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Fundamentals of Electric Motors and Transformers

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Introduction

Motors and transformers are the key driving force for industrial and residential appliances. We can't even imagine an industry without motors and transformers. In industry all types of linear or rotational force, movement, torque, etc are applied by motors. Industries are getting automated day by day, hence the use of motors are increasing with the same pace. The power supply to any medium or large scale industry comes through transformer as the utilities prefer to supply at higher grid voltage. Maximum portion of power that is consumed in any industry is by motors. So the efficiency is a great issue for an industry owner to think about. The efficiency of the major consumer, the motor must be of as high as possible. The efficiency of the transformer, through which all the power is consumed, must also be near 100 percent. So every personnel related to the decision making in industry must have the knowledge regarding the energy efficiency issue for motors and transformers.

Operation

To discuss about the operation of motors and transformers we must know the basic principles of Faraday's Law of Electromagnetic induction. According to Faraday if there is any rate of change of flux incorporated inside a conducting loop then there will be an EMF, hence voltage induced in the loop. If the loop is shorted or connected end to end, then a current will flow through the conductor. The current will flow in such a direction so that the rate of change of flux created due to this current will try to nullify the rate of change of flux which is responsible for creating this current. This theory is the core of all machines. Transformer is a non-rotational device and motor is a rotational machine. Faraday's law is equally applied to both of these machines. So we first need to know how we can apply the same theory to all the requirements in the industry and other household appliances. To explain the operation of transformer and motor we need to follow the following basics:

A Straight conductor

Transformers and motors are all constructed by coils which are nothing but a wire or more scientifically we can say a conductor. If we apply AC voltages across a straight conductor shown in figure 1, then if the AC voltage source is capable of supplying sufficient current to burn the conductor, it is certain that the conductor will burn. Because it has a lower resistance and Ohm's law will not hesitate to burn it! So the result is clear that the wire will burn within a second. Now the question is, what happens when a coil or an inductor, made with the same conductor, never burns with the AC source applied across it.

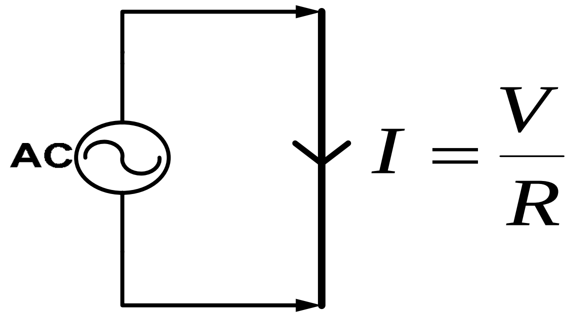

Fig.1 AC source across a straight conductor

Inductor

An inductor is just a conductor which is twisted to make a coil. If we supply AC source across an inductor as shown in figure 2, it never burns. From Faraday's law we know, if a rate of change of flux is cut through a loop of conductor then an EMF is induced across it. In case of inductor the applied AC source tries to flow an alternating current through it. Due to this alternating current an alternating flux is created inside the loop. This alternating flux will induce an EMF across the inductor. The more current will flow the more EMF will induce across it. But this induced voltage cannot exceed the applied voltage. So that amount of current will flow across the inductor which can induce the same amount of the applied voltage. This fact ascertains that the current will not increase to an abrupt value. As a result the inductor doesn't burn.

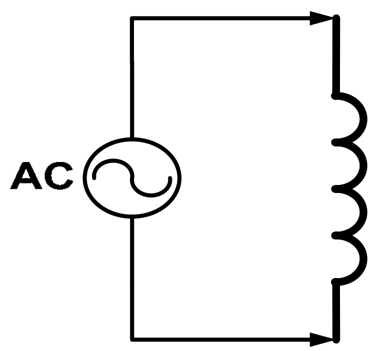

Fig.2 AC source across an inductor

Transformer

A transformer [1] is an extended version of an inductor. The flux that is created inside the inductor is used here to induce voltages at other coil, which is termed as secondary coil. If the rate of change of flux can induce voltage across the primary coil, from which it is created, then it is also possible to induce voltage across secondary coil, provided that we can pull the flux to flow through the other coil. The rate of change of flux will induce voltage as many turn we use. If the turn is double the turn in primary then the voltage will also be double. If we increase the number of secondary coils, then voltage will be induced in all the secondary coils according to the number of turns present in each secondary coil. We can increase or decrease the secondary voltage level according to our requirement. If the secondary voltage is increased then it is called step up transformer and for the decreasing case it is called step down transformer. Each secondary voltage will act as a separate voltage source. Here the other advantage we get from a transformer is that each secondary voltage source is an isolated voltage source. There is no electrical connection between the primary and the secondary. Whatever voltage level is that, the secondary is totally an isolated part.

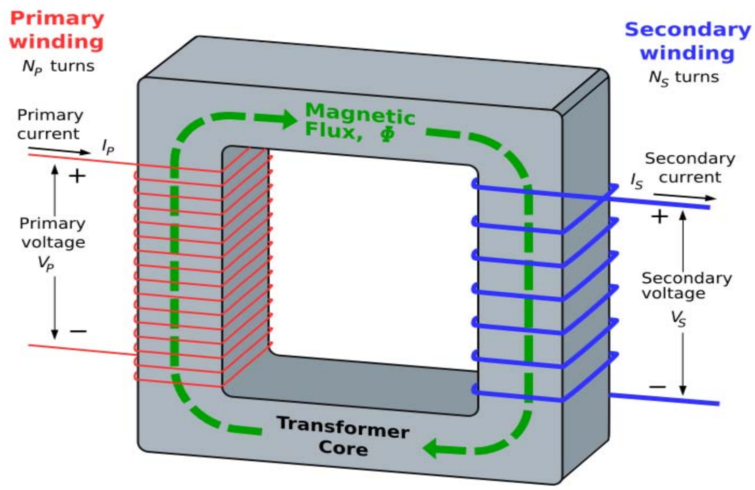

Fig.3 A transformer

Motor

A motor is an extended version of a transformer. Here we can introduce the analogy between a transformer and a motor that is a motor is like a transformer with a moving secondary. The primary that is not moving is called stator and the secondary that is moving is called rotor. The type of motor that is used worldwide with a greater percentage is the three phase induction motor.

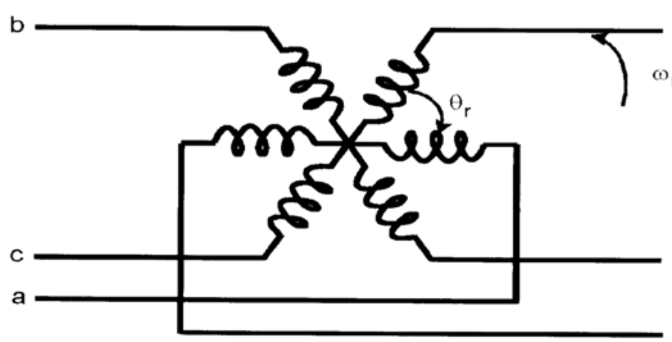

Fig.4 An induction machine stator and rotor coil orientation

The principle is somewhat like a transformer. If we place three coil at 120 degree physical alignment and also apply three phase ac supply which is also with 120 degree electrical phase relation, then the resultant flux, that is created from the vectorial space summation of the three phase fluxes, will rotate at the frequency of the supply voltage. Here the magnitude of the flux is same throughout the rotation. Now this revolving flux will cut the rotor and there will be an induced voltage across the rotor as well. As the rotor is short

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circuited there will be a flow of current through the short circuited loop. This current will create a flux which will interact with the revolving flux. There will be a force exerted upon this flux from the rotor. The current in the rotor will flow in such a direction so that it can decrease the rate of change of flux from which it is created. As a result the rotor will try to revolve in the direction of the revolving flux to reduce the rate of change of flux cut. When the rotor revolves then the relative velocity with the stator decrease and the rotor will rotate with a slip so that it can provide the necessary torque of the load.

Types and Applications of Transformers

Autotransformer

An autotransformer has only a single winding with two end terminals, plus a third at an intermediate tap point. The primary voltage is applied across two of the terminals, and the secondary voltage taken from one of these and the third terminal. The primary and secondary circuits therefore have a number of windings turns in common. An adjustable autotransformer is made by the secondary connection through a sliding brush, giving a variable turns ratio.

Polyphase transformers

For three-phase power, three separate single-phase transformers can be used, or all three phases can be connected to a single polyphase transformer. In this case, the magnetic circuits are connected together, the core thus containing a three-phase flow of flux. The three primary windings are connected together and the three secondary windings are connected together. The most common connections are Y-Δ, Δ-Y, Δ-Δ and Y-Y. If a winding is connected to earth (grounded), the earth connection point is usually the center point of a Y winding.

Leakage transformers

A leakage transformer, also called a stray-field transformer, has a significantly higher leakage inductance than other transformers, sometimes increased by a magnetic bypass or shunt in its core between primary and secondary, which is sometimes adjustable with a set screw. This provides a transformer with an inherent current limitation due to the loose coupling between its primary and the secondary windings. The output and input currents are low enough to prevent thermal overload under all load conditions – even if the secondary is shorted. Leakage transformers are used for arc welding and high voltage discharge lamps.

Resonant transformers

A resonant transformer is a kind of the leakage transformer. It uses the leakage inductance of its secondary windings in combination with external capacitors, to create one or more resonant circuits. Resonant transformers such as the Tesla coil can generate very high voltages, and are able to provide much higher current than electrostatic high-voltage generation machines such as the Van de Graaff generator.

Instrument transformers

A current transformer is a measurement device designed to provide a current in its secondary coil proportional to the current flowing in its primary. Current transformers are commonly used in metering and protective relaying, where they facilitate the safe measurement of large currents. The current transformer isolates measurement and control circuitry from the high voltages typically present on the circuit being measured. Voltage transformers (VTs)--also referred to as potential transformers (PTs)--are used for metering and protection in high-voltage circuits. They are designed to present negligible load to the supply being measured and to have a precise voltage ratio to accurately step down high voltages so that metering and protective relay equipment can be operated at a lower potential.

Zigzag transformer

A zigzag transformer is a special purpose transformer. It has primary windings but no secondary winding. One application is to derive an earth reference point for an ungrounded electrical system. Another is to control harmonic currents.

Pulse transformers

A pulse transformer is a transformer that is optimized for transmitting rectangular electrical pulses (that is, pulses with fast rise and fall times and constant amplitude). Small versions called signal types are used in digital logic and telecommunications circuits, often for matching logic drivers to transmission lines. Medium-sized power versions are used in power-control circuits such as camera flash controllers. Larger power versions are used in the electrical power distribution industry to interface low-voltage control circuitry to the high-voltage gates of power semiconductors. Special high voltage pulse transformers are also used to generate high power pulses for radar, particle accelerators, or other high energy pulsed power applications.

Speaker transformers

In the same way that transformers are used to create high voltage power transmission circuits that minimize transmission losses, speaker transformers allow many individual loudspeakers to be powered from a single audio circuit operated at higher-than normal speaker voltages. This application is common in public address applications. Such circuits are commonly referred to as constant voltage or 70 volt speaker circuits although the audio waveform is obviously a constantly changing voltage.

Isolation transformers

An isolation transformer is a device that transfers energy from the alternating current (AC) supply to an electrical or electronic load. It isolates the windings to prevent transmitting certain types of harmonics.

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Buck boost transformers

Buck Boost Transformers make small adjustments to the incoming voltage. They are often used to change voltage from 208v to 240v for lighting applications. One major advantages of Buck boost transformers are their low cost, compact size and light weight.

Pad mounted transformers

Pad Mounted Transformers are usually single phase or three phase and is used where safety is a main concern. Typical Application is restaurant, commercial building, shopping mall, institutional.

Pole mounted transformers

Pole Mounted Transformers are used for distribution in areas with overhead primary lines. Outside a typical house one can see one of these devices mounted on the top of an electrical pole.

Oil filled transformers

Oil-filled transformers are transformers that use insulating oil as insulating materials. The oil helps cool the transformer. Because it also provides part of the electrical insulation between internal live parts, transformer oil must remain stable at high temperatures over an extended period.

Dry type transformers

Dry type transformers require minimum maintenance to provide many years of reliable trouble free service. Unlike liquid fill transformers which are cooled with oil or fire resistant liquid dielectric, dry type units utilize only environmentally safe, CSA and UL recognized high temperature insulation systems. Dry type transformers provide a safe and reliable power source which does not require fire proof vaults, catch basins or the venting of toxic gasses. These important safety factors allow the installation of dry type transformers inside buildings close to the load, which improves overall system regulation and reduces costly secondary line losses.

Dry type transformers are a rather mature product and technology but, of all the components in a power system, a transformer replacement can be a physically challenging event, extended delivery of a replacement or repair unit and expensive transportation costs. These are transformers whose core and coils are not immersed in insulating oil.

Fire-resistant dry type or "cast resin" transformers are well suited for installation in high-rise buildings, hospitals, underground tunnels, school, steel factories, chemical plants and places where fire safety is a great concern. Hazard free to the environment, dry type transformers have over the years proven to be highly reliable.

“Dry type” simply means it is cooled by normal air ventilation. The dry type transformer does not require a liquid such as oil or silicone or any other liquid to cool the electrical core and coils.

Loss, Efficiency and Costing

Transformers reduce the voltage of the electricity supplied by the utility to a level suitable for use by the electric equipment. Since all of the electricity used by a company passes through a transformer, even a small efficiency improvement will result in significant electricity savings. High-efficiency transformers are now available that can reduce total electricity use by approximately 1 percent. Reduced electricity use provides cost savings for a company.

Two types of energy losses occur in transformers: *load* and *no-load* losses.

Load losses result from resistance in the copper or aluminum windings. Load losses (also called winding losses) vary with the square of the electrical current (or load) flowing through the windings. At low loads (e.g. under 30 percent loading), core losses account for the majority of losses, but as the load increases, winding losses quickly dominate and account for 50 to 90 percent of transformer losses at full load. Winding losses can be reduced through improved conductor design, including proper materials selection and increases in the amount of copper conductor employed.

No-load losses result from resistance in the transformer's laminated steel core. These losses (also called core losses) occur whenever a transformer is energized and remain essentially constant regardless of how much electric power is flowing through it. To reduce core losses, high-efficiency transformers are designed with a better grade of core steel and with thinner core laminations than standard-efficiency models.

Total transformer losses are a combination of the core and winding losses. Unfortunately, some efforts to reduce winding losses increase core losses and vice versa. For example, increasing the amount of conductor used reduces the winding losses, but it may necessitate using a larger core, which would increase core losses. Manufacturers are developing techniques that optimize these losses based on the expected loading.

Annual energy losses and cost of these losses

The annual energy losses of a transformer can be estimated from the following formula [2]:

$$W_{loss} = 8760(P_o + P_k L^2)$$

Where,
W_{Loss} - is the annual energy loss in kWh.
P_o - is the no-load loss in kW.
P_k - is the short-circuit loss (or load loss) in kW.
L - is the average per-unit load on the transformer.
8760 - is the number of hours in a year.

To calculate the cost of these losses, they need to be converted to the moment of purchase by assigning capital values, to be able to put them into the same perspective as the purchase price. This is called the Total Capitalized Cost of the losses, TCCloss. This can be calculated using the following formula [2]:

$$TCC_{loss} = 8760 W_{loss} \frac{(1+i)^n - 1}{i(1+i)^n} C$$

Where,
C - is the estimated average cost per kWh in each year.
i - is the estimated interest rate.
n - is the expected life time of the transformer.

Life Cycle Cost of Transformers

To perform the economical analysis of transformer, it is necessary to calculate its life cycle cost, sometimes called total cost of ownership, over the life span of transformer or, in other words, the capitalized cost of the transformer. All these terms mean the same – in one formula, costs of purchasing, operating and maintaining the transformer need to be compared taking into account the time value of money. The concept of the 'time value of money' is that a sum of money received today has a higher value – because it is available to be exploited – than a similar sum of money received at some future date. In practice, some simplification can be made. While each transformer will have its own purchase price and loss factors, other costs, such as installation, maintenance and decommissioning will be similar for similar technologies and can be eliminated from the calculation. Only when different technologies are compared e.g. air cooled dry type transformers with oil cooled transformers will these elements need to be taken into account. Taking only purchase price and the cost of losses into account the Total Cost of Ownership can be calculated by [2]:

$$TCO = PP + AP_o + BP_k$$

Where,
PP - is the purchase price of transformer,
A - represents the assigned cost of no-load losses per watt,
P_o - is the rated no-load loss,
B - is the assigned cost of load losses per watt,
P_k - is the rated load loss.

Types and Applications of Motors

Three-phase AC induction motors

Where a polyphase electrical supply is available, the three-phase (or polyphase) AC induction motor is commonly used, especially for higher-powered motors. The phase differences between the three phases of the polyphase electrical supply create a rotating electromagnetic field in the motor.

Through electromagnetic induction, the time changing and reversing (alternating in direction polyphase currents) rotating magnetic field induces a time changing and reversing (alternating in direction)current in the conductors in the rotor; this sets up a time changing and counterbalancing moving electromagnetic field that causes the rotor to turn in the direction the field is rotating. The rotor always moves (rotates) slightly behind the phase peak of the primary magnetic field of the stator and is thus always moving slower than the rotating magnetic field produced by the polyphase electrical supply.

Induction motors are the workhorses of industry and motors up to about 500 kW (670 horsepower) in output are produced in highly standardized frame sizes, making them nearly completely interchangeable between manufacturers. Very large induction motors are capable of tens of thousands of kW in output, for pipeline compressors, wind-tunnel drives and overland conveyor systems.

There are two types of rotors used in induction motors: squirrel cage rotors and wound rotors.

Squirrel-cage rotor

Most common AC motors use the squirrel cage rotor, which will be found in virtually all domestic and light industrial alternating current motors. The squirrel cage takes its name from its shape - a ring at either end of the rotor, with bars connecting the rings running the length of the rotor. It is typically cast aluminum or copper poured between the iron laminates of the rotor, and usually only the end rings will be visible.

Wound rotor

An alternate design, called the wound rotor, is used when variable speed is required. In this case, the rotor has the same number of poles as the stator and the windings are made of wire, connected to slip rings on the shaft. Carbon brushes connect the slip rings to an external controller such as a variable resistor that allows changing the motor's slip rate.

Three-phase AC synchronous motors

If connections to the rotor coils of a three-phase motor are taken out on slip-rings and fed a separate field current to create a continuous magnetic field (or if the rotor consists of a permanent magnet), the result is called a synchronous motor because the rotor will rotate synchronously with the rotating magnetic field produced by the polyphase electrical supply. The synchronous motor can also be used as an AC generator or alternator.

One use for this type of motor is its use in a power factor correction scheme. They are referred to as synchronous condensers. This exploits a feature of the machine where it consumes power at a leading power factor when its rotor is over excited. It thus appears to the supply to be a capacitor, and could thus be used to correct the lagging power factor that is usually presented to the electric supply by inductive loads. The excitation is adjusted until a near unity power factor is obtained (often automatically). Machines used for this purpose are easily identified as they have no shaft extensions. Synchronous motors are valued in any case because their power factor is much better than that of induction motors, making them preferred for very high power applications.

Two-phase AC servo motors

A typical two-phase AC servo motor has a squirrel-cage rotor and a field consisting of two windings: a constant-voltage (AC) main winding and a control-voltage (AC) winding in quadrature with the main winding as to produce a rotating magnetic field. The electrical resistance of the rotor is made high intentionally so that the speed-torque curve is fairly linear. Two-phase servo motors are inherently high-speed, low-torque devices, heavily geared down to drive the load.

Single-phase AC induction motors

Three-phase motors inherently produce a rotating magnetic field. However, when only single-phase power is available, the rotating magnetic field must be produced using other means. Several methods are commonly use. A common single-phase motor is the shaded-pole motor, which is used in devices requiring low starting torque, such as electric fans or other small household appliances. In this motor, small single-turn copper "shading coils" create the moving magnetic field. Another common single-phase AC motor is the split-phase induction motor, commonly used in major appliances such as washing machines and clothes dryers. Compared to the shaded pole motor, these motors can generally provide much greater starting torque by using a special startup winding in conjunction with a centrifugal switch. Another variation is the permanent-split capacitor (PSC) motor (also known as a capacitor start and run motor). This motor operates similarly to the capacitor-start motor described above, but there is no centrifugal starting switch, and the start windings (second windings) are permanently connected to the power source (through a capacitor), along with the run windings. PSC motors are frequently used in air handlers, blowers, and fans (including ceiling fans) and other cases where a variable speed is desired.

Repulsion motor

Repulsion motors are wound-rotor single-phase AC motors that are similar to universal motors. In a repulsion motor, the armature brushes are shorted together rather than connected in series with the field.

Single-phase AC synchronous motors

Small single-phase AC motors can also be designed with magnetized rotors (or several variations on that idea). The rotors in these motors do not require any induced current so they do not slip backward against the mains frequency. Instead, they rotate synchronously with the mains frequency. Because of their highly accurate speed, such motors are usually used to power mechanical clocks, audio turntables, and tape drives; formerly they were also much used in accurate timing instruments such as strip-chart recorders or telescope drive mechanisms. The shaded-pole synchronous motor is one version.

Brushed DC electric motor

A brushed DC motor is an internally commutated electric motor designed to be run from a DC power source.

Reluctance motor

A reluctance motor is a type of synchronous electric motor which induces non-permanent magnetic poles on the ferromagnetic rotor. Torque is generated through the phenomenon of magnetic reluctance. A reluctance motor, in its various incarnations, may be known as a:

- synchronous reluctance motor
- variable reluctance motor
- switched reluctance motor (SRM)

- variable reluctance stepping motor

SRM's are used in some washing machine designs. SRM's are commonly used in the control rod drive mechanisms of nuclear reactors.

Unipolar motor

A unipolar motor is a type of small DC electric motor commonly found in small, portable cassette players. Its name is derived from its construction, which employs a magnetic strip wrapped around the inner wall of the housing such that one of its poles faces the inside, while the other faces outward.

Linear motor

A linear motor or linear induction motor is essentially a multi-phase alternating current electric motor that has had its stator "unrolled" so that instead of producing a torque it produces a linear force along its length. When a linear motor is used to accelerate beams of ions or subatomic particles, it is called a particle accelerator. The design is usually rather different as the particles move close to the speed of light and are generally electrically charged.

Brushless DC electric motor

A brushless DC motor (BLDC) is a synchronous electric motor which is powered by direct-current electricity (DC) and which has an electronically controlled commutation system, instead of a mechanical commutation system based on brushes. In such motors, current and torque, voltage and rpm are linearly related. BLDC motors can potentially be deployed in any area currently fulfilled by brushed DC motors. Cost and control complexity prevents BLDC motors from replacing brushed motors in most common areas of use. Nevertheless, BLDC motors have come to dominate many applications: Consumer devices such as computer hard drives, CD/DVD players, and PC cooling fans use BLDC motors almost exclusively. Low speed, low power brushless DC motors are used in direct-drive turntables. High power BLDC motors are found in electric vehicles and some industrial machinery. These motors are essentially AC synchronous motors with permanent magnet rotors.

Stepper motor

A stepper motor (or step motor) is a brushless, synchronous electric motor that can divide a full rotation into a large number of steps. Computer-controlled stepper motors are one of the most versatile forms of positioning systems. They are typically digitally controlled as part of an open loop system, and are simpler and more rugged than closed loop servo systems.

Industrial applications are in high speed pick and place equipment and multi-axis machine CNC machines often directly driving lead screws or ball screws. In the field of lasers and optics they are frequently used in precision positioning equipment such as linear actuators, linear stages, rotation stages, goniometers, and mirror mounts. Other uses are in packaging machinery, and positioning of valve pilot stages for fluid control systems.

Commercially, stepper motors are used in floppy disk drives, flatbed scanners, computer printers, plotters and many more devices.

5 Steps to Better Motor Applications

Step 1: Know the load characteristics [3]

For line-operated motors, loads fall into three general categories: constant torque, torque that changes abruptly, and torque that change gradually over time.

Bulk material conveyors, extruders, positive displacement pumps, and compressors without air unloaders run at relatively steady levels of torque. Sizing a motor for these applications is simple once the torque (or horsepower) for the application is known. Load demands by elevators, compactors, punch presses, saws, and batch conveyors change abruptly from low to high in a short time, often in a fraction of a second. The most critical consideration for selecting a motor in these cases is to choose one whose speed-torque curve exceeds the load torque curve.

Loads from centrifugal pumps, fans, blowers, compressors with unloaders, and similar equipment tend to be variable over time. In choosing a motor for these conditions, consider the highest continuous load point, which typically occurs at the highest speed.

Step 2: Get a handle on horsepower

The rule of thumb for motor horsepower is: Select only what you need, and avoid the temptation to oversize or undersize. Calculate the required horsepower from this formula:

$$Horsepower = Torque \times Speed / 5250$$

Where torque is in lb-ft and speed is in rpm.

Step 3: Getting started

Another consideration is inertia, particularly during startup. Every load represents some value of inertia, but punch presses, ball mills, crushers, gearboxes that drive large rolls, and certain types of pumps require high starting torques due to the huge mass of the rotating elements. Motors for these applications need to have special ratings so that the temperature rise at startup does not exceed the allowable temperature limit. A properly sized motor must be able to turn the load from a dead stop (locked-rotor torque), pull it up to operating speed (pull-up torque), and then maintain the operating speed. Motors are rated as one of four “design types” for their ability to endure the heat of that starting and pull up. In ascending order of their ability to start inertial loads, NEMA designates these as design type A, B, C, and D. Type B is the industry standard and is a good choice for most commercial and industrial applications

Step 4: Adjust for duty cycle

Duty cycle is the load that a motor must handle over the period when it starts, runs, and stops.

Continuous duty is—by far—the simplest and most efficient application. The duty cycle begins with startup, then long periods of steady operation where the heat in the motor can stabilize as it runs. A motor in continuous duty can be operated safely at or near its rated capacity because the temperature has a chance to stabilize.

Intermittent duty is more complicated. The life of commercial airplanes is measured by their number of landings; in the same way, the life of a motor is proportional to the number of starts it makes. Frequent starts shorten life because inrush current at startup heats the conductor rapidly. Because of this heat, motors have a limited number of starts and stops that they can make in an hour.

Step 5: The last consideration, motor hypoxia

If your motor is going to operate at altitudes that are substantially above sea level, then it will be unable to operate at its full service factor because, at altitude, air is less dense and does not cool as well. Thus, for the motor to stay within safe limits of temperature rise, it must be derated on a sliding scale. Up to an altitude of 3,300 ft, SF = 1.15; at 9000 ft, it declines to 1.00. This is an important consideration for mining elevators, conveyors, blowers, and other equipment that operates at high altitudes.

Should You Buy New or Rewind?

When you have a motor failure you'll need to decide if you should buy a new motor or fix the old one. A common cause of motor failure is problems with the motor windings, and the solution often is to rewind the old motor. Because it is economical in terms of initial cost, rewinding of motors is very common particularly for motors of more than 10 horsepower. However, the motor rewinding process often results in a loss of motor efficiency. It is generally cost-effective to replace motors under 10 horsepower with new high-efficiency motors rather than rewind them. When deciding whether to buy a new motor or rewind the old one, consider the cost difference between the rewind and a new high-efficiency motor, and the potential increase in energy costs of a rewound motor that is less efficient than the original. The quality of the rewind has a big impact on operating cost. A poorly rewound motor may lose up to 3% in efficiency. A 100 HP motor may use several hundred dollars more in electricity each year due to this drop in efficiency, compared to its original efficiency. The operating cost may be even more compared to a new high efficiency motor.

Conclusion

The basic principle s of transformer and motors are discussed in this article. Their operation and uses are also discussed here.

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