**CHAPTER 1**

**INTRODUCTION**

This work presents the numerical method for finding the lumped circuit model parameters of the variable speed frequency controlled induction motor. If electrical transients could be interpreted in terms of parameters of a physical model, and then the cause of the impending failure might be identified. When the variable speed frequency controlled induction motors are used, the advantages of these devices obtained but the technical problems can be encountered. This work describes the way that can solved the disadvantages and technical problems and can be effectively used the advantages. Over the years, the various problems are encountered in the industrial zone when the designing ordinary induction motors with constant voltage and frequency (uncontrolled) are used. These problems are temperature effect (at low frequency or at low speed), insulation breakdown effect and saturation effect. The next important point is uncontrolled induction motor are running in the transient state at starting condition but running in steady state in other time. However, the variable speed drives (controlled) induction motors are running in the transient state every time. So, the particular designing of induction motor with variable speed frequency controlled induction motor was done. This design can be made to optimize and to obtain best efficiency in a certain frequency range and a certain voltage range. Old model like α-β, d-q and u-v can guarantee for the steady state condition but not for the dynamic state condition. To accurate the dynamic state, it can be guaranteed from the transient analysis. In this thesis, the best and simplest numerical method for determining the real phase values (voltage, flux linkage) of the stator is developed, since the vector control of variable speed frequency controlled induction motor demands these values as the feedback parameters.

**1.1 History review**

The history of electrical motors goes back as far as 1820, when Hans Christian Oersted discovered the magnetic effect of an electric current. One year later, Michael Faraday discovered the electromagnetic rotation and built the first primitive D.C. motor. Faraday went on to discover electromagnetic induction in 1831, but it was not until 1883 that Tesla invented the A.C asynchronous motor.

Currently, the main types of electric motors are still the same, DC, AC asynchronous and synchronous, all based on Oersted, Faraday and Tesla's theories developed and discovered more than a hundred years ago.Since its invention, the AC asynchronous motor, also named induction motor, has become the most widespread electrical motor in use today.

The main advantage is that induction motors do not require an electrical connection between stationary and rotating parts of the motor. Therefore, they do not need any mechanical commutator (brushes), leading to the fact that they are maintenance free motors. Induction motors also have low weight and inertia, high efficiency and a high overload capability. Therefore, they are cheaper and more robust, and less proves to any failure at high speeds. Furthermore, the motor can work in explosive environments because no sparks are produced.

Taking into account all the advantages outlined above, induction motors must be considered the perfect electrical to mechanical energy converter. However, mechanical energy is more than often required at variable speeds, where the speed control system is not a trivial matter.The only effective way of producing an infinitely variable speed frequency controlled induction motor is to supply the induction motor with three phase voltages of variable frequency and variable amplitude. A variable frequency is required because the rotor speed depends on the speed of the rotating magnetic field provided by the stator. A variable voltage is required because the motor impedance reduces at low frequencies and consequently the current has to be limited by means of reducing the supply voltages. DC motors have excellent speed and torque response; they have inherent disadvantages of commutator and mechanical brushes, which undergo wear and tear with time. AC induction machines are more complex and involved, compared to DC machines. Induction machines have low starting torque and the motor carry large amplitude of starting currents.

Before the days of power electronics, a limited speed control of induction motor was achieved by switching the three-stator windings from delta connection to star connection, allowing the voltage at the motor windings to be reduced. Induction motors are also available with more than three stator windings to allow a change of the number of pole pairs. However, a motor with several windings is more expensive because more than three connections to the motor are needed and only certain discrete speeds are available. Another alternative method of speed control can be realised by means of a wound rotor induction motor, where the rotor winding ends are brought out to slip rings. However, this method obviously removes most of the advantages of induction motors and it also introduces additional losses. By connecting resistors or reactances in series with the stator windings of the induction motors, poor performance is achieved. At that time the above described methods were the only ones available to control the speed of induction motors, whereas infinitely variable speed drives with good performances for DC motors already existed. These drives not only permitted the operation in four quadrants but also covered a wide power range. Moreover, they had a good efficiency, and with a suitable control even a good dynamic response. However, its main drawback was the compulsory requirement of brushes.

With the enormous advance made in semiconductor technology during the last 20 years, the required conditions for developing proper a induction motor drives are present. These conditions can be divided mainly in two groups.

* The decreasing cost and improved performance in power electronics switching devices.
* The possibility of implementing complex algorithm in the new microprocessors.

However, one precondition had to be made, which has the development of suitable methods to control the speed of the induction motors, because in contrast to its mechanical simplicity their complexity regarding their mathematical model (multivariable or non linear) is not a trivial matter.

* 1. **Polyphase Induction Machines**

Polyphase induction machine can work as an induction generator, but for most of the application, its performance is unsatisfactory. In view of this, attention is directed mainly towards polyphase induction motors.

**(a) Stator**.

The stator of an induction motor consists of stator frame, stator core, polyphase (3 or 2- phase) distributed winding, two end covers, bearings etc. The stator core is a stack of cylindrical steel laminations which are slotted along their inner periphery for housing the 3-phase winding. The stator core fits closely in the cast-iron stator frame. The two end-covers made of cast-iron and the stator frame, provide only mechanical support to the stator core and are not designed to carry the stator flux.

The essential parts of a 3-phase induction motor are illustrated in Fig-1.1 (a) and (b). For simplicity, the stator is shown to have 6 slots, though actually the number of stator slots is far more than six, depending upon the three phase winding design. Three coils aa’, bb’ and cc’ represent the winding of the three phases a, b and c respectively. Three windings are space displaced 120o electrical and may be connected star or delta as illustrated in Fig-1.1(c). Many a time, the six ends of the three phase windings are brought out to the terminal box on the stator frame. The six ends are suitably marked to indicate the starting and finishing ends of the three-phase windings. Note that three-phase winding in the stator slots is uniformly distributed along the air gap periphery.Large size motors use open slots so that already prepared and properly insulated coils can be easily inserted in open slots. Small size induction motors use semiclosed slots so as to reduce the effective gap length between stator and rotor.

The air gap between stator and rotor should be as small as is mechanically possible; this will

1. Reduce the leakage flux between stator and rotor
2. Lead to better operating power factor of the induction motor.

**(b) Rotor**

The induction motor has two types of rotors; the squirrel cage rotor and the wound rotor. Both types of rotors make use of circular laminations tightly assembled on the shaft or on the cast-iron spider carried by the shaft.

For the squirrel cage type, the rotor winding consists of uninsulated conductors, in the form of copper or aluminium bars embedded in the semi-closed slots. These solid bars are short circuited at both ends by end-rings of the same material. For good electrical connection, the bars are riveted, brazed or welded with the two end rings (Fig-1.2). In smaller sizes, below 40 kW, the assembled rotor core is placed in a mould and the molten conducting material, usually aluminium, is forced into the slots. Thus the rotor bars, end rings and cooling fan, are cast in the operation. Without the rotor core, the rotor bar and end rings look like the cage of a squirrel, hence the name squirrel cage induction motor. Note that the rotor bar forms a uniformly distributed winding in the rotor slots. As the rotor bar are short –circuited by two end rings, no external resistance can be inserted in the rotor circuit of a squirrel cage induction motor.

In the wound rotor type, the rotor slots accommodate an insulated winding similar to that used on the stator. The rotor winding is uniformly distributed and is usually connected in star. The three leads from the stator connection are then connected to three slip rings or collector rings mounted on but insulated from the shaft, Fig 3.4 (b). Carbon brushes pressing on the slip rings allow, external resistors to be inserted in series with the rotor winding for speed and starting-torque control. Actually, the wound-rotor type of induction motor costs more and requires increased maintenance; it is therefore only used where

1. The driven load requires speed control or
2. High starting torque is required.

Since the rotor is wound with polyphase windings and carries slip rings, it is called wound-rotor or slip-ring induction motor. In both the types, the rotor slots are not parallel to the shaft axis, i.e., the rotor slots are skewed for obtaining a quiteter and smoother operation of the induction motor.

The squirrel cage type is simpler and more economical in construction than the wound-rotor type. Further the cage type is more rugged and requires less maintenance than the wound rotor type, since the former does not require slip rings and carbon brushes.

A polyphase induction motor receives electrical energy from one alternating voltage source; it is , therefore, called a singly excited machine. The stator carries the field winding; armature winding is on the rotor. The stator windings connected to the supply is called the primary winding, similar to the transformer primary winding. The rotor winding is called the secondary winding, since it receives energy from the stator by mutual flux, as in the case of a transformer. In order words, an induction motor may be regarded as a generalized transformer with electrical power transformation from stator to rotor, along with a change in frequency and a flow of mechanical power.

This motor has come to be called as induction motor, because stator delivers energy to rotor by means of induction (i.e. transformer action). The type of the rotor used, decided the name of the particular type of induction motor.

**1.3 Electromagnetic (or interaction) torque**

Fig-1.3 (a) illustrates a salient-pole stator with 2 poles and a cylindrical rotor with one conductor. When stator coils are energized, stator magnetic flux is set up and its path is as shown in Fig-1.3 (a), with no current in the rotor conductor. If rotor conductor carries a current indicated by, say dot, then the magnetic flux picture is as depicted in Fig-1.3(b), with no current in the stator coil. When stator coils and rotor conductor, both carry currents, then the flux produced by the rotor current interacts with the stator-produced flux, giving the resultant magnetic flux distribution as illustrated in Fig-1.3(c). Since the magnetic flux lines behave like stretched rubber bands, the rotor conductor experiences a force in the upward direction. The clockwise torque developed due to the interaction of stator and rotor magnetic fields, is called interaction or electromagnetic torque.Consider now one current-carrying coil on the rotor. The direction of current in the coil is indicated by dot under stator-north pole and by cross under stator south pole,Fig-1.3(d). The rotor current produces rotor flux and this creates two poles on the rotor. The stator S pole attracts rotor N pole and repels rotor S pole, resulting in clockwise torque. Similarly stator N pole attracts rotor S pole and repels rotor N pole, resulting again in clockwise torque. The total torque developed in this manner, Fig 1.3 (d), is called interaction or electromagnetic torque. The physical understanding of interaction torque can further be highlighted by referring to Fig-1.3(e). In this figure, one permanent magnet free to rotate, is placed in the field of a stationary magnet. The tendency of the two fields to align themselves in the same direction is called interaction torque. The angle between stator-field axis and rotor-field axis is called the torque angle Fig-1.3 (a). Note that the torque angle in Fig-1.3 (d) is . The magnitude of electromagnetic or interaction torque in all rotating machines is given by

(1.1)

**1.4 Transient Processes in Electric Machines**

Transients in electric machines arise from changes in the voltages and frequencies at machine terminals, the load on the shaft, machine parameters, during connection of a machine to or its disconnection from the bus, etc. In real conditions, transient processes can natural­ly occur during a simultaneous variation of a few factors. The com­binations of the factors affecting the dynamics can be manifold, so the researcher must have enough experience and knowledge to choose the prevailing set of factors, thereby simplifying the problem. There is a great variety of transients which are much more complex than steady-state processes.

By their importance and the influence they have on the operation of machines, the transients can be divided into the pro­cesses brought about during starting, braking, reversing, restarting, and load variation. These processes can appear at symmetric and asymmetric voltages in symmetric and asymmetric, machines. The dynamics of asynchronous and synchronous machines has its own features. A commutator or any other frequency converter introduces its own specific features into the dynamic behavior of the machine. The transients in transformers and other electromagnetic energy converters differ from the transients in rotating electric machines.

Transients often determine the choice of the installed power of equipment, the mass of electric machines and electromagnetic loads they have to carry. This is particularly the case for impact-load heavy-duty drives, reversing quick-acting drives, etc.

To analyze transient processes, we should formulate the mathematical model of the transients, convert the equations to the forms convenient for the simulation of the processes on a computer and solve these equations. From the qualitative analysis of the processes of starting, rever­sing, and restarting it follows; that these processes differ from each other by the character of variation of currents, torques, and angular velocities. The effect of parameters on the course of various tran­sients is different. The analysis of transients is made by solving the system of transient dynamic equations.

**1.5 The laws of electromechanical energy conversion**

Although the theory and practice of electromechanical energy conversion have a long history and achieved great successes, the basic energy conversion laws have been stated only quite recently. Let us formulate these laws.

**First law; the efficiency of electromechanical energy conversion cannot equal 100%.**All energy converters can be divided into simple and complex ones. In single converters, the energy of one form is converted to the energy of another form. An example is the conversion of electric energy heat in an electric heater. In complex converters, which constitute the majority of machines, the energy of one form is converted to the energy of two forms (and, rarer, to three or more forms). These are converters of energy from luminous to electrical form, chemical to mechanical form, nuclear to electrical form, etc. In complex converters there commonly occurs an attendant conversion of energy to heat.

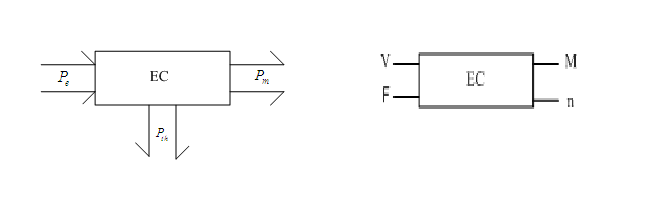


Fig (1.4) the energy flow distribution fig (1.5) the electric machine as a two port

in an electric machine

Electromechanical energy converters belong to the group of complex converters because the processes of energy conversion here always go with the conversion of electric energy Pe or mechanical energy Pm to thermal energy Pth ECs exhibit the flows of electromagnetic, mechanical, and thermal energies (fig-1.4).

The objective pursued in evolving a ECs is to reduce the loss- thermal energy flows- and thus to decrease the overall dimensions and cost of the machine. The efficiency of some converters available today reaches 98%, and that of transformers runs as high as 99.8%, which is indicative of exceptional technical achievements.

It is to be borne in mind that high efficiencies are achievable in high-power converters. In low-power ECs the efficiency reaches merely a few percent since the major amount of mechanical or electric energy evolves as heat.

It is impossible to produce an electric machine in which conversion of energy to heat would be nonexistent; otherwise it must be furnished with superconducting windings. As well be shown below, electromechanical energy conversion equations have no solutions at zero resistances.

We can visualize a lossless machine (without iron and having superconducting windings), but to enable such a machine to convert energy, we need to insert a resistance into the current network external to the machine. In this arrangement, it is the electromechanical system beyond the machine that develops losses. An electric machine can be treated without regard to the external electromechanical system only under definite conditions, when, for example, the line resistance is equal to zero, i.e. the machine operates from or into the bus of infinite power.

The processes of electromechanical energy conversion must be studied with due regard for all electrical and mechanical loops.

An EC that does not develop losses becomes a storage or tank of energy rather than the energy converter. Energy storage devices are electrical engineering arrangements resembling in design electric machines.

Energy storage devices can be built as both as both static devices and rotating machines, for example, as a gyro with superconducting windings. This is an electric machine that can rotate permanently since there is no loss in it. But an anti torque moment applied to its shaft will bring the machine to a stop. This machine cannot act as an energy converter.

An electromechanical converter can be represented as a two port (fig- 1.5) accepting, for example, stimuli(voltage V and electrical frequency f) at a pair of electrical terminals (electrical port) and producing representation of an electric machine applies to solving problems in electro mechanics where the processes of energy conversion inside the machine do not have a dominant significance.

**Second law; All electromechanical converters are reversible, i.e. they can act as motors and as generator.**

The reversibility is an important advantage of ECs over other energy converters such as steam turbines, diesel engines, jet engines, etc. The energy conversion mode of operation of an electric machine depends on the moment of resistance (torque or anti torque) on its shaft, Mr . If the electric energy is drawn from the power line, this EC operates in the motoring mode. If the flow of mechanical energy delivered to the EC shaft transforms to the flow of electromagnetic energy, the machine operates in the generating mode.

The active power reverses its direction with a change of the operational function from generation to motoring, but the flow of thermal energy does not generally change its direction. Losses in common ECs are irreversible.

There is a great variety of ECs including electric machines which convert heat to electric or mechanical energy. To provide linkage between windings (loops) and currents it is necessary to produce an electromagnetic field. The rotating field in electric machines is set up by alternating or direct currents. The reactive power may flow in an EC operating in the steady state from either the stator or rotor, or from both simultaneously.

One of the corollaries of the first and the second law is that an EC also represents an energy concentrator. The electromagnetic energy, being distributed at infinity along an electric power line, is stored in magnetic field energy converters within the air gap between the stator and rotor. In transformers, the energy is stored in the magnetic core and in the space between the primary and secondary, where leakage fluxes close on themselves, falling to be common to both windings.

The air gap of a comparatively small volume can concentrate huge powers. It is of importance to note that in turbine generators of maximum powers and induction machines of the single series, the power density (W/mm3) in the air gap is equal to approximately 0.5 in view of this fact, designing of electric machines can be begun with the estimation of the gap volume and then proceeded with the calculation of windings and geometrical parameters of the magnetic system. Active and reactive flows of energy can be coincident or opposite in direction irrespective of whether the EC runs as a generator or motor. This means that the active power may come from the stator and the reactive power from the rotor, and vice versa.

ECs also operate in the no-load condition at which they convert electric or mechanical power into heat. Synchronous machines connected in parallel with the line and run at no load are called synchronous capacitors.

During its operation, an electric machine releases thermal energy. It is possible to produce an electric machine furnished with a thermopile in order to absorb heat inside the machine at the cold junctions as a result of the Peltier effect (thereby preventing it from heating) and to evolve thermal energy at the hot junctions outside the machine. However, the available semiconductor couples offer cooling at low current densities, so the gain resulting from the improved cooling can only be brought about at the cost of an increase in the overall dimensions of the machine and a worsening of its energy characteristics. This attests that the thermal energy fluxes as well as the mechanical energy and electric energy fluxes in an EC must be regarded as closed energy loops.

The condition of resonance exists in electric machines just as it does in most energy converters. Electrical and mechanical phenomena that occur in ECs are resonant. Electric machines exhibit electromechanical resonance at which the rotational speed of the field, f1, is related to the mechanical rotational speed of the rotor, n, measured in revolutions per second, by the expression

# (1.2)

Where p is the number of pole pairs.

In a two-pole machine, the power line frequency and the synchronous speed of the rotor are the same. Electric machines are built in such a manner that the wave of a magnetizing force in the air gap distributes itself integrally among the poles, so the processes of energy conversion in two pole and multipolar machines are essentially identical, the only difference being that in the latter machine, the synchronous speed of the field and the mechanical speed of the rotor are a factor of p lower.

**Third law; Electromechanical energy conversion is due to the fields that are stationary with respect to each other.**

The rotor and stator fields in the air gap of a machine, which are stationary with respect with respect to each other, produce a flux of thermal energy, thus indirectly affecting the distribution of the fluxes of mechanical and electric energies.

The windings of electric machines must carry polyphase currents and show a proper arrangement to produce a rotating field in the air gap. A rotating field can be set up by a two phase current system with the windings displaces in space from one another and the currents shifted in time by, by a three phase current system, with the windings apart in space and in time; and, in the general case, by an m-phase current system, with the windings displaced /m in space and currents shifted /m in time. Direct current can also produce a rotating field, in which case the dc winding must rotate. The winding carrying alternating currents to produce a rotating field are usually stationary with respect to each other produce a resultant field and electromagnetic torque.

(1.3)

Where ωe is the angular velocity (speed) of the field; and Pem is the electromagnetic power.

The fields displacing in the air gap with respect to each other produce a flux of thermal energy, thus indirectly affecting the distribution of the fluxes of mechanical and electric energies.

The windings of electric machines must carry polyphase currents and show a proper arrangement to produce a rotating field in the air gap. A rotating field can be set up by a two phase current system, with the windings apart in space and in time; and, in the general case, by an m-phase current system, with the windings displaced 360/m in space and currents in shifted /m in time. Direct current can also produce a rotating field, in which case the dc winding must rotate. The windings carrying alternating currents to produce a rotating field are usually stationary.

In a synchronous machine, the rotating field is largely set up by the currents in the windings disposed on the stator. The field rotates at a speed ωs. The rotor runs at the same speed, ωr=ωs, therefore the frequency of the rotor current is fs = 0, i.e. direct current flows through the rotor winding.

In a dc machine, the field (excitation) winding is on the stator, and the excitation field is stationary, rotating the armature, which is the rotor here, produces the rotating armature field, which revolves at the same speed as the rotor but in the opposite direction.

In induction machines, the frequency of current in the rotor is

f2= f1s (1.4)

where the slip ( speed differential that is a fraction of synchronous speed )

(1.5)

Therefore, the speed (angular velocity) of the rotor plus the speed with which the rotor field travels with respect to the rotor structure is always equal to the speed of the field . If the rotor turns at a speed higher than in the same direction as the field excited by stator currents, the rotor field travels in the opposite direction to the rotor, so the stator and rotor fields are again stationary with respect to each other.

In transformers the windings are stationary, and thus the frequencies in the primary and secondary are the same. It can then be assumed that the fields of primary and the secondary travel at the same speed. The concept of stationary of fields in transformers is of little consequence for the analysis of the processes of energy transformations.

The third law facilities the analysis of energy conversion processes in electric machines and forms the basic for the representation of energy conversion equations. For electric field and electromagnetic field energy converters the field stationary concept does not have such a great significance as it does for magnetic field energy concentrations exhibiting electromechanical resonance.

Since electromechanics is part of physics, all basic physical laws are applicable to electric machines. To these belong first of all the laws of energy conservation, Ampere’s law (circuit law), Ohm’s law, etc. At the root of the equations describing energy conversion in electric machines are Maxwell’s equations and Kirchhoff’s laws.