Energy Audit of Electric Motors: A Review

[1]Sudhir U. Patil, [2]Sandip U. Patil, [3]H.R.Thakare, S.P.Ingale
[1,2,3,4]Assist. Professor
[1, 3,4] Mechanical Department, [2]Electronics and Telecommunication Engineering Department,
[1,3]SNJB's Late. Sau. K. B. Jain College of Engineering, Nashik, India
[2] M.G.M. COE and Technology, Kamothe, Navi Mumbai.

Abstract: In any developing country to meet energy demand and energy supply is difficult. Therefore energy input is very important concern due to meet increasing demand. In Industrial sector great opportunity to reduce energy consumption through implementation of energy efficient electric motors. This paper presents literature review of energy efficient electric motors, different speed control methods.
***Keywords* - - Motor Losses, EEM, VSD**

I. Introduction

In industrial sector electric motors consume more than 60 % of total electrical energy [1]. Electric motors have stationary winding (stator), rotating winding (rotor), bearings, enclosure (frame). Electric energy converted into mechanical energy by the interaction between rotor winding and stator (magnetic field setup) [2].

II. Types of Electric Motors

2.1 Induction Motors

Induction motors drives production lines, fans and blowers, pumps, conveyors and compressors. There are two magnetic fields induced in induction motors, primary magnetic field and secondary magnetic field induced in stator winding and rotor respectively. The oppose of secondary magnetic field of rotor is main cause of rotation of rotor.

2.2 Direct-Current Motors

These motors are use where over broad speed range smooth acceleration or high starting torque requires.

2.3 Synchronous Motors

Magnetic field is produce in stator and rotor of synchronous motor by supplying AC power to stator and DC power to rotor from separate source respectively. These magnetic fields are rotate at same speed since both are interlock [2].

III. MOTOR LOSSES

Intrinsic losses are important in motors to determine motor efficiency. There are two types of intrinsic losses – independent of motor load called fixed losses and dependant on motor load called as variable losses. Slight changes in conventional design one can reduce intrinsic losses [2].

3.1 Fixed Losses

Fixed losses consist of magnetic core losses and friction and windage losses. Magnetic core losses (sometimes called iron losses) consist of eddy current and hysteresis losses in the stator. They vary with the core material and geometry and with input voltage. Friction and windage losses are caused by friction in the bearings of the motor and aerodynamic losses associated with the ventilation fan and other rotating parts.

3.2 Variable losses

Variable losses consist of resistance losses in the stator and in the rotor and miscellaneous stray losses. Resistance to current flow in the stator and rotor result in heat generation that is proportional to the resistance of the material and the square of the current ($I^2 R$). Stray losses arise from a variety of sources and are difficult to either measure directly or to calculate, but are generally proportional to the square of the rotor current. Part-load performance characteristics of a motor also depend on its design. Both η and PF fall to very low levels at low loads.

3.3 Core loss

Losses in magnetic steel of stator-rotor called core losses. Hysterisis effect and eddy current effect in magnetic steel of stator-rotor are main cause of core losses and these effects are found due to magnetization of core material. These losses have share of 20–25% of the total losses and which are independent of load.

3.4 Windage and friction

Friction and windage losses results from bearing friction, windage and circulating air through the motor and account for 8 – 12 % of total losses. These losses are independent of load. The efficient motors have lower operating temperatures and noise levels, greater ability to accelerate higher-inertia loads, and are less affected by supply voltage fluctuations.

3.5 Stator and Rotor I^2R Losses

These losses are major losses and typically account for 55% to 60% of the total losses. I2R losses are heating losses resulting from current passing through stator and rotor conductors. I2R losses are the function of a conductor resistance, the square of current. Resistance of conductor is a function of conductor material, length and cross sectional area. The suitable selection of copper conductor size will reduce the resistance. Reducing the motor current is most readily accomplished by decreasing the magnetizing component of current. This involves lowering the operating flux density and possible shortening of air gap. Rotor I2R losses are a function of the rotor conductors (usually aluminum) and the rotor slip. Utilization of copper conductors will reduce the winding resistance. Motor operation closer to synchronous speed will also reduce rotor I2R losses.

3.6 Rotor losses

Rotor losses are defined as I2R heating in the rotor winding [3]. Rotor losses reduce by use of larger rotor conductor bars increases size of cross section, lowering conductor resistance (R) and losses due to current flow (I) [2].

IV. ENERGY EFFICIENT MOTORS:

Energy efficient motors cover a wide range of ratings and the full load efficiencies are higher by 3 to 7 %. The mounting dimensions are also maintained as per IS1231 to enable easy replacement. As a result of the modifications to improve performance, the costs of energy-efficient motors are higher than those of standard motors. The higher cost will often be paid back rapidly in saved operating costs, particularly in new applications or end-of-life motor replacements. In cases where existing motors have not reached the end of their useful life, the economics will be less clearly positive. Because the favorable economics of energy-efficient motors are based on savings in operating costs, there may be certain cases which are generally economically ill-suited to energy efficient motors. These include highly intermittent duty or special torque applications such as hoists and cranes, traction drives, punch presses, machine tools, and centrifuges. In addition, energy, efficient designs of multi-speed motors are generally not available. Furthermore, energy efficient motors are not yet available for many special applications, e.g. for flame-proof operation in oil-field or fire pumps or for very low speed applications (below 750 rpm). Also, most energy-efficient motors produced today are designed only for continuous duty cycle operation. Given the tendency of over sizing on the one hand and ground realities like ; voltage, frequency variations, efficacy of rewinding in case of a burnout, on the other hand, benefits of EEM's can be achieved only by careful selection, implementation, operation and maintenance efforts of energy managers.

Selecting the motors for particular application some factors such as service of manufacturer, product name, and availability are also important with efficiency. While energy efficient motors have more cost as compare to conventional induction motors [4]. A summary of energy efficiency improvements in EEMs is given in the Table 1.

Table 4.1 Energy Efficient Motors

power loss area	**efficiency improvement**
1. Iron	Use of thinner gauge, lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, which reduces losses due to lower operating flux densities.
2. Stator I^2R	Use of more copper and larger conductors increases cross sectional area of stator windings. This lowers resistance (R) of the windings and reduces losses due to current flow (i).
3. Rotor I^2R	Use of larger rotor conductor bars increases size of cross section, lowering conductor resistance (R) and losses due to current flow (i).
4. Friction & Windage	Use of low loss fan design reduces losses due to air movement.
5. Stray load Loss	Use of optimized design and strict quality control procedures minimizes stray load losses.

V. FACTORS AFFECTING ENERGY EFFICIENCY & MINIMIZING MOTOR LOSSES IN OPERATION

5.1 Power Supply Quality

Motor performance is affected considerably by the quality of input power that is the actual volts and frequency available at motor terminals vis-à-vis rated values as well as voltage and frequency variations and voltage unbalance across the three phases. Motors in India must comply with standards set by the Bureau of Indian Standards (BIS) for tolerance to variations in input power quality. The BIS standards specify that a motor should be capable of delivering its rated output with a voltage variation of +/- 6 % and frequency variation of +/- 3 %. Fluctuations much larger than these are quite common in utility-supplied electricity in India. Voltage fluctuations can have detrimental impacts on motor performance.

Voltage unbalance, the condition where the voltages in the three phases are not equal, can be still more detrimental to motor performance and motor life. Unbalance typically occurs as a result of supplying single-phase loads disproportionately from one of the phases. It can also result from the use of different sizes of cables in the distribution system.

The options that can be exercised to minimize voltage unbalance include:

i) Balancing any single phase loads equally among all the three phases

ii) Segregating any single phase loads which disturb the load balance and feed them from a separate line / transformer.

5.2 Reducing Under-loading

Probably the most common practice contributing to sub-optimal motor efficiency is that of under-loading. Under-loading results in lower efficiency and power factor, and higher-than necessary first cost for the motor and related control equipment. Under-loading is common for several reasons. Original equipment manufacturers tend to use a large safety factor in motors they select. Under-loading of the motor may also occur from under-utilization of the equipment. Another common reason for under loading is selection of a larger motor to enable the output to be maintained at the desired level even when input voltages are abnormally low. Finally, under-loading also results from selecting a large motor for an application requiring high starting torque where a special motor, designed for high torque, would have been suitable.

A careful evaluation of the load would determine the capacity of the motor that should be selected. Another aspect to consider is the incremental gain in efficiency achievable by changing the motor. Larger motors have inherently higher rated efficiencies than smaller motors. Therefore, the replacement of motors operating at 60 – 70 % of capacity or higher is generally not recommended.

However, there are no rigid rules governing motor selection; the savings potential needs to be evaluated on a case-to-case basis. When downsizing, it may be preferable to select an energy-efficient motor, the efficiency of which may be higher than that of a standard motor of higher capacity.

For motors, which consistently operate at loads below 40 % of rated capacity, an inexpensive and effective measure might be to operate in star mode. A change from the standard delta operation to star operation involves re-configuring the wiring of the three phases of power input at the terminal box. Operating in the star mode leads to a voltage reduction by a factor of '√3'. Motor is electrically downsized by star mode operation, but performance characteristics as a function of load remain unchanged. Thus, full-load operation in star mode gives higher efficiency and power factor than partial load operation in the delta mode. However, motor operation in the star mode is possible only for applications where the torque-to-speed requirement is lower at reduced load.

As speed of the motor reduces in star mode this option may be avoided in case the motor is connected to a production facility whose output is related to the motor speed. For applications with high initial torque and low running torque needs, Del-Star starters are also available in market, which help in load following de-rating of electric motors after initial start-up.

5.3 Sizing to Variable Load

Industrial motors frequently operate under varying load conditions due to process requirements. A common practice in cases where such variable-loads are found is to select a motor based on the highest anticipated load. In many instances, an alternative approach is typically less costly, more efficient, and provides equally satisfactory operation. With this approach, the optimum rating for the motor is selected on the basis of the load duration curve for the particular application. Thus, rather than selecting a motor of high rating that would operate at full capacity for only a short period, a motor would be selected with a rating slightly lower than the peak anticipated load and would operate at overload for a short period of time. Since operating within the thermal capacity of the motor insulation is of greatest concern in a motor operating at higher than its rated load, the motor rating is selected as that which would result in the same temperature rise under continuous full-load operation as the weighted average temperature rise over the actual operating cycle. Under extreme load changes, e.g. frequent starts / stops, or high inertial loads, this method of calculating the motor rating is unsuitable since it would underestimate the heating that would occur. Where loads vary substantially with time, in addition to proper motor sizing, the control strategy employed can have a significant impact on motor electricity use. Traditionally, mechanical means (e.g. throttle valves in piping systems) have been used when lower output is required. More efficient speed control mechanisms include multi-speed motors, eddy-current couplings, fluid couplings, and solid-state electronic variable speed drives.

5.4 Power Factor Correction

As noted earlier, induction motors are characterized by power factors less than unity, leading to lower overall efficiency (and higher overall operating cost) associated with a plant's electrical system. Capacitors connected in parallel (shunted) with the motor are typically used to improve the power factor. The impacts of PF correction include reduced kVA demand (and hence reduced utility demand charges), reduced I2R losses in cables upstream of the capacitor (and hence reduced energy charges), reduced voltage drop in the cables (leading to improved voltage regulation), and an increase in the overall efficiency of the plant electrical system. It should be noted that PF capacitor improves power factor from the point of installation back to the generating side. It means that, if a PF capacitor is installed at the starter terminals of the motor, it won't improve the operating PF of the motor, but the PF from starter terminals to the power generating side will improve, i.e., the benefits of PF would be only on upstream side.

The size of capacitor required for a particular motor depends upon the no-load reactive kVA (kVAR) drawn by the motor, which can be determined only from no-load testing of the motor. In general, the capacitor is then selected to not exceed 90 % of the no-load kVAR of the motor. (Higher capacitors could result in over-voltages and motor burn-outs).

5.5 Maintenance

Inadequate maintenance of motors can significantly increase losses and lead to unreliable operation. Improper lubrication can cause increased friction in both the motor and associated drive transmission equipment. Resistance losses in the motor, which rise with temperature, would increase. Providing adequate ventilation and keeping motor cooling ducts clean can help dissipate heat to reduce excessive losses. The life of the insulation in the motor would also be longer: for every 10°C increase in motor operating temperature over the recommended peak, the time before rewinding would be needed is estimated to be halved

A checklist of good maintenance practices to help insure proper motor operation would include:

• Inspecting motors regularly for wear in bearings and housings (to reduce frictional losses) and for dirt/dust in motor ventilating ducts (to ensure proper heat dissipation).

• Checking load conditions to ensure that the motor is not over or under loaded. A change in motor load from the last test indicates a change in the driven load, the cause of which should be understood.

• Lubricating appropriately. Manufacturers generally give recommendations for how and when to lubricate their motors. Inadequate lubrication can cause problems, as noted above. Over lubrication can also create problems, e.g. excess oil or grease from the motor bearings can enter the motor and saturate the motor insulation, causing premature failure or creating a fire risk.

• Checking periodically for proper alignment of the motor and the driven equipment. Improper alignment can cause shafts and bearings to wear quickly, resulting in damage to both the motor and the driven equipment.

• Ensuring that supply wiring and terminal box are properly sized and installed. Inspect regularly the connections at the motor and starter to be sure that they are clean and tight.

5.6 Age

Most motor cores in India are manufactured from silicon steel or de-carbonized cold-rolled steel, the electrical properties of which do not change measurably with age. However, poor maintenance (inadequate lubrication of bearings, insufficient cleaning of air cooling passages, etc.) can cause a deterioration in motor efficiency over time. Ambient conditions can also have a detrimental effect on motor performance. For example, excessively high temperatures, high dust loading, corrosive atmosphere, and humidity can impair insulation properties; mechanical stresses due to load cycling can lead to misalignment. However, with adequate care, motor performance can be maintained.

VI. MOTOR LOAD SURVEY: METHODOLOGY

Large industries have a massive population of LT motors. Load survey of LT motors can be taken-up methodically to identify improvement options as illustrated in following case study.

i) Sampling Criteria

Towards the objective of selecting representative LT motor drives among the motor population, for analysis, the criteria considered are:

– Utilization factor i.e., hours of operation with preference given to continuously operated drive motors.

– Sample representative basis, where one drive motor analysis can be reasoned as representative for the population. Ex : Cooling Tower Fans, Air Washer Units, etc.

– Conservation potential basis, where drive motors with inefficient capacity controls on the machine side, fluctuating load drive systems, etc., are looked into.

ii) Measurements

Studies on selected LT motors involve measurement of electrical load parameters namely volts, amperes, power factor, kW drawn.

Observations on machine side parameters such as speed, load, pressure, temperature, etc., (as relevant) are also taken. Availability of online instruments for routine measurements, availability of tail-end capacitors for PF correction, energy meters for monitoring is also looked into for each case.

iii) Analysis

Analysis of observations on representative LT motors and connected drives is carried out towards following outputs:

– Motor load on kW basis and estimated energy consumption.

– Scope for improving monitoring systems to enable sustenance of a regular in-house Energy Audit function.

– Scope areas for energy conservation with related cost benefits and source information.

The observations are to indicate:

% loading on kW, % voltage unbalance if any, voltage, current, frequency, power factor, machine side conditions like load / unload condition, pressure, flow, temperature, damper / throttle operation, whether it is a rewound motor, idle operations, metering provisions, etc.

The findings / recommendations may include:

• Identified motors with less than 50 % loading, 50 – 75 % loading, 75 – 100 % loading, over 100 % loading.

• Identified motors with low voltage / power factor / voltage imbalance for needed improvement measures.

• Identified motors with machine side losses / inefficiencies like idle operations, throttling / damper operations for avenues like automatic controls / interlocks, variable speed drives, etc.

Motor load survey is aimed not only as a measure to identify motor efficiency areas but equally importantly, as a means to check combined efficiency of the motor, driven machine and controller if any. The margins in motor efficiency may be less than 10 % of consumption often, but the load survey would help to bring out savings in driven machines / systems, which can give 30 – 40 % energy savings.

VII. SPEED CONTROL OF AC INDUCTION MOTORS

Traditionally, DC motors have been employed when variable speed capability was desired. By controlling the armature (rotor) voltage and field current of a separately excited DC motor, a wide range of output speeds can be obtained. DC motors are available in a wide range of sizes, but their use is generally restricted to a few low speed, low-to-medium power applications like machine tools and rolling mills because of problems with mechanical commutation at large sizes. Also, they are restricted for use only in clean, non-hazardous areas because of the risk of sparking at the brushes. DC motors are also expensive relative to AC motors.

Because of the limitations of DC systems, AC motors are increasingly the focus for variable speed applications. Both AC synchronous and induction motors are suitable for variable speed control. Induction motors are generally more popular, however, because of their ruggedness and lower maintenance requirements. AC induction motors are inexpensive (half or less of the cost of a DC motor) and also provide a high power to weight ratio (about twice that of a DC motor). An induction motor is an asynchronous motor, the speed of which can be varied by changing the supply frequency. The control strategy to be adopted in any particular case will depend on a number of factors including investment cost, load reliability and any special control requirements. Thus, for any particular application, a detailed review of the load characteristics, historical data on process flows, the features required of the speed control system, the electricity tariffs and the investment costs would be a prerequisite to the selection of a speed control system. The characteristics of the load are particularly important. Load refers essentially to the torque output and corresponding speed required. Loads can be broadly classified as either constant power or Constant torque. Constant torque loads are those for which the output power requirement may vary with the speed of operation but the torque does not vary. Conveyors, rotary kilns, and constant-displacement pumps are typical examples of constant torque loads. Variable torque loads are those for which the torque required varies with the speed of operation. Centrifugal pumps and fans are typical examples of variable torque loads (torque varies as the square of the speed). Constant power loads are those for which the torque requirements typically change inversely with speed. Machine tools are a typical example of a constant power load.

The largest potential for electricity savings with variable speed drives is generally in variable torque applications, for example centrifugal pumps and fans, where the power requirement changes as the cube of speed. Constant torque loads are also suitable for VSD application.

7.1 Multi-speed motors

Motors can be wound such that two speeds, in the ratio of 2:1, can be obtained. Motors can also be wound with two separate windings, each giving 2 operating speeds, for a total of four speeds. Multi-speed motors can be designed for applications involving constant torque, variable torque, or for constant output power. Multi-speed motors are suitable for applications, which require limited speed control (two or four fixed speeds instead of continuously variable speed), in which cases they tend to be very economical. They have lower efficiency than single-speed motors

7.2 Adjustable Frequency AC Drives

Adjustable frequency drives are also commonly called inverters. They are available in a range of kW rating from fractional to 750 kW. They are designed to operate standard induction motors. This allows them to be easily added to an existing system. The inverters are often sold separately because the motor may already be in place. If necessary, a motor can be included with the drive or supplied separately. The basic drive consists of the inverter itself which coverts the 50 Hz incoming power to a variable frequency and variable voltage. The variable frequency is the actual requirement, which will control the motor speed. There are three major types of inverters designs available today. These are known as Current Source Inverters (CSI), Variable Voltage Inverters (VVI), and Pulse Width Modulated Inverters (PWM).

7.3 Direct Current Drives (DC)

The DC drive technology is the oldest form of electrical speed control. The drive system consists of a DC motor and a controller. The motor is constructed with armature and field windings. Both of these windings require a DC excitation for motor operation. Usually the field winding is excited with a constant level voltage from the controller. Then, applying a DC voltage from the controller to the armature of the motor will operate the motor. The armature connections are made through a brush and commutator assembly. The speed of the motor is directly proportional to the applied voltage. The controller is a phase controlled bridge rectifier with logic circuits to control the DC voltage delivered to the motor armature. Speed control is achieved by regulating the armature voltage to the motor. Often a tacho generator is included to achieve good speed regulation. The tacho would be mounted on the motor and produces a speed feedback signal that is used within the controller.

7.4 Wound Rotor AC Motor Drives (Slip Ring Induction Motors)

Wound rotor motor drives use a specially constructed motor to accomplish speed control. The motor rotor is constructed with windings which are brought out of the motor through slip rings on the motor shaft. These windings are connected to a controller which places variable resistors in series with the windings. The torque performance of the motor can be controlled using these variable resistors. Wound rotor motors are most common in the range of 300 HP and above.

CONCLUSION

In industrial sector considerable amount of energy could be save by use of energy efficient motors. This review paper gives losses in induction motors, difference between EEM and induction motors, different methods of motor speed control and also gives motor load survey methodology.

REFRENCES

[1] Molla Shahadat Hossain Lipu, Tahia Fahrin Karim "Energy Efficiency Opportunities and Savings Potential for Electric Motor and Its Impact on GHG Emissions Reduction" International Journal of Electrical and Computer Engineering (IJECE) Vol. 3, No. 4, August 2013, pp. 533~542 ISSN: 2088-8708.
[2] https://beeindia.gov.in/sites/default/files/3Ch2.pdf

[3] R. Saidur, “ A review on electrical motors energy use and energy savings” Renewable and Sustainable Energy Reviews 14 (2010) 877–898.

[4] Anı´bal T. de Almeida a, Paula Fonseca a, Paolo Bertoldi b, “ Energy-efficient motor systems in the industrial and in the services sectors in the European Union: characterisation, potentials, barriers and policies”, Energy 28 (2003) 673–690

