Basic Principles and Functions of Electrical Machines

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ABSTRACT

Recent advances in power electronics and high-speed microprocessors have led to considerable attention in electrical machines with regard to their applications in industrial drives. This paper brings to the fore, various types of electrical machines, their operations, and applications, as well as the method of determining their parameters. Various ways of protecting electric machines against overloads and mechanical faults are also highlighted. It is anticipated that the work presented in this paper will be of immense benefit to practicing engineers especially in areas of machine design, maintenance, and protection.

(Keywords: electrical machines, operation design, maintenance, protection, stator)

INTRODUCTION

The Direct Current (D.C.) machine, the synchronous machine, and the induction machine are the major electromechanical conversion devices in industry [1]. The merits of the squirrel cage induction machine are: lightness, simplicity, ruggedness, robustness, less initial cost, higher torque-inertia ratio, capability of much higher speeds, ease of maintenance, etc [2, 3]. The most important feature which declares it as a tough competitor to D.C. machines in the drives field is that its cost per KVA is approximately one fifty of its counter-part and it possesses higher suitability in hostile environment.

Unfortunately, induction machines suffer from the drawback that, in contrast to D.C. machines, their speed cannot be easily and effectively adjusted continuously over a wide range of operating conditions [4]. On the other hand, the synchronous machine has the merit of being operated under a wide range of power factors, both lagging and leading, and are much better suited for bulk power generation. In the induction motor, alternating current is applied to the stator and alternating currents are induced in the rotor by transformer action.

In the synchronous machine, direct current is supplied to the rotor and Alternating Current (A.C.) flows in the stator. On the other hand, a D.C. machine is a machine that is excited from D.C. sources only or that itself acts as a source of D.C. [5]. It is a common practice in industry to employ A.C. motors whenever they are inherently suitable or can be given appropriate characteristics by means of power electronics devices. Yet, the increasing complexity of industrial processes demands greater flexibility from electrical machines in terms of special characteristics and speed control. It is in this field that the D.C. machines, fed from the A.C. supply through rectifiers, are making their mark.

In this paper, we shall discuss the various types of electric machines, thereafter, we shall look at the basic features and principles of operation of electric machines. Determination of machine parameters, basic protections, maintenance, and electric machine applications are also discussed.

CLASSIFICATION OF ELECTRIC MACHINES

There are several methods of classifying electric machines [6]:

- **Electric power supply -** Electric machines are classified as D.C. and A.C. machines as well as according to their stator and rotor constructions as shown in Figure 1.

- **National Electric Manufacturers' Association (NEMA) Standards -** NEMA standards are voluntary standards of the National Electric Manufacturers Association and represent general practice in industry. They define a product, process, or procedure with reference to nomenclature composition, construction, dimensions, tolerances, operating characteristics, performance, quality, rating, and testing. NEMA classifications of Electric Machines are summarized in Table 1.

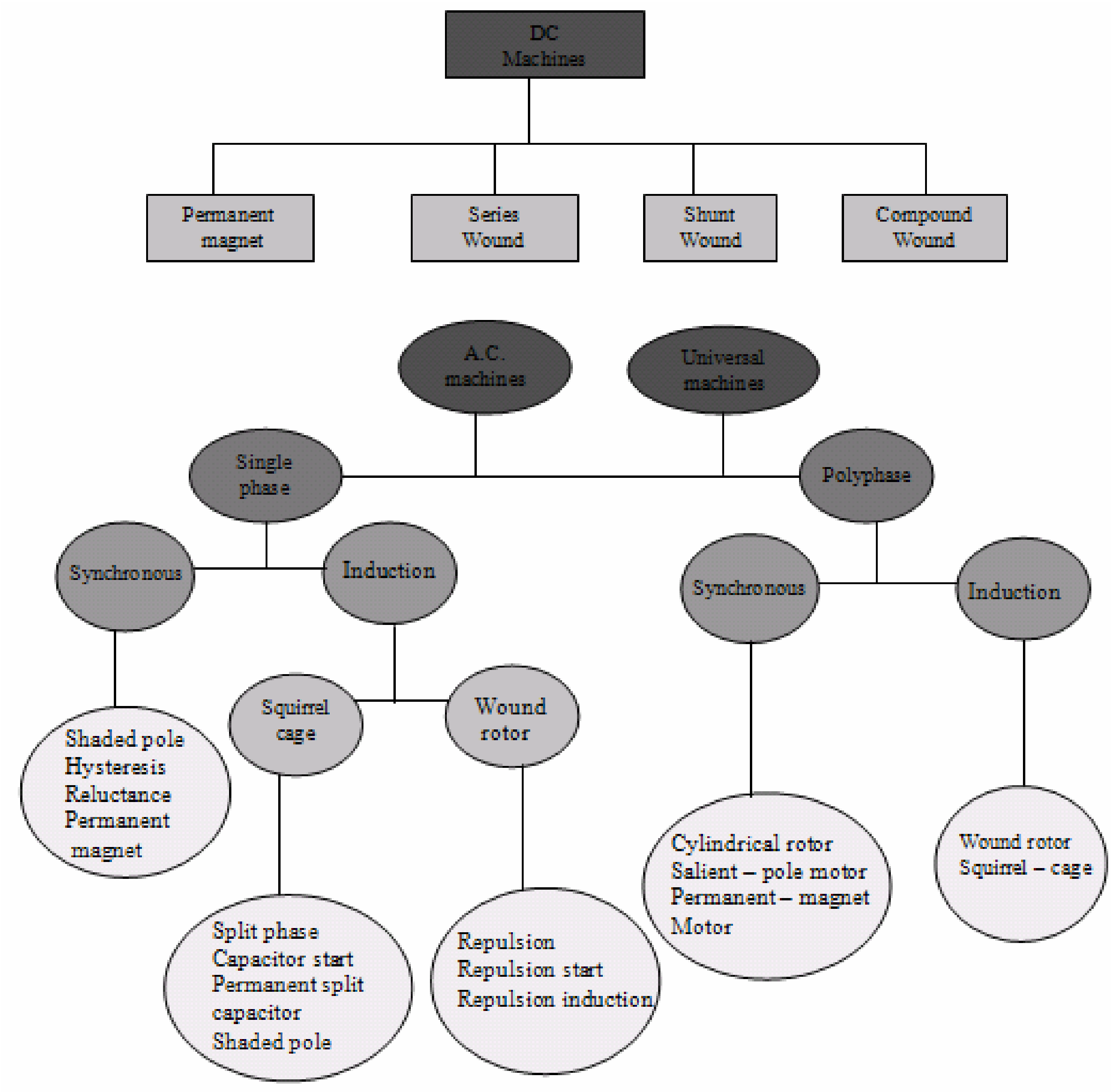

Figure 1: Classification of Electric Machines.

Table 1: NEMA Classifications.

Types	Features
A. Open:	
i. Drip-proof	Operate with dripping liquids up to 15^0 from vertical
ii. Guarded	Guarded by limited size openings (less than 0.75 inch)
iii. Externally ventilated	Ventilated with separate motor driven blower, can have other types of protection
B. Totally enclosed:	
i. Non-ventilated (TENV)	Not equipped for external cooling
ii. Fan-cooled (TEFC)	Cooled by external integral fan
iii. Water-cooled	Cooled by circulating water

BASIC FEATURES OF ELECTRIC MACHINES

The basic structural features of a D.C. machine are:

- Stator - The stator carries the field winding. The stator together with the rotor constitutes the magnetic circuit or core of the machine. It is a hollow cylinder.
- Rotor - It carries the armature winding. The armature is the load carrying member. The rotor is cylindrical in shape.
- Armature Winding - This winding rotates in the magnetic field set up at the stationary winding. It is the load carrying member mounted on the rotor. An armature winding is a continuous winding; that is, it has no beginning or end. It is composed of a number of coils in series as is shown in Figure 2.

Depending on the manner in which the coil ends are connected to the commutator bars, armature windings can be grouped into two: lap windings and wave windings. Wave winding gives greater voltage and smaller current ratings while the lap winding supplies greater current and smaller voltage ratings [7].

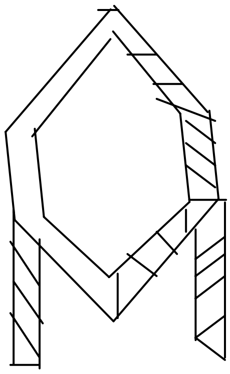

Figure 2: An Armature Coil.

- Field Winding - This is an exciting system which may be an electrical winding or a permanent magnet and which is located on the stator.
- Commutator - The coils on the armature are terminated and interconnected through the commutator which comprised of a number of bars or commutator segments which are insulated from each other. The commutator rotates with the rotor and serves to rectify the induced voltage and the current in the armature both of which are A.C.
- Brushes - These are conducting carbon graphite spring loaded to ride on the commutator and act as interface between the external circuit and the armature winding.
- Poles - The field winding is placed in poles, the number of which is determined by the voltage and current ratings of the machine.
- Slot/Teeth - For mechanical support, protection from abrasion, and further electrical insulation, non-conducting slot liners are often wedged between the coils and the slot walls. The magnetic material between the slots is called teeth. Figure 3 shows a cross-sectional views of slot/Teeth geometry

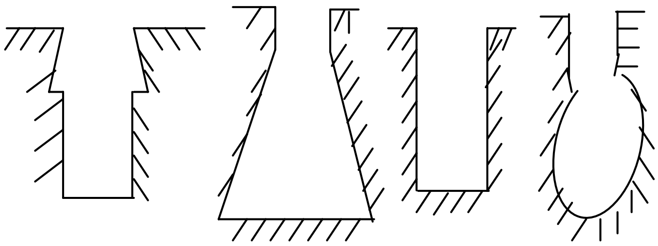

Figure 3: Typical Armature Slot Geometry.

On the other hand, the basic constructional features of an A.C. machine (e.g induction machine) are:

- Rigid Frame - The whole construction ensures compact and adaptable design at low weight and low vibration level in all operating conditions and throughout the whole speed range [8]. Figure 4 shows a basic ABB Rigid Frame Design.

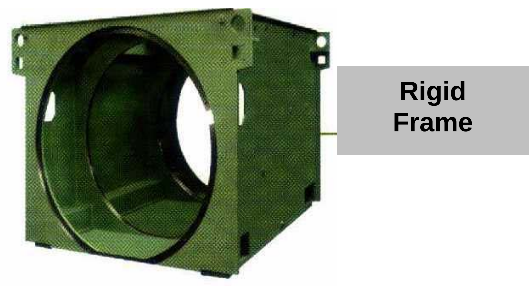

Figure 4: ABB Rigid Frame

- Stator Package - The stator core is a stack of thin electrical sheet steel laminations insulated by a heat resistant inorganic resin. The radial cooling ducts ensure uniform and efficient cooling. The stator package, shown in Figure 5 forms a solid block which retains its rigidity throughout the long lifetime of the machine.

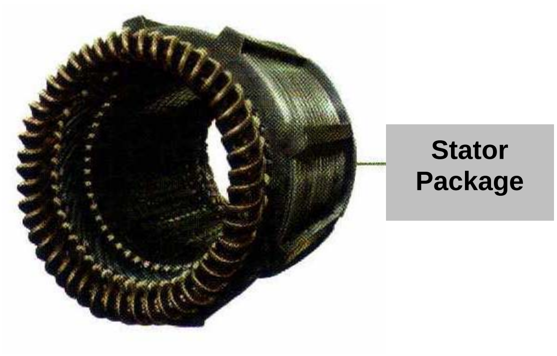

Figure 5: ABB Stator Package

- Rotor Construction - The rotor of A.C. machines can be of wound type or squirrel cage type. A typical squirrel cage rotor is shown in Figure 6. Depending on the number of poles and whether the shaft is of the spider or cylindrical type, the rotor core is shrunk onto the shaft and the conductor bars tightly caulked into the slots to prevent bar vibration.

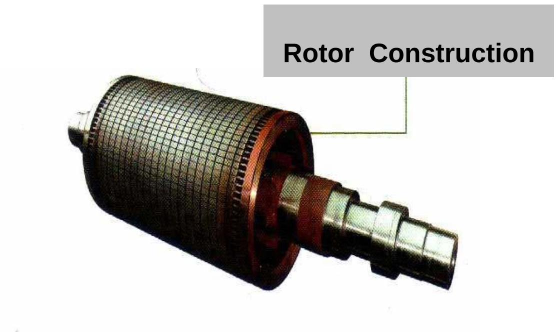

Figure 6: ABB Rotor Construction

- Rugged Bearing Assemblies - The bearings are designed for reliable continuous operation and ease of maintenance. Depending on the rated power, either spherical seated self aligning sleeve bearings or anti-friction bearings with a life time of over 100,000 hours are available [8]. See Figure 7 for ABB rugged bearing assemblies.

Figure 7: ABB Rugged Bearing Assemblies

BASIC PRINCIPALS OF OPERATION

Electric motors and generators are a group of devices used to convert mechanical energy into electrical energy, or electrical energy into mechanical energy, by electromagnetic means. A machine that converts mechanical energy into electrical energy is called a generator, alternator, or dynamo, and a machine that converts electrical energy into mechanical energy is called a motor.

Two related physical principles underlie the operation of generators and motors. The first is the principle of electromagnetic induction discovered by Michael Faraday in 1831 [9]. If a conductor is moved through a magnetic field, or if the strength of a stationary conducting loop is made to vary, a current is set up or induced in the conductor. The converse of this principle is that of electromagnetic reaction, first discovered by Andre' Ampere in 1820 [10]. If a current is passed through a conductor located in a magnetic field, the field exerts a mechanical force on it.

Both motors and generators consist of two basic units, the field, which is the electromagnet with its coils, and the armature (the structure that supports the conductors which cut the magnetic field and carry the induced current in a generator or the exciting current in a motor). The armature is usually a laminated soft-iron core around which conducting wires are wound in coils.

DETERMINATION OF MACHINE PARAMETERS

The nameplate gives sufficient information on the rated current, power, frequency, voltage, winding temperature, and stator winding connection. However, it may be necessary to determine the winding resistances and reactances as well as the mechanical properties of the machine in order to evaluate the machine performance under both steady and dynamic conditions. For instance, the following tests are usually carried out to determine the parameters of an asynchronous machine.

- No-Load Test - The aims of the no – load test are to determine:
    - ❖ Stator ohmic/copper losses
    - ❖ Stator core losses due to hysteresis and eddy current
    - ❖ Rotational losses due to friction and windage
    - ❖ Magnetizing inductance.

The test is carried out at rated frequency and with balanced polyphase voltages applied to the stator terminals. Readings are taken at rated voltage, after the motor has been running for a considerable period of time necessary for the bearings to be properly lubricated. At no–load, the machine slip and the rotor current are very small thereby resulting to a negligible no–load rotor loss.

- Blocked–Rotor Test - The blocked–rotor test provides information necessary to determine:
    - ❖ The winding resistances
    - ❖ The leakage reactances

In this test, the rotor is blocked by external means to prevent rotation. In the blocked–rotor test, the slip is unity (s ≅ 1) and the mechanical load resistance, RM is zero; thereby resulting in a very low input impedance of the equivalent circuit.

- Retardation Test - The retardation test is carried out to determine the test motor moment of inertia. In this test, a no–load is carried out with and without additional standard induction machines can be obtained from manufacturer's data as well as from the Finite–Element–Analysis (FEA) calculation results [11] such standard curves are shown in Figure 8 and Figure 9.

ELECTRIC MACHINES PROTECTION AND MAINTENANCE

Electrical and mechanical faults can impose unacceptable conditions and protective devices are therefore provided to quickly disconnect the machine from grid. In order to ensure that electrical machines receive adequate protection, extensive testing is performed to verify the high quality of assembly. After a machine of a particular type has been type tested for electrical characteristics, all subsequent machines of the same type undergo a routine test programme.

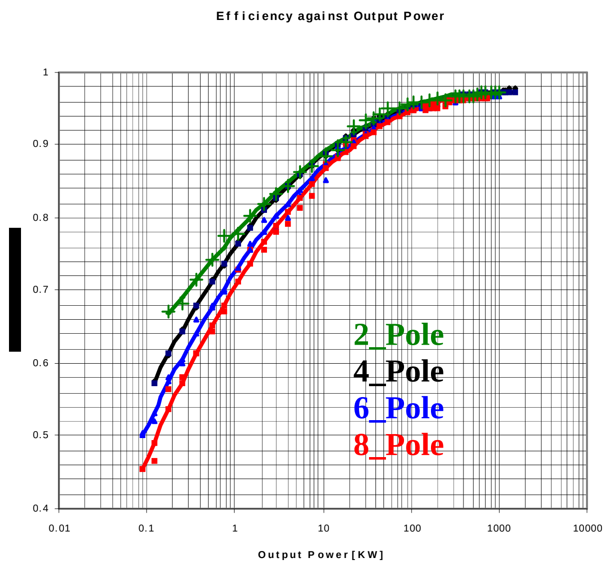

Figure 8: Efficiency of Induction Machine.

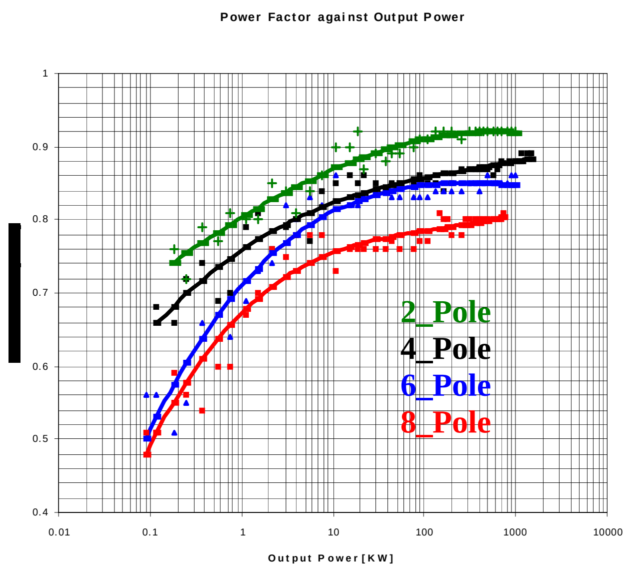

Figure 9: Power factor of Induction Machine

Routine and type test programmes can take these forms:

- Routine test programme
    - ❖ Bearing control
    - ❖ Control of the insulation
    - ❖ Ohmic resistance measurement
    - ❖ Vibration measurement
    - ❖ Short circuit test
    - ❖ No- load test
    - ❖ High voltage test

- Type test programme
  - ❖ Routine test
  - ❖ No-load curve
  - ❖ Load point
  - ❖ Heat run test

After the type test programme, the electrical machine is identified with a protective symbol. Degrees of protection by enclosures for electrical machines are quoted with the letters IP and two characteristic numerals. The first numeral designates the degree of protection for persons against contact with live or moving parts inside the enclosure and of machines against ingress of solid foreign bodies. The second numeral designates the degree of protection against harmful ingress of water. Some of the degrees of protection are IP23, IP54, IP55, and IP56. For instance, in IP23, the first numeral means operation against contact by a finger with live or moving parts inside the enclosure while the second numeral denotes protection against water.

Generally, when deciding on a particular type of motor protection, this should be done with actual operating conditions in mind. Motors are protected by current–dependent motor protection circuit breakers and/or over current relays. These are particularly effective in cases like locked rotor or interrupted run-up, and are therefore indispensable in large machines with thermally critical rotor [12].

The temperature-dependent devices serve to protect the motor against the effects of excessive winding heating due to overload, increased ambient temperature, impaired cooling, intermittent operation, high switching frequency, and phase failure.

Unscheduled downtime and resultant high repair cost reduce profits. There is a need to set objectives to manage maintenance, schedule repair, adjustments, and control cost. When carrying out servicing or repairing electric machines, like power generation equipment, do the following:

- Make sure the unit is off-line
- Make sure the generator engine is stopped
- Make sure all batteries are disconnected
- Make sure all capacitors are discharged.

The generator is a component of the generator set and should be tested with the entire system. The service manual for the voltage regulator provide tests to determine if the generator is the cause of a generator set malfunction.

The following procedure should be used to help identify and define the problem [13]:

1. Perform visual checks to help identify the problem.
2. If previous tests were performed from the voltage regulator service manual, use the test results to help identify the problem.
3. Check troubleshooting knowledge-bases to help identify the problem.
4. Perform the Generator Functional Test to help identify the problem.

After the work has been carried out the machine is to be marked by an additional repair name plate with the following data:

- Date
- Operative firm
- If necessary, mode of repair
- If necessary, signature of the expert.

ELECTRIC MACHINES APPLICATIONS

Figure 10, Figure 11, and Figure 12 show some of the practical applications of electric machines [12].

- **Asynchronous Machines**
  - ❖ Petroleum and chemical pumps
  - ❖ Cooling towers
  - ❖ Air-handling equipment
  - ❖ Compressors
  - ❖ Process machinery
  - ❖ Blowers and fans
  - ❖ Drilling machines
  - ❖ Grinders
  - ❖ Lathes
  - ❖ Conveyors
  - ❖ Crushers, etc.

- **Synchronous Machines**
  - ❖ Power generation
  - ❖ Wind energy turbines
  - ❖ Power factor correction
  - ❖ Voltage regulation improvement of transmission lines
  - ❖ Electric clock drives
  - ❖ Gasoline engine drives
  - ❖ Servo drives
  - ❖ Compressors, etc

- **D.C. Machines**
  - ❖ Rolling mills
  - ❖ Elevators
  - ❖ Conveyors
  - ❖ Electric locomotives
  - ❖ Rapid transit systems
  - ❖ Cranes and hoists
  - ❖ Lathes
  - ❖ Machine tools
  - ❖ Blowers and fans, etc.

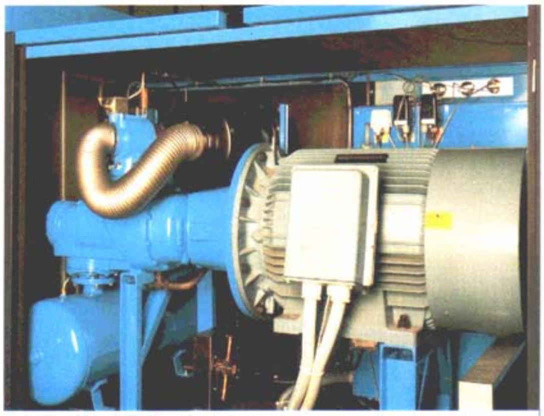

Figure 10: SCHORCH Motor 90KW, 400V, 2975rpm, Compressor drive

Figure 11: SCHORCH Motors 160KW, 400V, 1485rpm, Driving pumps

Figure12: SCHORCH Hydrogenerator 45KW, 400V, 1025rpm

CONCLUSION

This paper has presented the basic principles of electric machines. The basic features and the conventional method of determining the machine parameters have also been highlighted.

The authors also elucidated the various ways of protecting electric machines against overloads and mechanical faults. Areas of application of electric machines have been itemized in order to show the importance of these devices in process industries.

This work has carefully neglected the mathematical analysis of electric machines. The treatment is beyond the scope of this endeavour. However, it must be pointed out that powerful numerical software such as MATLAB/SIMULINK, ANSOFT, SIMPLORER, SIMPOW, and SMT have been used by machine manufacturing companies to study both the electrical and mechanical behaviour of electrical machines prior to design.

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