**Chapter -1**

**Introduction**

1.1 Constructional Features of Rotating Electrical Machines

All the rotating machines, used for generation purpose, electric drives or for control systems, have many common essential features from construction point of view. For example, every rotating electrical machine must process

1. Stator (stationary member)
2. Rotor (rotating member)
3. Air-gap separating the stator and rotor and
4. Shaft, bearing, foundation etc.

In addition to it, every electrical machine usually has

1. Exciting or field windings, which produces the working flux and
2. Armature winding in which the working e.m.f. is induced by the working flux.

The current in a winding that varies as the machine is loading is called load current. The current that produces only a working magnetic flux and does not vary with the load on the machine is called magnetization current, exciting current or field current. The winding on the machine that carries only load current is called armature winding. The winding that handles only exciting current is called field winding. Current in the field windings is always dc. A winding which handles both the exciting current and load current and load current is called the primary winding of that device. The primary winding is usually the power-input winding. The power-output winding for such machines is called the secondary winding.

The armature winding handles all the power that is being converted or transformed. The rating of armature winding is equal to the power rating of the machine. The field winding power rating is about ½ to 2% of the rated power of the machine. The power input to dc field winding is dissipated as loss in the field winding (once the required field current is established).

The armature windings of both the dc and ac machines have to deal with alternating current only-this is the reason why the armature structures of all rotating machines are laminated in order to reduce the eddy current losses. Further, almost all the rotating machines have even number of alternate N and S poles (called heterpolar structure). If power is fed to or taken from the rotor it is obvious that sliding contacts are essential. All types of large rotating machines are provided with radial and axial ventilating ducts for cooling purposes.

In this article, important constructional features of more common types of rotating electrical machines are described.

1.2 Electromagnetic (or interaction) torque

Fig 3.1 (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. 3.1(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 3.1(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 3.1 (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 3.1(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 3.1(d), is called interaction or electromagnetic torque.

The physical understanding of interaction torque can further be highlighted by referring to Fig 3.1(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 3.1 (a). Note that the torque angle in Fig 3.1(d) is . The magnitude of electromagnetic or interaction torque in all rotating machines is given by

(1.1)

1.3 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.

**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.3.4 (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 winding are space displaced 120o electrical and may be connected star or delta as illustrated in Fig.3.4(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.

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 3.5). 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.

**1.4 Induction and Interaction**

There are two related principles forming the foundations upon which are based all electromagnetic machines concerned in the conversion of electrical energy to or from mechanical energy. These are (a) the law of induction and (b) the law of interaction. They have an empirical derivation, and have been verified again and again without apparent failure.

(1) Law of induction. The essentials for the production of an electromotive force are electric and magnetic circuits, mutually interlinked. The summation of the products of lines of magnetic induction with complete turns of the circuit is termed the total line-linkages. A line –linkage is defined with reference to the conception of a magnetic field as being composed of unit area is a measure of the field induction or flux-density B; and whose direction and sense at any point indicate the direction and sense in which a unit north-seeking magnetic pole would be urged if placed in the field at that point. Experiment has shown that where the number of line-linkages, in a given pair of mutually linked magnetic and electric circuit. This e.m.f persists only while the change is taking place and has a magnetic proportional to the rate of the change with time. The instantaneous e.m.f.

(1.2)

Where N represents line-linkages. The negative sign is indicative of the direction of the e.m.f. round the circuit, to show that it is such as to oppose the change. Thus if the electric circuit were closed on itself, and the number of line-linkages formed by it and some externally-produced magnetic field were reduced, then the e.m.f induced would produce a current in the closed circuit, generating a self-magnetic field superimposed upon the external field and tending to make up the deficiency caused by the reduction of line linkages.

For engineering purposes the induction law is generally used in the simplified form-

(1.3)

Hence Tc is the number of turns in the electric circuit, all of which are linked completely with all the lines of induction of a given magnetic field. Such a case never occurs in practice, but close approximations to it are common; consequently eq() is frequently employed for engineering purposes. It is interesting to note that experiment shows the alternative form, to be inadmissible: the number of turns in a circuit linked with a magnetic flux may be changed under certain conditions without any evidence o an e.m.f. appearing, whereas the change of the flux linking a circuit always causes an induced e.m.f therein.

The electromagnetic method of producing an e.m.f. in a circuit (in order that the e.m.f. shall produce a current and thus enable electrical energy to be delivered) is therefore to provide a magnetic field linked with an electric circuit, and to change the number of line-linkages .Considering for simplicity that the electric circuit comprises a coil of turns, then the change of line-linkages may be accomplished in a variety of ways-

1. Supposing the flux constant in value, the coil may move through the flux (relative motion of flux and coil);
2. Supposing the coil stationary with reference to the flux, the flux may vary in magnetic (flux pulsation);
3. Both changes may occur together; i.e. the coil may move through a varying flux.

In practice, a further elaboration is due to alternative ways of making connection to the coil or circuit, namely (a) tapping (e.g.slip-rings), or (b) a commutator and brushes. The several combinations now possible are dealt with in detail in appendix 1,

(2) Law of interaction .When a conductor of length cm., carrying a current amperes, lies in and perpendicular to the direction of a magnetic field of density gauss (or lines of induction per cm2), a mechanical force is developed on it of magnitude.

(1.4)

in a direction perpendicular to both current and field. A conception of the mechanism by which this force is produced is provided by the following considerations. Lines of induction have the property of tending to shorten their length, and at the same time to exert lateral pressure on neighbouring lines. (Strictly, the actual field behaves as if it were composed of lines of induction having the property, etc.) In Fig(00) , B represents the density of an original magnetic field. The introduction of a conductor carrying a current brings at the same time a new magnetic field due to the current itself, which field would be concentric with the wire were the latter isolated. Since it is not possible in Nature to have two separate fluxes in the space at the same time (although for convenience of analysis we may often presume the contrary), the original field and the conductor field combine to form a resultant field (Fig (0)).

The “elastic thread” nature of the lines of induction makes them tend to straighten, urging the conductor to move in a direction at right angles to both the current and the original field. The force produced per cm. length depends on the strength B of the original field, and on the disturbing field (proportional to ) ; whence eq;f;d .The field density actually existing round the conductor is not B .It is greater than B on one side and less on the other, The resultant field is not uniform, but distorted, and the distortion is an essential feature in the production of the mechanical force, which is proportional, as indicated, to the strength B of the original field, and on the disturbing field (proportional to ); whence eq(0). The field density actually existing round the conductor is not on one side and less on the other. The resultant field is not uniform, but distorted, and the distortion is an essential feature in the production of the mechanical force, which is proportional, as indicated, to the strength of the original field.

**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.

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 1.1).

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 1.8) 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

# (1.5)

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 90 in space from one another and the currents shifted in time by 90, by a three phase current system, with the windings120 apart in space and 120 in time; and, in the general case, by an m-phase current system, with the windings displaced 360/m in space and currents shifted 360/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.

(1.6)

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 120 apart in space and 120 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 360/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 (1.7)

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

(1.8)

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.

The application of the automated electric drive makes it possible to considerably increase the effectiveness of technological processes in different branches of production. At present in different of industry, systems by heat- and water supplies that work with a constant or slowly changing load moment, the widest use obtained adjustable electrical machines (3m) with the nourishment from the inverter, which consume more than half of the entire manufactured electric power.

At present one of the important tasks of the mathematical theory of electrical machines is the creation of the generalized mathematical model, with the aid of which it is possible to investigate the dynamic behaviors of works 3m that feeds from the inverter, and controlled by microprocessor.

There are different approaches of the solution of mathematical model. Usually this problem is solved on the base of the field theory and theory of chains. Field theory is developed on the basis of Maxwell's equations, while the theory of chains - on the basis of Kirchhoff's equations. In spite of achievements in the creation of the models of electrical machines on the base of the equations of field, more successfully are simulated electrical machines with the aid of the equations, comprised on the basis of the theory of chains [1].

**1.6. System of differential Equations for Induction motor**

During the composition of equations and in the examination of the transient processes of asynchronous machines we use the conventional assumptions and the limitations, connected with the concept ( the idealized machine ): machine is not saturated, there are no losses in steel; phase windings are symmetrical and are moved at angle of 90. Deg for two phase machines and to 120 for the three-phase; mmf (magnetomotive forces) of windings magnetic fields are distributed sinusoidally along the circle of air gap; air gap is uniform; rotor is symmetrical. Real distributed winding is substituted concentrated, and its MMF is accepted by equal MMF of real winding.

If necessary can be taken into account saturation of magnetic circuit, loss in steel, asymmetry of rotor, etc.; however, this considerably complicates the form of equations and their solution.

The mathematical description of the processes of the electromechanical conversion of energy in asynchronous machines is characterized by known complexity. In connection with this the composition of the differential equations of asynchronous machines is one of the most important preparation stages of task for the solution of induction motor and inverter. Asynchronous machines are the most extended type of electrical machines; therefore the creation of their mathematical models is especially expedient, since in this case the solution of the wide circle of the tasks, united under the generality of algorithm, becomes possible.

Without stopping on general questions of mathematical the theory of electrical machines, called the sometimes generalized theory, let us examine equations for the cases most common in practice.

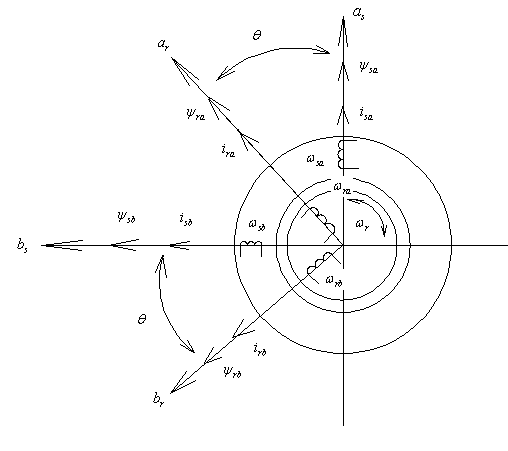
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Fig 1.1.State Space model of machine in the untransformed (natural) coordinate system

**1.7. Mathematical model of the generalized electrical machine**

For the generalized electrical machine (fig. 1.1) they are valid: the equation of the voltage

 (1.9)

Equation of internal torque

 (1.10)

Equation of motion

 (1.11)

The system of equations of the electromechanical conversion of energy, which describes the processes of the conversion of energy, consists of four equations of Kirchhoff for four windings (1.9), and also (1.10) and (1.11), which sometimes are united and is obtained system from five equations.

In these equations  - respectively voltage and currents in the windings of stator-rotor unit for the axes; - resistance of stator and rotor; M – mutual inductance; - the complete inductances of the windings of stator-rotor unit along the axes.

The inductances of windings are determined on the known relationships:

  (1.12)

Where  - the leakage inductance of the windings of stator-rotor unit along the axes.

With the study of the generalized machine it is assumed that the windings of stator-rotor unit have the identical number of turns, i.e., the given electrical machine is examined. Mutual inductance and leakage inductance of the winding of phase in (1.9) are determined by calculated or experimentally (according to the equivalent circuits and the formulas of design). It is assumed that there is rotor, and the leakage fluxes, connected only with one winding of rotor or stator.

Equation (1.9) they are written for the fixed machine. Assuming that the revolving rotor to the fixed rotor– some of the important stages in the conversion of the equations, with the aid of which is constructed mathematical model of Electrical drives. in order to preserve the invariance of power in the real machine and the machine with the fixed windings, into the equations introduce the expressions Rotational EMFs, equal  for the rotor winding along the axis and  for the rotor along the axis. Equations Kirchhoff (1.9) contain the expressions of voltagees, voltage drops across effective resistance, Rotational EMF and transformation EMF:

. (1.13)

Analogously it is possible to write down transformation EMF for the windings, arranged along the axis.

In the equation of motion (1.11) J – the moment of inertia. If electrical machine is investigated together with the drive mechanism, then in expression J the moment of the inertia of rotor and the moment of the inertia of drive mechanism led to the frequency of the rotation of rotor must be considered.

In the electrical machines the moment of resistance of ms is usually constant, in the electromechanical systems – it changes in the time. The systems of equations of electrical machines differ from the systems of equations of other electrotechnical devices in terms of the presence of the equation of internal torque.

**1.8. Equations of the generalized electrical machine in different the systems coordinates**

Let us examine the idealized two-phase electrical machine, in which the rotor windings revolve and the stator windings are fixed. After combining with the axes of windings the orthogonal systems of coordinates of stator-rotor unit  we will obtain machine in the untransformed system of coordinates (fig 1.1). The vector of the currents of phase and fluxs linkage in this model tyuey sovladayut with the axes of windings.

The systems of coordinates of rotor and stator are moved relative to each other, in this case the angle  between the axes determines the relative angular velocity **** (1.14)

The differential equations of voltages in the natural or untransformed phase coordinates for the models of machine (fig 1.1) take the form  (1.15)

Current frequencies (1.15) in stator-rotor unit are different, and signs (-)before the voltagees of rotor mean that the equations are written down for the engine operating mode.

Fluxs linkage of windings in (1.16)

 (1.16)

Here the coefficients before the currents change 2 times in comparison with the current frequency.

If we substitute values (1.15) and (1.16), then it is obtained bulky equations, it is necessary that the currents in stator-rotor unit would have identical frequencies and to ensure the invariance of power, i.e., to preserve shaft horsepower, losses, required power in the given machine by the same as in the real.

Let us examine the processes of the conversion of energy in air gap of real machine. Because of the specific combination of windings in the space and the temporary displacement of currents and voltages in the clearance the rotating field is formed. With the symmetrical sine voltages on the outputs of the idealized machine in air gap is a circular field. Current frequencies in stator-rotor unit in accordance with the third law of [electromechanics](../Shortcut%20to%20mathematical_models_of_electric_machines.lnk) are interrelated and the fields of stator-rotor unit are fixed relative to each other.

Circular field in the generalized electrical machine it is possible about to obtain, if we to the stator windings bring the voltages

 (1.17)

It is convenient to represent circular field in air gap by the resulting vectors with respect to the induction also of fluxs linkage;

** **

In the form of the united resulting vectors it is possible to represent the primary voltages  and rotor  and also the armature currents  and rotor.

The equations, written down for the resulting vectors, take the form

**** (1.20) where ****

Record in equations in the form (1.20) is simplest writing of the equations of voltages 3phase in the theory of electrical machines.

In order to be dismantled at the transformation of coordinates in the electrical machines, let us examine commutator machine with the revolving brushes (Fig. 1.2). In this machine on the stator 1 it is arranged the alternating voltage, which creates in the clearance rotating field. The three-phase voltage , which creates rotating field with the synchronous angular velocity brings to phases A, B, C of the three-phase stator winding ωs. On rotor 2 is a single-phase winding, whose sections are connected to the collector, machine has the revolving brushes, fastened to traverse 3.

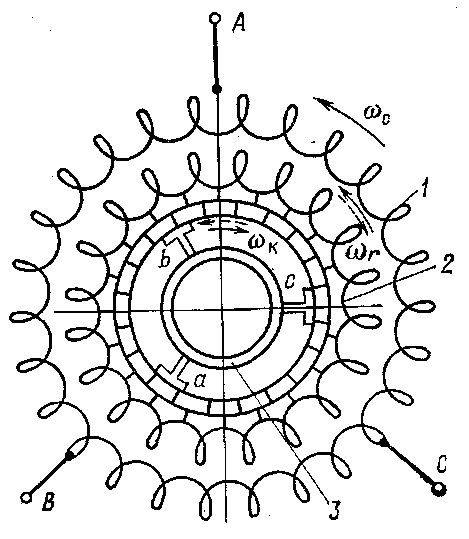


Fig. (1.2) the schematic of electrical machine with the revolving brushes

Rotor revolves with the angular velocity ωr , current frequency in rotor f 2  = f 1 s, in this case the fields of stator-rotor unit are fixed relative to each other.

Power in this machine is abstracted from the revolving brushes.If stator is fixed, then frequency f k  on the brushes of collector depends on the synchronous angular velocity of the field ωfrom  the angular velocity of the brushes: ωs±ωk . The coordinate system rigidly is connected with the traverse.

Changing the angular velocity of the coordinate system ωk, we obtain sweep frequency f  k . Thus, in the arbitrary coordinate system, which revolves with the arbitrary speed, the current frequencies and voltage are determined by the frequencies of the rotation of field and coordinate system. The conversion of energy and the invariance of power is connected with these frequencies. For the coordinate axes, which revolve with the arbitrary speed,

 (1.21)

Since cos θ + j sin θ = e +.jθ , vector equations for to the ordinary axes, which revolve with the arbitrary speed

 (1.22)

Differentiating (1.22), we will obtain  (1.23)

Equations for the resulting vectors are obtained in the coordinate axes, which revolve with the arbitrary speed, and are the simplest and common form of Kirchhoff's equations for the generalized machine. Different coordinate systems are used during the analysis (calculation) of static and transient regimes 3m:

1. A, B, C – the phase coordinate system. Closest in its physical essence to the object being simulated. Deficiency – the coefficients of inductive coupling m e I await by windings variables.
2. α β - the system, fixed relative to stator in the space. Axis α  is usually identical to the axis of phase a. in this system of equations of electromagnetic state order into polt about the Ra of times less. In connection with the projection of the depicting vectors to these axes, current and primary voltage in the axis α they coincide with current and voltage of the phase and of stator.
3. D, q – the system, rigidly connected with the rotor. It is adapted for the analysis r and boats of synchronous machines. Axis d is combined with the longitudinal axis of rotor. Along axes d and q to vozdu wclearance between the rotor and the stator is constant. For the model is characteristic the fact that in the steady-state synchronous regime the components of the depicting vectors are time-constant, which substantially simplifies the analysis of static characteristics synchronous 3m.
4. U, v – the synchronously revolving (is usually synchronously with the vector EMF or the voltage of the power source) coordinate system. It is applied for analysis and formulating of the laws of control of the systems of automatic ale to troprivoda.

For the fixed coordinate system α, β ( ωto = 0), when axes are connected with the stator, equations (1.23) take the form

 (1.24)

After decomposing the resulting vectors along the axes α, β, we will obtain

  (1.25)

Substituting in (1.17) the expressions of the fluxs linkage

  (1.26)

we will obtain the equations of the electromechanical conversion of energy in the coordinate system α, β, expressed through the currents. Upon transfer from the untransformed coordinate system to the system α, β from (fig 1.1) it is necessary to determine the projections of voltages and currents of rotor on the axis of stator according to the relationships

 (1.27)

 (1.28)

The second, most common coordinate system – the system, in which coordinates d and q it is rigid they are connected with the rotor. Here ωto =ωr . It follows from (1.23 ) The second, most common coordinate system – the system, in which coordinates d and q it is rigid they are connected with the rotor. Here ωto =ωr . It follows from (1.23 )

 (1.29)

After decomposing the resulting vectors along axes d and q , we will obtain the equations of the generalized machine

  (1.30)

After expressing the fluxs linkage through the currents, inductance and mutual inductance, just as for the coordinate system α, β , we will obtain the equations of the electromechanical conversion of energy in axes d, q , expressed through the currents:

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 (1.31)

Equations of the electromechanical conversion of energy in the system of coordinates u, v, which revolve with the arbitrary angular velocity ωk, they take the form



(1.32)

 (1.33)

The equations of the generalized electrical machine in the system of coordinates u, v – are most general. From them they are obtained equations in the coordinate system α, β, if we in (1.32) and (1.33) substitute ωto  = 0. Equations in the system of coordinates d, q (1.30) and (1.31) are obtained from (1.32) and (1.33), if we consider that ωto = ωr .

It is possible to consider that in electromechanics there is a countless number of coordinate systems. However, in the practice they found use in basic coordinate system α, β; d, q and u, v.

Coordinate system α, β it is expedient to use for the study of asynchronous machines, the system of coordinates d, q – for describing the processes of the conversion of energy in the synchronous machines, the system of coordinates u, v – with the study of machines with the revolving rotor and the stator. With the nourishment of machine from the frequency converters it is convenient to supply untransformed voltages to the windings and to simulate system of equations with the periodic coefficients.