Chapter (1)

Basic Consideration in Design

1.1 Introduction

The aim of design is to obtain completely the dimensions of all the parts of the machine to furnish these data to the manufacturer. The design should be carried out based on the given specification using available materials economically and to achieve the followings:

1. Lower cost
2. Lower weight
3. Reduced size
4. Better operation performance

The design is worked out by resorting to various approximation methods based on accumulated experience realized in different formulae, equations, tables, charts etc.

The methods of preparing design in industrial concerns vary between the service design offices. Their way of design is certainly different from those based on first principles, which are normally used in the class room for designing the electrical machines. To design the electrical machines properly one should be quite familiar with the following aspects of electrical engineering.

1. Various electrical materials i.e. magnetic, conducting and insulating and their properties.
2. Properties of magnetic and electric fields.
3. Laws governing electrical circuit.
4. Laws of electromagnetic induction.
5. Calculation of magnetic circuits.
6. Construction of various types of electrical machines and their behavior under working conditions

In addition to above, on needs a good knowledge of strength of material, metallurg, mechanic and laws of heat transfer.

While designing an electrical machine much emphasis should be placed on lowering its cost by saving the materials and reducing to a minimum labour consuming operations in its manufacturer. The design should be satisfactory with respect to electric strength, mechanical ruggedness, dynamic and thermal resistance of windings in the event of short circuit.

In order to meet the above requirements during the design of electrical machines, the designer should be well conversant with the prices of the basic materials used in the machines. He should also be well familiar with the amount of labour consumed in the production of machine parts and assemblies. Hence the process of design is much related with the production. Thus only the joint efforts of the designer and the production engineer can develop new design of electrical machines, satisfying closely the technical requirements with good reliability in service and with minimum cost.

From the above discussion it is quite obvious that the art of successful design is to select proper materials and to resolve the conflict for space between magnetic, conducting and insulating materials so as to produce and highly efficient machine.

1.2 Specification

The design of an electrical machine requires a specification of main data like output in KVA, line voltage, power factor, frequency, number of phases, type of connections, temperature rise of windings and cores, rated speed etc. Besides the main data mentioned above certain specifications of performance are usually drawn up by the customer or a consulting engineer on his behalf in case of industrial designs of electrical machines.

The detailed specifications of various electrical machines in order to initate their design are listed below:

1. Transformer

Power output in KVA or MVA; voltage ratio on no load; Frequency; number of phase; class (Power or distribution); *lv and hv* windings connections; percentage tappings; phasor group reference for 3-phase transformers; maximum temperature rise;

1. Rotating machines
2. Direct Current Machine

Generator or motor : type of field excitation: rated output power; rated voltage; speed ; type of enclosure; type of duty (short time, intermittent, continuous); Field exciting voltage; Maximum temperature rise.

1. Alternating Current Machine

Generator or motor; type (induction, synchronous); rated output; rated voltage; frequency; speed; number of phases; connection of winding; type of rotor winding (Squirrel cage; slip ring for motor); type of duty; type of enclosure; type of cooling; exciter voltage (for synchronous machines); maximum temperature rise.

Based on the main data and the properly assumed values of specific loadings, the process of design in initiated with the determination of the main dimensions of the machine, which in turn decide the design of other parts of the machine. The design data for the various parts of the machine are then used to calculate the performance. The performance thus calculated should satisfy the service conditions specified for the machine. In case service conditions are not specified then the calculated performance of the designed machine must be within certain expected values.

1.3 Output Coefficient

The starting point of the design of an electrical rotating machine is the output coefficient, which in terms of output, main dimensions and speed is given by,

Output coefficient,

Where,

P-the output of the machine in KVA

D- the diameter of the armature in metre

L-the gross length of the armature in metre

N-the speed of the machine in r.p.m

For the rotating electrical machines, the output coefficient is also proportional to the product of two groups of terms, the first related to the magnetic loading and the second to the current loading.

For larger machines, the output coefficient is high and the variation in its value is relatively small, because of nearly constant flux density and less variation in specific electrical loading. However this coefficient varies greatly for small size machines. The working value of the output coefficient depends also upon the speed of the machine and on the ventilation system. The value of output coefficient can by considerably increased by providing a fan of relatively large diameter mounted on the shaft of the machine. The approximate limiting values of the output coefficient giving D2L in cubic metre are of the order of 4.0 to 6.5 for large machines, 3.0 to 4.0 for medium size and 1.0 to 3.0 for small to medium size machines.

In determining preliminary dimensions for an electrical machine, a sufficiently close value for the output coefficient should be chosen, by giving due consideration to the performance of the machine which depends upon the magnetic and electric loading assumed for the calculation of output coefficient. Once a proper value of output coefficient is selected, the product D2L in cubic metre can be found out. To separate the diameter and length of the armature, the designer must select such a relationship between these two, as to result in minimum cost of active materials and labour charges.

1.4 Importance of specific loadings

Specific magnetic and electric loadings play an important role in the design of electrical machines. The process of design of any electrical machine is really initiated with the suitable assumptions of these values. As such the main dimensions and the design of other parts of the machine is basically dependent upon the proper selection of the specific magnetic and electric loadings.

Specific magnetic loading ‘B’ or the mean flux density over the air gap surface of the machine is defined as the ratio of total magnetic loading to the area of the gap i.e.

Where P – Number of poles

- Flux per pole, webers

D- Diameter of armature or stator bore, meters

L- Armature or stator core length, meters

Y- Pole pitch

Specific electric loading, ‘q’ is defined as the total number of ampere conductors per unit of the circumference of the armature or stator i.e.

Where

- the armature current, amperes

- number of armature conductors

In any rotating electrical machine, power output of the machine is directly proportional to the following quantities.

* D2L indicating the volume enclosed by the gap surface
* N, the speed of the rotor in r.p.m
* B the specific magnetic loading
* Q the specific electric loading

The above discussion clearly shows that for the same output and speed, the rotating machine will have a losses volume. If designed for higher values of specific loadings. Hence the choice of higher values of specific loadings lead to the following advantages:

Advantages due to higher specific loadings:

1. Reduction in the volume of the machine
2. Reduction in the size of the machine
3. Lower cost of the material required
4. Lower weight of the machine
5. Lower over all cost of the machine

Thus to produce a cheaper machine with reduction in its size, the values of specific loadings must be pushed to the largest possible.

However the choice of higher value of specific loadings will lead to the following disadvantages.

(A) Disadvantage due to higher magnetic loading, Bav

1. Increased iron losses
2. Larger requirement of m.m.f.
3. Higher field copper losses(DC Machine, Synmachines)
4. Higher tooth density
5. Tendency of saturation of magnetic parts
6. Increased magnetization current and poorer power factor (Induction motor)
7. Reduced leakage reactance and larger initial current on sudden short circuit(syn Machine)
8. Increased temperature rise due to higher losses
9. Increased noise

(B) Disadvantage due to higher specific electric loading, q:

1. Increased armature copper losses.
2. Increased leakage reactance because of larger turns per phase (Ind, & Syn, machine)
3. Increased temperature rise because of higher copper losses.
4. Increased reactance voltage and inferior commutation(DC machine)
5. Increased field excitation causing more flield copper losses (DC machine)
6. Poorer regulation and stability impaired (syn machine)
7. Reduction in over load capacity

Hence the choice of increased values of specific loadings gives rise to appreciably higher total losses, increased no load current, poorer power factor and higher temperature rise.

From the above discussion it is thus concluded that a compromise is to be made between the conflicting factors, while suitable values are assigned to the specific magnetic and electric loadings. In general following factors must be given due consideration while selecting the values for flux density and specific electric loading for electrical machines.

1. Temperature rise
2. Over load capacity
3. Size of the machine
4. Cost of the machine
5. Power factor
6. Efficiency
7. Noise.

1.5 The principle of electrical machine design

The problem of the manufacture of electrical machinery is to build as economically as possible, a machine to fulfill prescribed guarantees regarding its performance and suitability, i.e. its specification. The design is therefore subordinated to the question of economic manufacture. Only the heteropolar arrangement (alternate N.and S.poles) is employed in modern machines.

1.5.1 Factors in Design

All modern commercial machines are of the electromagnetic type, although electrostatic considerations are also of importance, particularly in high-voltage transformers. Account must be taken in the design of the following:

1. The magnetic circuit, or path of the magnetic flux.
2. The electric circuits or windings, in which the e.m.f.s. are induced and which serve to conduct the currents.
3. The dielectric circuit, or insulation, for separating parts of the machine having potential differences, to confine the current to prescribed paths.
4. The heat-flow and cooling arrangements, or ventilation.
5. The mechanical design.

The art of successful design might be said to lie in resolving the conflict for space between iron, copper, insulation, and air. Over all lies the necessity for economy in manufacturing costs and in subsequent operating and maintenance charges.

1.5.2 Limitations in Design

The nature of the constructional materials available, and other limitations, require consideration of:

1. *Saturation* of the magnetic circuit, on account of core losses and excitation (i.e. the production of the necessary m.m.f.).
2. *Temperature-Rise,* limited to avoid damage to the insulation.
3. *Insulation*, on account of breakdown by excessive voltage gradient, mechanical damage, or heat.
4. *Mechanical Strength*, particularly for large and high-speed machines.
5. *Efficiency*, It is costly to achieve for large and high-speed machines.
6. *Customer’ Specifications.*
7. *Commutation.*
8. *Power Factor.*

The attainment of minimum losses for a given total cost of machine is one criterion of excellence of design.

1.5.3 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.

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-

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.

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.

1.6 Generator and motors

The two laws or principles are embodied in electrical machines. In a generator, an e.m.f. is produced by the movement of a coil in a magnetic field. The current produced by the e.m.f. interacts with the field to produce a mechanical force opposing the movement, and against which the essential movement has to be maintained. The electrical power is produced therefore at the expense of mechanical power; that is to say, the generator develops electrical power form the mechanical power supplied to it.

In a motor, we may suppose a conductor or coil to lead in a magnetic field. If current is supplied to the coil, a mechanical force is manifested and due to this force the coil will move. Immediately that relative movement takes place between coil and field, however, an e.m.f. is induced, in opposition to the current. To maintain the current and the associated motor action, it is therefore necessary to apply to the coil, from an external source, a voltage sufficient to overcome the induced e.m.f. Thus the motor requires electrical power to produce a corresponding amount of mechanical power.

1.7 Basic motor action

The magnetic field surrounding a current-carrying conductor figures prominently in the interactions giving rise to basic motor action. The simple experiment shown in Fig. 1.1 demonstrates the concentric pattern, as well as the directivity of the current produced flux. The practicalities of toroids, solenoids, inductors, transformers, etc. may recall rather uninteresting expositions of this topic in their training texts. The point to be made here is that this concentric flux around a current-carrying conductor lies at the very heart of the force manifested as 'motor action'. How this comes about may be gleaned from the situation depicted in Fig. 1.2.



Fig.1.1 Concentric magnetic flux around a current-carrying conductor. Either several compasses, or a single compass moved in successive positions around the conductor will serve the purpose of the experiment. The circular pattern of the magnetic field plays a prominent role in the armatures, field windings, stators, and rotors of the various types of electric motors. Significantly in motor operation, a reversal in current direction reverses the direction of the magnetic lines of force.

Here we see a current-carrying conductor immersed in a magnetic field provided by the poles of a horseshoe magnet. The net field due to the interaction of the circular field of the conductor and the otherwise-linear field from the poles of the magnet are greatly distorted. One can visualize the resemblance of this magnetic flux pattern with the pressure inequalities causing the lift of an aircraft wing. In any event, it is evident that there is dense magnetic flux on the bottom surface of the conductor and sparse flux on the top. Not only do the magnetic lines of force constituting the flux display rubber-band physical properties, but they strongly repel one another. It is thus easily seen that this distorted field pattern must exert an upward force on the current-carrying conductor. We have, in other words, 'motor action'. Note that a reversal of *either* the direction of the main field from the magnet, or the direction of the current in the conductor will produce *downward* motor action.

Besides the physical motion of the current-carrying conductor in Fig. 1.2, or more precisely, *because of it,* a voltage is induced in the conductor so polarized as to oppose the current causing the motor action. This simultaneous behavior as agenerat0ris the practical manifestation of Lenz’s law. In a general, but inviolate way, it tells us that 'any change in magnetic flux linkage is accompanied by effects *opposing* the change'.



Fig. 1.2 Motor action exerted on current-carrying conductor in a magnetic field. Endowing magnetic lines of force with the elastic property of rubberbands enables one to visualize the motion imparted to a current-carrying conductor. The interaction of the magnetic fields as shown is found in virtually all electric motors. Downward motion of the conductor would occur if either (not both) the current direction or the magnetic poles were reversed.

1.7.2 The electric motor as an energy converter

At the very outset, we should concern ourselves with what electric motors do. A popular but erroneous notion is that electric motors create or produce mechanical energy. Mechanical energy is definitely not *created;* yes, it may be said to be *produced* at the shaft of the motor, but this is, at best, only a partial answer. We must point out that this mechanical energy comes at the *expense* of some other form of energy. The simple and true fact of the matter is that the electric motor (and the electric generator, as well) is an *energy converter.* More specifically, the motor converts electrical energy into mechanical energy. In so doing, it is never 100% efficient-in the overall budget of energy availability, there are always inevitable energy losses. These losses may manifest themselves as still other forms of energy, such as heat, light, sound, friction, radiation, etc. Energy, itself is the capability of doing work. In the practical world, it would be well to say that *available* energy represents the capability of doing *useful work.* Because of nature's previous activities, most of the useful energy sources stem from various chemical, gravitational, and nuclear arrangements of planetary matter. In contrast to such earthly energy sources, solar radiation represents a dynamic and ongoing source of energy.

All our electric motor does or can do is to directly or indirectly participate as an energy converter in which another form(s) of energy gets transformed into our desired mechanical energy. Practically, we see this conversion or transformation as electricity *in* and mechanical work *out.* *Power* and energy tend to be used interchangeably in popular communications. Power is the *rate* of energy transfer. Or in other words, energy is the *product* of power and *time.* Thus, our monthly utility bill is based upon a number of kilowatt-hours. We, on earth can transform energy, but cannot create it. Interestingly, those seeking to circumvent natural law seem 'magnetically' attracted to electric motors. Such claims as the following routinely litter the desks of patent clerks and editors.

1.7.3 Motor graphs

Many graphs depicting motor performance show some parameter as a function of the line current or armature current, these being virtually the same quantity. For example, one might see speed or torque as the ordinate (the vertical axis) of the graph plotted against armature or line current as the abscissa (the horizontal axis of the graph). One naturally infers that the armature current is *somehow* varied and the corresponding values of speed or torque are then either measured or calculated. Those not familiar with motors usually suppose that the armature current is adjusted by means of a rheostat, a variable auto-transformer, or an adjustable power supply. This is *not* the case. Refer to Fig. 1.3.

The key word above is 'somehow'. The actual situation is that the armature current is *caused* to vary by applying different mechanical loads to the motor. In other words, the armature current reflects load changes. It is true that it would be difficult to determine the actual load values; armature current tracks load changes and is very easy to observe with an ammeter inserted in the motor line. Moreover, direct manipulation of the current would introduce complications in the interpretation of the results. Reiterating, a *variable load* is used to plot the majority of these graphs. This practice is so universal that it is often not explained that the various motor currents used to plot the graph are due to variation in the load applied to the shaft of the motor. It is simply assumed this is common knowledge, and often, it is a stumbling block for students.

On the other hand, it should not be assumed that the direct electrical variation of armature or line current is not a permissible and useful technique for certain applications. *Here,* however, the wise practitioner would append a notice to a graph showing the speed or torque relationship to armature or line current, stipulating that the relationships were valid under the condition of *constant load.*

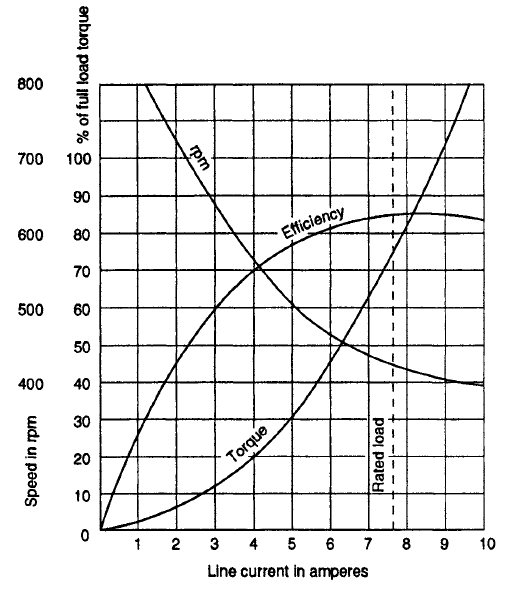
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Fig. 1.7 Graphical representation of the characteristics of a DC series-motor. A typical graph such as this could be misleading to persons not familiar with electric motor technology. The line current is not varied by a rheostat, autotransformer, or by any other means. Rather, the mechanical load imposed on the motor is varied and the corresponding line currents are recorded and plotted on the horizontal axis of the graph. This would, no doubt be clearer if the caption read 'Line Current in Amperes Due to Load'.

1.8 Motor nomenclature

Initial exposure to some of the nomenclature pertaining to electric motors can be confusing. An *armature,* to be sure, is the rotating member of DC motors. It is also the stationary member of certain AC motors. See Fig. 1.4. Although the physical difference is obvious, the identity of their electrical functions is not altogether a clear issue. Moreover, the field-winding of motors can be found as either the rotating or the stationary member. It follows that the same can be said for permanent-magnet fields. The overall situation is not clarified by allusion to rotating fields-these can be developed by physically rotating magnets or electro-magnets, or by stationary armatures impressed with polyphase currents.

Fortunately, such confusion can be resolved by using the term *stator* for the stationary member of all AC motors. Similarly, it is helpful to apply the term *rotor* to the rotating members of these motors. (Stepping motors and DC brushless motors, because they bear some constructional similarities to AC synchronous motors, are also said to have rotors.)



Fig. 1.4 Armatures of entirely different dynamos. (a) The armature of a DC motor. (Also similar to those used in AC repulsion motors.) (b) The armature of an AC three-phase induction motor. Confusion can be avoided by referring to the stationary winding of AC motors and alternators as the stator.

It is interesting to contemplate that the *stators* of three-phase induction motors, three-phase synchronous motors and three-phase brushless DC motors can be essentially similar. Indeed, the same machine can serve as either an alternator or a synchronous motor. Additionally, the rotating members referred to as armatures of certain AC repulsion-type motors can closely resemble the armatures used in DC motors. Thus, we *can* have an armature and a stator in the same machine.

Concerning repulsion motors, the inference appears to be that other motors are 'attraction' motors. However, Lenz's law shows that the force of repulsion is at the root of motor action in the classic DC and AC motors. (The purist might argue the stepping motor to be the exception, at least when operating in the stepping mode.) In the AC induction motor, the rotating field of the stator appears to attract the more slowly rotating rotor conductors. If, however, we think of the stator field as being stationary, the *relative* motion of the rotor is in the *opposite* direction to that of the actual rotating field. Thus, motor action arises from *repulsion* as would be predicted by Lenz's law-induced fields oppose the motion responsible for their production.

1.8.2 Horsepower rating of electric motors

To those with limited experience of working with electric motors, some of the observed conventions must appear just a bit strange. For example, when ordering a motor, one refers to its basic ability for converting electrical to mechanical energy by specifying its horsepower. Yet, it will be found that bmost of the manufacturer's data deal with torque. A little contemplation reveals the reason for this.

It turns out that torque, the turning effort, is more fundamental than horsepower which is the rate of supplying energy. Horsepower is the product of torque times speed, so that a given horsepower can correspond to a high torque and low speed, or to the converse combination. In practical applications, one is usually specifically interested in knowing the torque and the speed separately as they apply to the load on the motor. One should note that speed is very easily measured. Because of these considerations, the graphs of motor performance will either depict torque as the function of some other parameter such as armature current, or alternatively some parameter, such as speed, as a function of torque.

More quantatively, torque itself is the product of the force developed at the rim of a disc, cylinder or wheel times the distance to the centre. Thus, pound-feet is a common unit for this measurement. A practical manifestation of what has been said is the fact that the horsepower output of a motor at standstill is zero. Even giant motors develop zero horsepower at the instant an attempt is made to start them. On the other hand, torque, and specifically starting torque, tells us what we want to know about starting capability. Indeed, this performance characteristic is one of the primary considerations in motor selection and application.

In a general way, horsepower, because it is specified at a rated speed, motor current and motor voltage (and frequency), can provide guidance in selection of the size of the motor. However, in order to know whether it will serve a particular application, we must ascertain that the fight combination of speed and torque can be delivered.

1.8.3 Motor classification

Practitioners in the various applied sciences tend to view electric motors as genetic devices for converting electrical to mechanical energy. Certainly such a concept is entirely valid but in practice, however, it turns out to be just the tip of the iceberg; the very first prerequisite in grasping the basic framework of electric motor technology is an appreciation of the extensive classification needed to deal with these motors in the practical world. To begin with, there are direct current (DC) and alternating current (AC) motors. The alternating current types are then subdivided into single-phase and different polyphase designs and, of course, the size or capability of the motor is always an all-important issue. But, the power output doesn't tell us enough; we must also have data pertaining to speed and torque and, speaking of torque, a motor cannot render useful service if it won't start; therefore, specific knowledge about its starting torque is always a matter of priority.

Early in our appraisal of an electric motor, we find that it’s 'packaging' and constructional features merit deliberation. One can specify waterproof or explosion-proof types, or the motor can be packaged so as to be hermetically- sealed. Ventilation and allowable temperature rise should also not be ignored. A system may require vertical mounting of the motor, or there may be a need for dual output shafts. Torque and speed requirements sometimes mandate integrally-mounted gearboxes. Then, there are the ever-present compromises involving beating-selection against cost, maintenance and longevity.

As if this isn't sufficient, it is important to know the possible side-effects that may plague an otherwise satisfactory operation. Some types of motors are more prone to generating radio and electromagnetic interference than others. Certain alternating-current motors can upset the supply line with a low power-factor.

Finally, because of solid-state electronics and computer techniques, the classification of electric motors according to function and response has become increasingly complex. Interestingly, however, the diversity of motor-types and control techniques now point the way to a widely expanded range of useful implementations.

1.9 Basic concepts of rotating electrical machines

1.9.1 Physical concepts of Torque Production

A brief resume of the physical concepts of torque production in rotating electrical machines is presented.

1.9.1 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

1.9.2 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.

1.10 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.