The main drawback of this method is that the strong second harmonic torque pulsation is induced due to the interaction of positive and negative rotating components of MMF. In [TOL 93], an online estimation technique is proposed, based on the $d-q$ model in the frequency domain. The q -axis component of the injected negative sequence component is kept at zero, so that the machine torque is undisturbed. The d -axis component affects the flux of the machine. FFT is used to analyze the currents and voltages and the fundamental components of the sampled spectral values are used to determine the parameters. Average speed is used for the identification of parameters [TOL 93]. In [CHA 92], an attempt to create online tests similar to the no-load and full-load tests is made. In [GAB 82], a pseudo-random binary sequence signal is used for perturbation of the system by injecting it into the d -axis and correlating with q -axis stator current response. The sign of correlation gives the direction for rotor time constant updating. This method however does not work satisfactorily under light loads. In [SUG 87], a sinusoidal perturbation is injected into the flux producing stator current component channel. Though rotor resistance can be estimated under any load and speed condition, the cost is high due to the installation of two flux search coils. Solutions described in [SAI 89, CER 95, TUN 94] all along to the same category. A very different approach is the one described in [CIL 98, BEG 95, BEG 94] where rotor slot harmonics in stator current are tracked and used for online updating of the rotor time constant.

B. Observer-Based Techniques

In [LOR 93], Loron and Laliberté describe the motor model and the development and tuning of an extended Kalman filter (EKF) for parameter estimation during normal operating conditions without introducing any test signals. The proposed method requires terminal and rotor speed measurements and is useful for auto tuning an indirect field-oriented controller or an adaptive direct field-oriented controller. In [ZAI 92], Zai, DeMarco, and Lipo propose a method for detection of the inverse rotor time constant using the EKF by treating the rotor

time constant as the state variable along with the stator and rotor currents. This is similar to a previously mentioned method that injected perturbation in the system, except that in this case, the perturbation is not provided externally. Instead, the wide-band harmonics contained in a PWM inverter output voltage serve as an excitation. This method works on the assumption that when the motor speed changes, the machine model becomes a two-input/two output time-varying system with superimposed noise input. The drawbacks are that this method assumes that all other parameters are known and the variation in the magnetizing inductance can introduce large errors into the rotor time constant estimation. The application of the EKF for slip calculation for tuning an indirect field oriented drive is proposed in [FIN 98]. Using the property that in the steady state the Kalman gains are asymptotically constant for constant speeds, the Riccati difference equation is replaced by a look-up table that makes the system much simpler. The disadvantage is that, although the complexity of the Riccati equation is reduced, the full-order EKF is computationally very intensive as compared to the reduced order-based systems.

In [KAT 93], an online estimation of rotor resistance and the magnetizing inductance, using continuous form of the Kalman filter is proposed, though the actual estimation is done offline using the discrete form of the KF. For using the KF online, it is important to estimate the magnetizing inductance accurately as an inaccurate magnetizing inductance gives improper value of the rotor time constant. The method is based on the assumption that since the value of the magnetizing inductance follows the motor flux level, the magnetizing inductance can be estimated along with the rotor resistance and the rotor time constant using the KF. Other solutions, based on the Kalman filter, are those described in [DEL 96, WAD 95, PEN 93, ATK 96, SOT 99]. An extended Luenberger observer (ELO) for joint state and parameter estimation was developed in [DUT 95, DUT 93]. In [DUT 95, DUT 93], the authors have provided a comparison of the operation of the ELO and the EKF. In [DUT 95], a deterministic approach to designing the ELO with joint online estimation of motor states and parameters is presented. In [DUT 93], Du and Brdys implemented the scheme using three different full-order ELOs. The first ELO was used for rotor time constant and rotor flux estimation. The second one was used for shaft speed and rotor flux estimation and the third for shaft speed, load torque, and rotor flux estimation. In the case of joint state and parameter estimation, ELO turns out to be the advantageous solution. Since the induction motor is a nonlinear system, the observations from the EKF at individual time instants do not lead to an overall optimal observation. For the ELO, there is a great deal of flexibility in choosing the gain, unlike the EKF and the rate of convergence can be tuned without adversely affecting the steady state accuracy of the observer. The main advantage of the ELO over the EKF is that

the observer performance can be greatly enhanced by simply adjusting the gain matrix for rapid convergence of the estimates, which gives an unbiased estimation in the case of the ELO. The major problems related to EKF and ELO applications are computational intensity and the fact that all the inductances are treated as constants in the motor equations. In order to improve the accuracy of the EKF-based rotor resistance identification, it is suggested in [ZAI 92, KAT 93, PEN 93] to simultaneously identify the magnetizing inductance. Another possibility of improving the accuracy is the inclusion of the iron loss into the model [WAD 95].

C. Model Reference Adaptive System-Based Techniques

The third major group of online rotor resistance adaptation methods is based on principles of model reference adaptive control. This is the approach that has attracted most of the attention due to its relatively simple implementation requirements. The basic idea is that one quantity can be calculated in two different ways. The first value is calculated from references inside the control system. The second value is calculated from measured signals. One of the two values is independent of the rotor resistance (rotor time constant). The difference between the two is an error signal, whose existence is assigned entirely to the error in rotor resistance used in the control system. The error signal is used to drive an adaptive mechanism (PI controller) which provides correction of the rotor resistance. Any method that belongs to this group is based on utilization of the machine's model and its accuracy is therefore heavily dependent on the accuracy of the applied model. The number of methods that belong to this group is vast [GAR 80, AKA 82, KOY 85, KRI 85, LOE 85, LES 86, KAZ 86, OHN 86, DAL 87, OHM 89, LOR 90, ROW 91, SUM 93, VUK 93, KLA 94, TUN 94, UMA 94, GAN 95, GRI 97, WAI 99, KAN 99] and they primarily differ with respect to which quantity is selected for adaptation purposes. Reactive power-based method is not dependent on stator resistance at all and is probably the most frequently applied approach [GAR 80, KOY 85, KRI 85, ROW 91, SUM 93, GRI 97]. A method based on special criterion function, derived again from stator voltage and current measurement, is described in [VUK 93]. Next, air gap power can be selected as the quantity on which adaptation is based [DAL 87, OHM 89]. The reference air gap power is calculated from reference torque and frequency values, while the actual one has to be calculated from measured input power and estimated stator losses in the machine. Alternatively, dc link power can be measured instead of the machine's input power. In both cases, the accuracy of the method is heavily undermined by the need to estimate stator loss (and inverter losses if dc link power is measured). Other possibilities include selection of torque [ROW91, LOR 90], rotor back emf [LES 86, KAZ 86], rotor flux magnitude [ROW 91], rotor flux d-, and q-components [GAN

95], stored magnetic energy [TUN 94], product of stator q-axis current and rotor flux [UMA 94], stator fundamental rms voltage [LOE 85], stator d-axis or q -axis voltage components [UMA 94], or stator q-axis current component [AKA 82]. There are a couple of common features that all of the methods of this group share. First, rotor resistance adaptation is usually operational in steady-states only and is then disabled during transients. Thus, the adaptation can be based on steady-state model of the machine. Second, in the vast majority of cases, stator voltages are required for calculation of the adaptive quantity and they have either to be measured or reconstructed from the inverter firing signals and measured dc link voltage. Third, in most cases, identification does not work at zero speed and at zero load torque. Finally, identification heavily relies on the model of the machine, in which, most frequently, all of the other parameters are treated as constants. This is at the same time the major drawback of this group of methods. Indeed, an analysis of the parameter variation influence on accuracy of rotor resistance adaptation [KRI 86] shows that when rotor flux magnitude method is applied and actual leakage inductances deviate by 40% from the values used in the adaptation, rotor resistance is estimated with such an error that the response of the drive becomes worse than with no adaptation at all. Similar study, with very much the same conclusions, is described in [DIT 94] where parameter sensitivity is examined for d-axis stator voltage method, q-axis stator voltage method, air gap power method, and reactive power method. Due to high sensitivity of the model-based methods to other parameter variation effects, it is desirable to account for at least some of these in the process of rotor resistance adaptation.

Variation of the magnetizing inductance with saturation is for this reason sometimes taken into account, so that the accuracy of rotor resistance identification is improved [SIV 86, SUL 89, SUM 93, VUK 93]. The other drawback of this group of methods, impossibility of adaptation at zero speed and zero load torque is successfully eliminated in certain cases. For example, the schemes of [AKA 82, VUK 93] are operational at zero speed and at light loads although they do fail at zero load. Operation of a MRAS rotor resistance adaptation scheme is illustrated by means of experimentally recorded traces. The method based on special criterion function of [VUK 93], which enables rotor resistance adaptation at zero speed and under light loading conditions, is implemented. The error function, which serves as the input into the PI controller, is shown together with the rotor resistance estimate in per unit (i.e., ratio of rotor resistance in the controller to the actual one in the machine). The drive operates at zero speed with 0.2 per unit load torque. The adaptation mechanism operation is illustrated for step variation of rotor resistance used in the controller, of 50. As can be seen, rotor resistance adaptation works well as the resistance in the controller always returns, after the introduced

disturbances, to the previous value (i.e., $t_o=R_c/R_r=1$). Other methods of online rotor resistance adaptation, that do not belong to any of the three main groups, are reviewed next.

D. Other Methods

There exist a number of other possibilities for online rotor resistance (rotor time constant) adaptation, such as those described in [CHA 90, BAR 99, TOL 99]. For example, the method of [TOL 99] does not require either a special test signal or complex computations. It is based on a special switching technique of the current regulated PWM inverter, which allows measurement of the induced voltage across the disconnected stator phase. The rotor time constant is then identified directly from this measured voltage and measured stator currents. The technique provides up to six windows within one electric cycle to update the rotor time constant, which is sufficient for all practical purposes. A simulation illustration of the method is given, where estimated and actual rotor time constant are shown. The updating is performed only twice (rather than six times) during one electrical cycle.

Another possibility, opened up by the recent developments in the area of artificial intelligence (AI), is the application of artificial neural networks for the online rotor time constant (rotor resistance) adaptation. Such a possibility is explored in [MAY 98, YAN 94]. The other AI technique that can be utilized for online rotor time constant adaptation is the fuzzy logic [CER 97, TAC 98, ZID 01, BIM 01]. Recent emphasis on sensorless vector control has led to a development of a number of schemes for simultaneous rotor speed and rotor time constant online estimation, that are applicable in conjunction with the appropriate speed estimation model-based algorithms [KUB 94, LEE 96, HUR 96, ATT 97, KUB 98, AKA 99, AMB 99, AKA00, FAI 01]. These methods of rotor time constant estimation belong in vast majority of cases to one of the groups already reviewed in this section. An excellent review of the rotor resistance compensation schemes, available at the time, is the one of [KRI 91].

ONLINE ESTIMATION OF STATOR RESISTANCE

An industrially accepted standard for sensed rotor flux oriented control has become the indirect rotor flux oriented control (IRFOC), which does not require the knowledge of the stator resistance. Since the rotor time constant is of crucial importance for decoupled flux and torque control in IRFOC, the major effort was directed toward development of online techniques for rotor time constant identification, as shown by the review in Online Rotor Time Constant Estimation Techniques. The situation has however dramatically changed with the advent of sensorless vector control, which requires rotor speed estimation. Vast majority of speed estimation techniques are based on the induction machine model and involve the stator resistance as a parameter in the process of speed estimation. An accurate value of the

stator resistance is of utmost importance in this case for correct operation of the speed estimator in the low speed region. If stator resistance is detuned, large speed estimation errors and even instability at very low speeds result. It is for this reason that online estimation of stator resistance has received considerable attention during the last decade, as witnessed by a large number of publications devoted to this subject [AKI 94, UMA 95, KER 95, CAB 97, ZHO 97, BOS 98, HAB 98, MIR 98, LEE 98, GUI 99, ZAM 99, MAR 00, LAI 00, TAJ 00, MIT 01, SHI 01, TSU 01, VAS 01]. The other driving force behind the increased interest in online stator estimation was the introduction of direct torque control (DTC), which in its basic form relies on estimation of stator flux from measured stator voltages and currents. The accuracy of DTC, especially in the low frequency region, therefore heavily depends on the knowledge of the correct stator resistance value. In general, methods of stator resistance estimation are similar to those utilized for rotor time constant (rotor resistance) estimation and include application of observers, extended Kalman filters, model reference adaptive systems, and artificial intelligence.

In [FOR79, TAM 87] speed is estimated as a parameter of the induction machine model, given a priori knowledge of the machine electrical parameters. In [ABB 75, VEN 80, NAU 83, FOR 84], Steady-state slip using a variety of estimators is identified. Dynamic slip estimators were presented in [JOE 83, NAB 82]. A position estimator was described in [CUZ 90]. All of these methods assume knowledge of most or all of the electrical parameters. In [BEL 76, FIT 83, CON 87], off-line techniques for determining motor model parameters were presented. All of these methods require data in addition to knowledge of the stator electrical excitation and might even require disassembly of the machine. On-line parameter estimation techniques [IRI 84, KUB 85, CUZ 90, ATK 91, HUR 95] generally estimated a limited subset of the model parameters given knowledge of the remaining parameters. Many of these methods were focused on tracking the rotor resistance or time constant for field oriented control applications. Recursive estimation of both the model parameters and the mechanical state (rotor speed) using transient measurements was considered [SAN 85, VEL 88, MIN 89, VEL 89, VEL 92]. In these papers, induction motor problem was dealt in context with recursive estimation by assuming a separation of electrical and mechanical time constants and treating the mechanical slip as a parameter. Although the recursive estimation paradigm seemed promising because of difficulties like the sensitivity of the rotor resistance to temperature, these techniques required good a priori knowledge (better than 10% accuracy) of most of the parameters for successful performance. A common thread among these induction machine parameter and state estimation problems was the need for either a good

initial guess or accurate knowledge of machine parameters. The methods presented in this work, which are formally offline, could supplement many of the off- and on-line schemes above in practical engineering applications. For example, a controller designed around one of the on-line state estimators described above could, on installation with an unknown motor, apply a “parameter acquisition” test using our methods to determine parameters or initial guesses required for the state estimator.

1.6.2 Soft Computing Techniques

The soft Computing Techniques have been employed to assist the fault-detection task to correctly interpret the fault data, such as expert systems [FIL 00], fuzzy logic [SUL 07, ZID 08], fuzzy NN [BAL 07], artificial neural network (ANN) [CHO 91, DEM 02, KOW 03, YAN 04, AYH 06, SUH 07, MAR 07, BOU 08], wavelet transform technique [CHO 04, CUS 08, PON 09], and genetic algorithm [MAH 09].

1.6.2.1 Fuzzy system for parameter identification

A higher order fuzzy system identification method was given using subtractive clustering which was an extended application of subtractive clustering and a new powerful and flexible fuzzy algorithm for nonlinear dynamic system identification [DEM 00, SCH 01]. Use of linear parameter estimation techniques to determine the rotor resistance, self inductance of the rotor winding, as well as the stator leakage inductance of a three-phase induction machine was investigated [KOU 04].

To perform fault analysis on an induction motor using both experiments and simulation, and to study failure identification techniques applied for condition monitoring of the motor and finally to design an On-line condition monitoring system, fuzzy logic controller using Lab View was used [KUM 09].

A new two-step formulation for incipient fault detection in the stator windings of induction machines was given. The given methodology deals with the fault detection problem as a change point detection problem over the time series of the root mean square (rms) values of stator currents [HAS12]. During the operation of induction motor, stator resistance was changed incessantly with the temperature of the working machine. This situation might cause an error in rotor resistance estimation of the same magnitude and would produce an error between the actual and estimated motor torque which could lead to motor breakdown in worst cases. Therefore, Mohd Akmal Bin Rohani proposed an approach to estimate stator resistance of induction motor using fuzzy logic [ROH 10].

1.6.2.2 Artificial Neural Network technique

Artificial Neural Network (ANN) is a system based on the operation of biological neural networks; it is an abstract simulation of a real nervous system. ANN's have been applied with astonishing success in fields ranging from Computer science to Engineering to Medicine. In recent years, the most stimulating and profitable development is increasing usage of ANN in various areas of electrical machines and control. ANN's attempts to model the structure of the human brain and are based on self-learning. It is composed of a large number of highly interconnected processing elements called neurons working in unison to solve a particular problem. The structure is highly parallel, resulting in ability to self-organizes to represent information and rapidly solve problems in real life [SIL 06]. Generally, application of the ANN can be divided into the following categories:

- (i) Pattern recognition
- (ii) Grouping
- (iii) Association
- (iv) Control
- (v) Prediction
- (vi) Approximation of functions
- (vii) Optimization

Neural networks theory has been an active research area in recent years. Due to the adaptive ability of a network's learning process, applying neural networks to dynamics system identification and control has become promising alternative to process control [YAM 91, KHA 91, FUK 92]. Two conventional approaches have been addressed in the neural network literature to cope with the adaptive control problem. First, some design parameters are learned off-line by measuring the input-output signals and observing the motor behaviour, in some key events. In the second approach, an adaptive leaning is implemented and the control input is determined on-line as the output of a neural network [ETX 94].

The Induction motor is a nonlinear multivariable dynamic system with parameters that vary with temperature, frequency, saturation, and operating point. Considering that induction motors are widely used in industrial applications, these parameters have a significant effect on the accuracy and efficiency of the motors and, ultimately, the overall system performance. Therefore, it is essential to develop algorithms for online parameter estimation of the induction motor. Such algorithms can be performed in real time because of the progress in the use of digital signal processors (DSPs) and microelectronics. The Luenberger observer system is implemented for flux estimation, and the speed observer system is utilized for

rotor-speed estimation. The rotor parameters are the most important parameters for the control of the induction motor drives. The rotor resistance can change up to 150% over the entire operation [TOL 03]. A number of methods that are both for the detection of the rotor parameter and the prevention of its variation have been discussed. In [LOS 84], the rotor parameter estimation is proposed by estimating the rotor temperature. This is based on the fact that the temperature influences the fundamental frequency component of the terminal voltage for a given input current. This is a tedious process because the temperature of the rotor windings has to be measured every time. Many papers have shown the effect of motor parameters on the quality of flux and speed estimation in vector control systems [KRZ 91, JAD 96, KAW 00, RAI 00, ORL 01, TOL 03]. The online identification of the rotor resistance and mutual inductance are developed [WLA 08]. Artificial neural networks (ANNs) can be used to identify and control the nonlinear dynamic systems because they can approximate a wide range of nonlinear functions to any desired degree of accuracy. Moreover, they can be implemented in parallel and, therefore, shorter computational time can be achieved. In addition, they have immunity to harmonic ripples and have fault-tolerant capabilities. Since the 1990s, several investigations into the applications of neural networks in the field of electrical machines and power electronics have appeared [BOS 07]. In recent years, many papers have appeared which deal with the use of ANN in modulation systems [KAZ 94], in breakdown detection [RAI 00], in control [KUN 95, SIM 95, KUL00, PIN 01, KRZ 02, CIR 07, CIR 07], in the estimation of state variables [KUL00, ORL 01], and in the identification of induction-motor parameters [SIM 95, KAR 07]. In many papers [KRZ 91, BAL 00], the use of ANN has been tried for estimating the rotor angular speed. Among the methods used, it is possible to note two types of ANN designs. One is based on the machine model [BAL00], and the other one uses stator currents and voltages for direct speed estimation [ORL 01].

ANN has gained popularity over other techniques, as it is efficient in discovering similarities among large bodies of data. It is an effective alternative for performing motor fault detection while avoiding the need for a mathematical model. Because the ANN can adapt itself to learn arbitrarily complicated continuous nonlinear functions, it can learn the motor-incipient fault detection process, which enables it to give the accurate solution to a particular fault problem. In addition, the ANN can perform this function online through the use of inexpensive monitoring devices. These devices obtain the necessary measurements in a non invasive manner. The objective was to develop an alternative NN based fault-detection scheme that overcomes the limitations of the present schemes. It was observed that presented schemes were costly and applicable for large motors; furthermore many design parameters are

requested. In particular, concerning to long-time operating machines, these parameters cannot be available easily. In some existing schemes, either a detail mathematical model was required or many features had to be extracted, for which costly instrumentation was needed. In this scheme, only stator current was captured, and simple statistical parameters of current waveform were used as inputs to detect the four conditions of motor. As compared to existing schemes, the proposed scheme was simple, accurate, reliable, and economical. In most of the NN-based fault-detection schemes, a single network was used, whereas in the proposed scheme, a cascade connection of RBF–multilayer-perceptron (MLP) (RBF-MLP) network was developed to achieve a classification accuracy of 98.41%. For demonstration of cascade NN-based fault classifier, experimental results were used instead of simulation to make the classifier more practical. A new adaptive control scheme, composed of a neural identifier and a nonlinear controller, was applied to a linear induction motor [HAI 07, VIC 05].

1.6.2.3 Integration of ANN & FS

Prof. L.A. Zadeh proposed fuzzy logic as a model of a human thinking for nonlinear mapping of an input feature space into an output space [ZAD 65]. The artificial neural networks (ANNs) are another approach with large number of various architectures and learning strategies [LIP 87, HAY 94]. By combining these two approaches into a neuro-fuzzy model, it is possible to arrive at control structures with improved characteristics [LIN 96, JAN 97]. ANNs and fuzzy logic are widely used in the areas of modelling, identification, diagnostics and control of nonlinear systems. Two classes of ANNs that have received considerable attention in recent past are the feed-forward neural networks [NAR 90, NAR 96] and recurrent neural networks [KUC 95]. Research on fuzzy logic applications in control structure design shows a couple of general trends. The oldest one is based on heuristic knowledge and experience of a human expert with regard to the system behaviour [HAN 96]. More systematic approaches use procedure defined in deterministic manner [KUK 01], or various optimization methods, such as genetic algorithms [HOM 95], or simulated annealing [ISA 92]. The most promising approach encompasses numerous methods for self-organizing fuzzy model generation on the basis of given input-output numerical data [WAN 92, PAS 98]. The most successful realizations of the self-organizing fuzzy models are frequently obtained using clustering methods for partitioning the input-output space, combined with genetic algorithms(GA) [RUS 00], least-squares (LS) [BAR 98,SET 98], or gradient descent-LS [JAN 93] optimization methods for model parameter adaptation. However, there are small numbers of methods that can provide true on-line adaptation process of a fuzzy model. One of rare examples is Neuro FAST, a Takagi–Sugeno–Kang fuzzy model, where the input space

is automatically partitioned using a modified fuzzy adaptive resonance theory mechanism [TZA 01]. In order for the required system performance to be maintained, it is a prerequisite that computationally efficient and accurate identification models are in existence [COC 89]. The vector control technique, which is developed upon the field orientation principle proposed by Haase in 1968 and Blaschke in 1970, decouples the flux and torque control in an IM [TRZ 94]. However, either fuzzy logic control or ANN has its own drawbacks, which cannot be avoided and neglected. A simple fuzzy controller implemented in the motor drive speed control has a narrow speed operation and needs much manual adjusting by trial and error if high performance is required [UDD 02]. On the other hand, it is extremely tough to create a training data for ANN that can handle all the operating modes [UDD 04]. A neuro-fuzzy controller (NFC) for the IM motor drive has the advantages of both FLC and ANN. Over the last decade, researchers reported works on the application of NFC for variable speed drives [CON 94, LIN 96, BOS 97, GRA 98, RUB 02, RAS 04, UDD 04]. However, the conventional NFCs utilized in earlier works have a large number of membership functions and rules.

1.6.2.4 Genetic algorithm (GA)

There are many occasions where knowledge of motor parameters for system type studies are needed, albeit not at the level of accuracy needed for accurate efficiency determination for example. The source data for determination of such parameters is also often generic, such as torque data from a manufacturer describing a whole range of machines of a certain design. The equations relating the required motor parameters to the given data are often nonlinear in nature. Optimization techniques like the Newton-Raphson techniques have been applied to this type of problem with some success, although with the inherent problem of convergence to a local minimum instead of the global minimum. The optimum determined by the Newton-Raphson technique depends heavily on the initial guess of the parameter, with the possibility of a slightly different initial value causing the algorithm to converge to an entirely different solution. One important parameter required by the algorithm is the derivative of the function, which is not always available or may be difficult to calculate. These problems have encouraged the authors to investigate alternative techniques of solution. One of these is evolutionary algorithms. These methods encompass a broad class of algorithms, two of which are the genetic algorithm and the genetic programming techniques [RUD 94, GOL 89, DAV 91, MIT 96, REE 93, BLI 95, TEL 94, KOZ 96, KOZ 92, KOZ 94, MIC 92].

Possibilities of genetic algorithms application for parameters identification of induction motor was given by Edina Bajrektarević [BAJ 02]. The basic procedure to develop a genetic

algorithm was described and the examples of its application for parameter identification were introduced [MAR 02] In order to simplify the offline identification of induction motor parameters, a method based on optimization using a multi objective genetic algorithm was proposed by Tahir Sag and Mehmet Cunkas [SAG07]. The flux linkage model and torque model of an induction motor were adapted for the estimation [TRE10].

Estimation of parameters of three-phase induction motor in order to conduct on-site energy audits of existing motors was used to project a cost savings. This technique used only a few sets of data (voltage, current, speed, power factor or torque if possible) from the field test of motor (on-site), instead of the no load and blocked rotor tests, coupled with the genetic algorithm for evaluating the equivalent circuit parameters [PHU99].

1.6.2.5 Particle swarm optimization(PSO)

An efficient and reliable Particle Swarm based approach to Optimal Design of three-phase Induction Motor (ODIM) was proposed. The proposed approach employed a particle-swarm-optimization (PSO) technique to search for optimal values induction motor design parameters. The approach had been examined and tested [KAN07].

An adaptive system identification/parameter estimation algorithm for a three-phase cage induction motor based on particle swarm optimization (PSO) was given. The performance of the proposed algorithm was emphasized by comparing its results with those of the well-known stochastic optimization techniques of genetic algorithm (GA) and simulated annealing (SA) for the benchmark application with unknown parameters to identify [NIK10].

Parameter identification of an induction machine is of great importance in numerous industrial applications, including the assessment of machine performance and design of control schemes. Typical parameter identification of induction machines has been described and Parameter identification is based on the input–output signals and the model used [TEL 03]. Over the past few decades, with the indirect field-oriented control and non sinusoidal measurements, most of the methods can be roughly divided into three categories: signal injection-based method [HOL 06, WUY 06, KWO 09, ZHA 09], model reference adaptive system-based technique [TEL 03, MAR 07, MAI 08], and optimization techniques [ABD 05, KAR 07, ORL 07, WLA 08, TRE 09]. The signal injection-based method is to improve the estimation of low speed performance of sensor less schemes or to excite the machine to create various response signals. They often require extra hardware for signal injection. Applications of signal injection have been presented in dealing with the stator and rotor winding temperatures [WUY 06].The model reference adaptive system uses the error between the estimated and the reference signals to calculate the parameters. In optimization

techniques, parameter estimation has been investigated by using the artificial intelligence including the particle swarm optimization (PSO) and the least squares strategy [CIR 05, DIN 10]. These techniques have been reported to minimize the consequences of parameter sensitivity in vector controlled drives.

Many researchers have applied the inverter drive to control the exciting signals of the induction machine in the identifying process. Based on sinusoidal measurements, the voltage, current, active power, and rotor speed are used to identify the parameters of a large induction machine [BAB 07]. Laroche and Boutayeb [LAR 10] presented an original idea to estimate the parameters under the sinusoidal model. New identification methods were also developed for linear systems and can be extended to nonlinear systems. The hierarchical gradient identification method can estimate the parameters and states [DIN 09, DIN 10], the multi-innovation identification method has improved the convergence rate of gradient-based estimation, and both methods can be applied to non uniformly sampled systems [DIN 07, DIN 09, DIN 10]. Although many researchers have investigated the parameter identification of induction machines, little work has been seen doing a full enumeration of all parameters, including both the electrical and mechanical parameters. A method to identify all parameters of the induction machine with a no-load low-voltage starting test was proposed having simple structure without needing extra hardware, which could significantly simplify the procedures and save cost [LIN 12].

1.6.2.6 Other Techniques

Nowadays, a number of complex models were also available, often combining magnetic field theory with classic circuit approach which could now easily deal with once “hard-to calculate” effects of induction machine, such as magnetic saturation, iron losses etc [DEM 06].

The induction machine parameters were typically obtained from no-load, rated load and short circuit (locked rotor) measurements [STI 04]. The drive was usually supplied with symmetrical three phase voltages that contained only first harmonic. Such measurements gave precise machine's parameters only for symmetric machines. In case of machine's electrical asymmetry due to the broken rotor bars [BON 92, TOL 95, YIN 09] the usual measurements did not give accurate machine parameters. Many already developed mathematical models of induction machine with broken rotor bars were complex as they model the internal states of induction machine in great detail either by using high number of differential equations [SIZ 09, CUN 05] or even by finite element analysis (FEA) [FIS 01, FAI 08] to correctly model the magnetic circuit of the machine. The parameters for these

kinds of models could only be obtained either analytically or by FEA simulations. Newly introduced simplified two axes model of induction machine with rotor fault [NEM 10], allowed us to obtain the parameters either via FEA or through measurements.

On-line condition monitoring and diagnostic system of induction motor drives. It enabled a detection of broken rotor bars at an early stage of the fault propagation. The method was based on the analysis of stator current frequency spectrum, which could be measured without disturbing normal motor operation [FIS 08]. Two advanced motor drive subsystems with improved controllers had been designed and developed for an HEV power train. The two subsystems were the starter-generator electric drive and the propulsion motor drive. The contribution of this research would enable efficient utilization of the HEV power train [HAS 08].

A new technique for directly designing a linear digital controller for a single-phase pulse width modulation (PWM) converter systems, based on closed-loop identification. The design procedure consists of three steps. First, obtain a digital current controller for the inner loop system by using the error space approach, so that the power factor of the supply was close to one [YOU 10]. Two methods based on Shuffled Frog Leaping Algorithm (SFLA) and Imperialistic Competitive Algorithm (ICA) for determining the values of the steady-state equivalent circuit parameters of an induction motor was given [MAR 11]. Three Phase Induction Motors Induction motors were the work horse of the modern industry. A dynamical model of a 3- Φ induction motor was developed with an aim of parameter identification [SAD 11].

1.7 Proposed Work

It is understood from the literature survey that the parameters of induction motor may vary due to several factors such as: machine internal temperature, machine aging, magnetic saturation, the coupling effect between the internal system and external systems, and so forth. Thus, there is a need for an efficient and accurate parameter estimation technique for studies such as on-line analysis in which the operational model parameters may deviate substantially from their nominal values and affects the motor performance. The on-line measurement based approach has the advantage of the direct measurement of actual transient behaviors of induction motor and yields more accurate machine models.

Further, since the motor model is intended to represent motor transient behaviors under certain system operating conditions, on-line measured data are very useful in deriving an accurate motor model. Evolution of soft computing techniques has encouraged the researchers to develop efficient algorithms and tools for parameter estimation. The basic outline of the proposed work is as follows:

- To develop an efficient integrated approach using soft computing tools for parameter estimation of induction motor.
- To evaluate model parameters of the induction motor using above developed approach.
- To validate the results obtained by soft computing techniques by its hardware implementation and
- Evaluation of model at different operating conditions.

The Various stages of the proposed work are given in Figure-10.

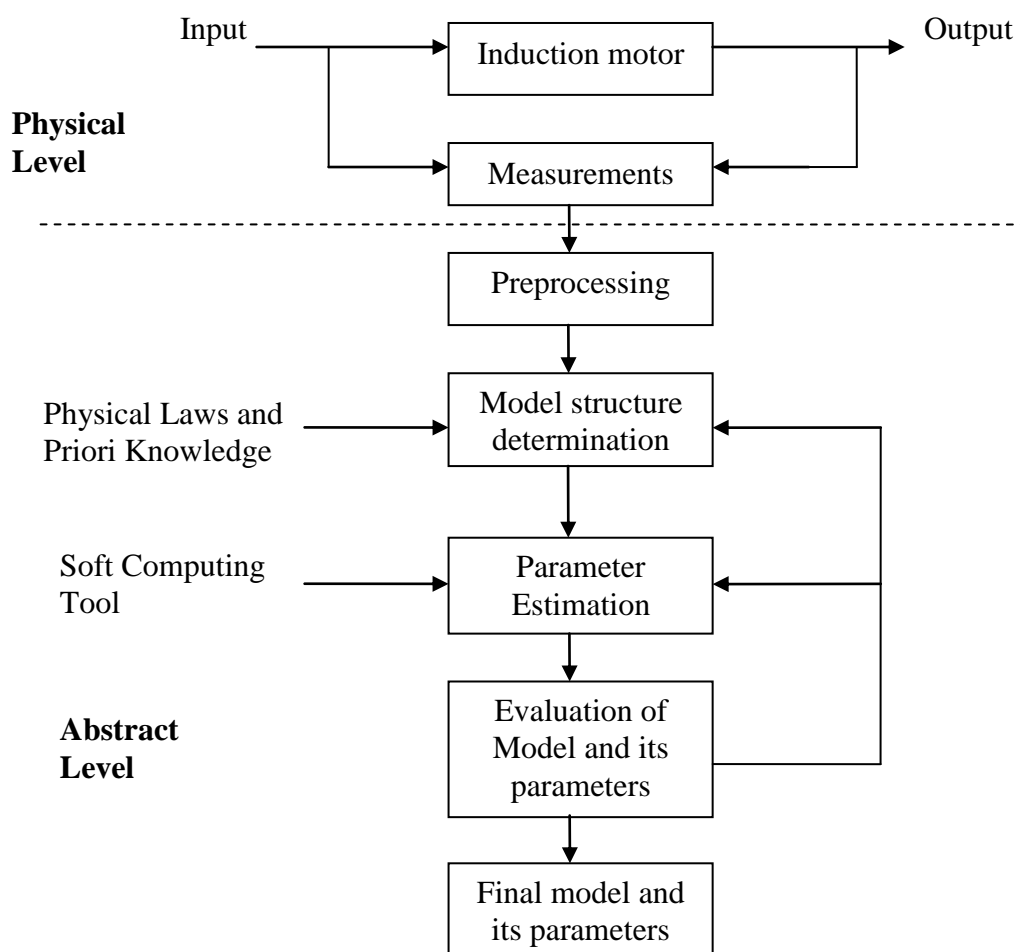


Figure-10: Flow chart of proposed method

1.8 References

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