

Understanding the Basics of Electrical Machines as an Energy Conversion Device for Research Initiatives

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Abstract

By understanding the basics of electrical machines and drives, research on the following important topics can be initiated: Principles of electromechanical energy conversion; analysis, modelling, and control of electric machinery; steady state performance characteristics of direct-current, induction, synchronous and reluctance machines; scalar control of induction machines; introduction to direct-and quadrature –axis theory; dynamic models of induction and synchronous motors; vector control of induction and synchronous motors. That's why we explain how electrical machines work as an energy conversion device.

Keywords: *Electrical Machines, Energy Conversion Device, Principles of electromechanical energy conversion; control of electric machinery*

INTRODUCTION

The electric machine is an electromechanical energy conversion device that processes and delivers power to the load. The same electric machine can operate as a motor to convert electrical power to mechanical power or operate as a generator to convert mechanical power to electrical power. The electric

machine in conjunction with the power electronic converter and the associated controller makes the motor drive. The power electronic converter is made of solid state devices and handles the flow of bulk power from the source to the motor input terminals. The advances in the power semiconductor technology over the past several decades enabled

the development of compact, efficient and reliable DC and AC electric motor drives.

The controller is made of microcontroller or digital signal processor and associated small signal electronics. The function of the controller is to process the user commands and various sensor feedback signals to generate the gate switching signals for the power converter semiconductor switches following a motor control algorithm. The sensor signals include machine rotor position, phase currents, inverter bus voltage, and machine and inverter temperature outputs. Fault protection and diagnostics is also part of the motor controller algorithm.

Research in the area of electric machines and drives is focused on design optimization using 2D and 3D finite element analysis, and drives design at the systems level considering operating requirements and control opportunities. The research is multifaceted seeking innovations in machine configurations, motor control concepts, parameter identifications, and noise and vibration analysis.

Motor drives are designed to make the system more efficient, fault tolerant, smoother in operation, smaller and matched to the applications. Modeling and design tools are developed to aid the machine design and drive development efforts. Particular research emphasis is on permanent magnet and reluctance type machines and drives.

BASIC ELECTRICAL MACHINES

The majority of electrical machines (motors and generators) sold today are still based on the Lorentz force and their principle of operation can be demonstrated by the example below in which a single turn coil carrying electrical current rotates in a magnetic field between the two poles of a magnet.

For multiple turn coils, the effective current is NI (Ampere Turns) where N is the number of turns in the coil. If the coil is supplied with a current the machine acts as a motor. If the coil is rotated mechanically, current is induced in the coil and the machine thus acts as a generator. In rotating machines the rotating element is called the rotor or armature and the fixed element is called the stator.

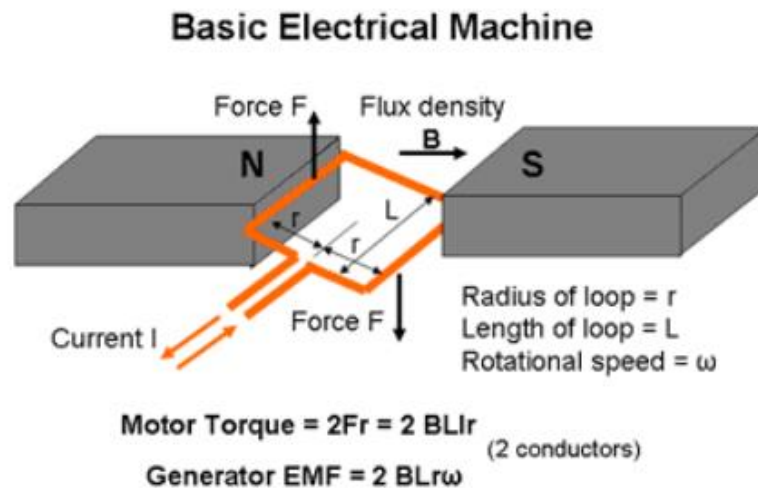


Fig 1: Basic Electrical Machine

ACTION AND REACTION

In practice, both the motor and the generator effects take place at the same time.

Passing the current through a conductor in the magnetic field causes the conductor to move through the field but once the conductor starts moving it becomes a generator creating a current through the conductor in the opposite direction to the applied current. Thus the motion of the conductor creates a “back EMF” which opposes the applied EMF.

Conversely moving the conductor through the field causes a current to flow through the conductor which in turn creates a force on the conductor opposing the applied force.

The actual current which flows in the conductor is given by:

$$I = (V - E)$$

R

Where V is the applied voltage, E is the back EMF and R is the resistance of the conductor (the armature of the motor).

THE EMF EQUATION

From the above, the back EMF in an electric motor is equal to the applied voltage less the volt drop across the armature.

$$E = V - RI$$

This is known as the "Motor EMF Equation".

The volt drop across the armature RI is sometimes called the Net Voltage

THE POWER EQUATION

Multiplying the voltage by the armature current to get the power gives the following relationship:

$$P = EI = VI - I^2R$$

It shows that the mechanical power delivered by the motor is equal to the back EMF times the armature current OR the electrical power applied to the motor less the I^2R losses in the windings. (Disregarding frictional losses).

This is known as the "Motor Power Equation".

OPERATING EQUILIBRIUM UNDER LOAD

The "Action and Reaction" effects outlined above provide an important automatic self-regulating feedback mechanism in both DC and AC motors for adapting to changes to the applied load. As the load on the motor is increased it tends to slow down, reducing the back EMF. This in turn allows more current

to flow generating more torque to accommodate the increased load until a point of balance or equilibrium is reached.

Thus the motor will set itself to an appropriate speed for the torque demanded. See also Power Handling below.

MAGNETIC FIELDS

The motor's magnetic field is provided by the stator and in the above example the stator is a permanent magnet however in the majority of electrical machines the magnetic field is provided electromagnetically by coils wound around the stator poles. The stator windings are also called the field windings and the motor is said to be "field energized".

The rotor is normally wound on an iron core to improve the efficiency of the machine's magnetic circuit.

MAGNETIC CIRCUITS

In the case of electrical machines, the magnetic circuit is the path of the magnetic flux through the stator body, across the air gap, through the rotor and back through the air gap into the stator. The length l of this path is

known as the mean magnetic path length MMPL

Magnetic circuits are designed to produce the maximum flux possible and to concentrate it in the air gap between the rotor and the stator through which the coils move. The flux Φ is measured in Webers.

The flux density B is measured in Teslas and is defined as the magnetic flux Φ per unit area A . Thus $B = \Phi/A$ where A is the area through which the flux passes.

From the equations above it can be seen that the torque generated by the electric motor or the EMF created by the generator are directly proportional to the magnetic flux density B in the region surrounding the moving electrical conductors and for efficient machines, B should be as high as possible. See **Figure 2**.

MAGNETOMOTIVE FORCE (MMF)

The magnetic flux arising in a magnetic circuit is proportional to the magneto motive force (MMF) creating it. For an electromagnet, the MMF is the effective current in the magnetizing coil measured in Ampere turns NI and, as

above, this is the actual current I times the number of turns N in the coil.

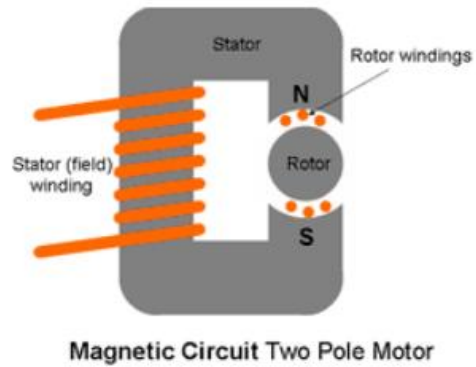


Fig 2: Magnetic Circuit Two Pole Motor

Thus $MMF = NI = \Phi \times R$ where R is the reluctance of the magnetic circuit. The reluctance is the inherent resistance of the material in the magnetic circuit to the setting up of the magnetic flux through it. (For iron the reluctance is very low. For air it is very high)

This equation for the flux in magnetic circuits is analogous to Ohm's law for the current in electric circuits in which:

$EMF = I \times R$ where R is the resistance of the electric circuit.

Because the reluctance of the air gap between the stator and the rotor is very high, the air gap should be as small

as possible to minimize the Ampere turns needed to create the desired flux density.

MAGNETIC FORCE (H) ALSO CALLED THE MAGNETIC FIELD STRENGTH

The magnetic field strength H is the MMF per unit length in a magnetic circuit. Thus:

$$H=NI$$

The magneto motive force is the cause of the magnetic field, the magnetic force is the effect.

FLUX DENSITY (B) AND MAGNETIC PERMEABILITY (μ)

For uniform fields, the flux density associated with the magnetic force is proportional to the field strength and is given by:

$$B=\mu_0\mu_rH$$

Where

μ_0 is the known as the magnetic constant or the permeability of free space.

μ_r is the relative permeability of the magnetic material.

Unfortunately, the relationship becomes non-linear as the flux density

increases and the magnetic material becomes saturated. Then the flux produced by increases in the magnetic field decreases and levels off and the relative permeability μ_r tends towards 0.

SATURATION

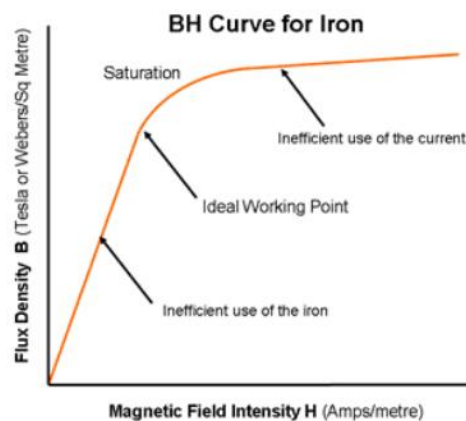


Figure: 3

MAGNETIC FIELD INTENSITY H (AMPS/METRE)

From the above it can be seen that increasing the MMF (Ampere turns) in a magnetic circuit increases the flux through the circuit but there is a limit to the flux density which can be created in magnetic materials such as iron when the material is said to be saturated. Above this point more and more MMF is needed to create less and less flux. In other words the reluctance increases sharply when

the material saturates. For maximum efficiency, electric machines are usually designed to work just below the onset of saturation.

MAGNETIC POLES

Electric machines can have multiple pole pairs. Multiple pole machines usually provide more efficient magnetic circuits and smoother torque characteristics.

COMMUTATION

The connection to the moving coil in the basic machine shown above is made via carbon brushes bearing on a pair of slip rings, one connected to each end of the coil. If the machine is used as a generator, the direction of the current generated will reverse every half cycle as the arm of the coil passes the opposite poles in succession.

If a unidirectional current is required, the slip rings are split and interconnected such that, each half cycle, the current is taken from alternate arms of the coil. This simple switching mechanism is called a commutator.

Similarly when the machine is used as a DC motor, the commutator switches the DC supply voltage to alternate arms

of the coil each half cycle in order to achieve unidirectional rotation. Thus in all wound rotor DC machines, both motors and generators, the current in the rotor windings is AC and it is the commutator which enables the corresponding DC input or output. There are however some notable exceptions. The world's first motors and generators invented by Faraday were unipolar or homopolar machines in which unidirectional current flowed in the conductors. Faraday's motor was a laboratory curiosity with no practical applications but his so called "Faraday Disk" dynamo was able to generate useful current.

For over 100 years, mechanical commutation was the only practical way of switching the direction of the current flow however since the 1970s the availability of high power semiconductors has made electronic commutation possible. In AC machines the complexities of commutation can be avoided since current can be induced in the rotor windings by transformer action with the stator windings, obviating the need for direct connections between the supply line and

the rotating windings. See Induction Motors.

Because the commutator is essentially a mechanical switch, rapidly making and breaking a high current circuit, the switch is prone to sparking and the generation of Radio Frequency Interference (RFI) which can disrupt the working of other electronic circuits in the vicinity. In very large motors the propensity for sparking can be reduced by the addition of "interpoles" or "commutating poles", narrow auxiliary windings midway between the main stator poles.

These are connected in series with the rotor windings and produce an MMF equal and opposite to the rotor MMF so that the effective flux between the main poles is zero. Commutation is designed to occur the instant when the current passes through zero between the negative and positive half cycles and this takes place when the rotor is midway between the main poles. By neutralizing the flux in this region the possibility of sparking is reduced.

CONCLUSION

Research in the area of electric machines and drives is focused on design

optimization using 2D and 3D finite element analysis, and drives design at the systems level considering operating requirements and control opportunities. The research is multifaceted seeking innovations in machine configurations, motor control concepts, parameter identifications, and noise and vibration analysis. Motor drives are designed to make the system more efficient, fault tolerant, smoother in operation, smaller and matched to the applications. This paper emphasizes the importance of modeling and design tools to aid the machine design and drive development efforts.

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