ENERGY EFFICIENT INDUSTRIAL MOTORS

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Abstract:
Electric motors are of utmost importance in industrial as well as agriculture sector. These motors found their application as constant speed drives with very low rating as well as variable speed drives with very high rating. This paper describes the various factors affecting the efficiency of motor and method to increase it on the basis of comparison with various standards. An incremental difference in the efficiency is also discussed.

Keywords**:** ***Energy Efficiency, Efficient Induction drive, Payback Period of Induction Drives, Energy saving in Induction drives.***

1. Introduction

Energy efficiency and energy conservation are very closely related to each other. With increase in demand of energy and due to uncertainties in oil supply and fluctuating price of conventional fuels, efficiency and conservation of energy has become an important aspect of industrial as well as rural development. A large amount of electrical energy is consumed by induction motor used for irrigation in rural sector and industrial purpose in urban sector. In country like India agriculture and industrial sector is developing rapidly, in same way electrical energy consumption is increasing.
A study conducted by Gujarat Energy Development Agency (GEDA) in India has indicated that a 5% improvement in overall efficiency of induction motor would save enough energy that would be comparable to energy produced by a new power plant of few hundred Mega Watts [1, 2].

2. Determining and Comparing Motor Efficiency

It is essential that a uniform efficiency definition should be used, when evaluating on basis of efficiency improvements or energy savings. It is often difficult to accurately compare manufacturers published, quoted, or tested efficiencies, as various values are used in catalogues and vendor literature [9]. Common definitions include-

2.1. *Average or Nominal Efficiency*

These terms are identical and refer to the average full load efficiency value obtained through testing a sample population of the same motor model. These are the most common standards used to compare motors.

2.2. *Guaranteed Minimum and Expected Minimum Efficiency*

All motors purchased or a stated percentage of the motors purchased are guaranteed to have efficiencies that equal or exceed this full load value.

2.3. *Apparent Efficiency*

Apparent efficiency is the product of motor power factor and minimum efficiency. With this definition energy consumption can vary considerably with the power factor.

2.4. *Calculated Efficiency*

This term refers to an average expected efficiency based upon a relationship between design parameters and test results. Specifications should not be based on calculated efficiency values.

3. Requirement of Increasing Efficiency of Induction Motor

On the basis of study of the behavior of various electrical equipments available in the market, it is concluded that electric motors are not usually very high on the priority list when energy efficiency is considered. However there are some fundamental considerations that would increase the importance of electric motor efficiency [3]. These are:

- In the present scenario electric motors are consuming about 40% to 50% of the total generated electrical energy.
- The cost of total electrical energy used by an electric motor is about 120% of its purchase price.

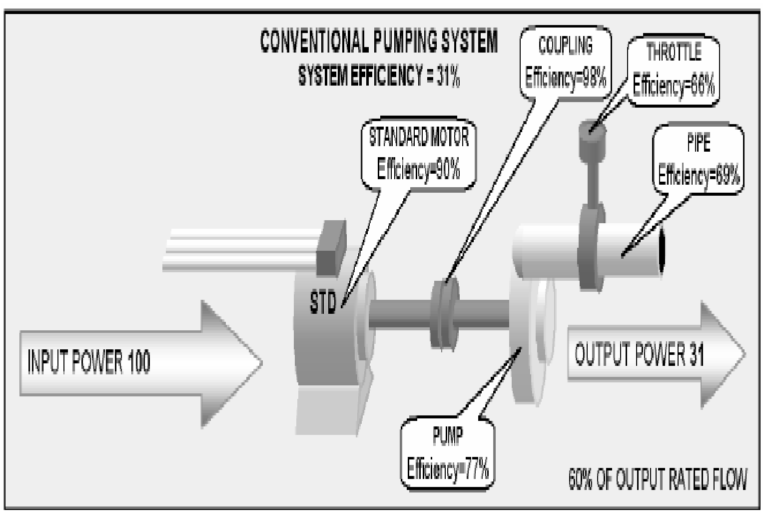

Fig. 1a. Power flow in conventional pumping set

- A standard motor efficiencies vary between 65% to 95% depends upon its construction, size and type so by increasing the efficiency about 0.5% and so on we can save considerable amount of electrical energy.
- In India increase in efficiency of the electric motor about 1% to 10% will definitely contribute in fulfilling the dream of Indian government “Electricity to All by the year 2020”.

As the third world develops, demand for electrical energy is expected to double over the next 30 years [3].

In Fig-1 the energy efficiency of the standard pumping set and energy efficient pumping set is compared.

In Fig-1(a), an input power of 100 hp in standard pumping set is given and with this input, the output power of 31 hp. Thus the efficiency of this standard pumping set is 31% [4].

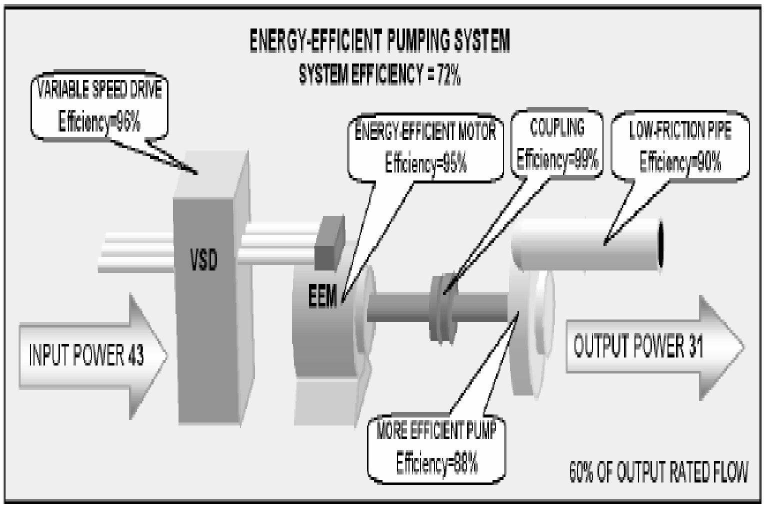

Fig. 1b. Power flow in energy efficient pumping set

While in Fig-1(b), Energy efficient pumping set is presented and with the help of this figure it can be calculated that for the output power of 31 hp only 43 hp of input power is required so the efficiency of this energy efficient pumping set becomes 72% [4].

In this way on the basis of the comparison of Fig 1(a) and 1(b), one can conclude that by using energy efficient pumping set we can save the energy up to 41%.

4. Restrictions to The Development of Energy Efficient Motors

There are number of factors that restrict the development of energy efficient electric motors. The following are few principle factors among these:

- Ignorance
- Mental structure of consumers
- International standards

4.1. *Ignorance*

It is well known that electric motors are electro-mechanical power converters. Torque and speed are important features of the motors. So the torque and speed requirement of the driven equipment should match with the motor used to drive those equipments. If these features are not matched then fault is obvious and indirectly it will affect the efficiency of motor.

4.2. *Mental structure of consumers*

Electric motors are not sold to the users directly. Mostly manufacturers of the motors sell to the original equipment, manufacturers that fit the motors to their fans, compressors, pump etc. or to stockiest who sell to the retail user markets. Neither the original equipment manufacturers nor the stockiest has to bear the cost of running the motors thus in general they are only interested in low first cost and this is meant to be low efficiency[3].

Fig.2 shows lifetime supply chain for motors [3]. It is evident from Fig. 2 that all the groups in the supply chain depends upon the user, if the user doesn't buy the motor there is no reasons for the others in the chain to exist. If all the groups in the supply chain are really working their best for the user then motor efficiency becomes a dominant factor because of high ratio of motor lifetime running cost to the motor initial purchase price.

4.3. *International standards*

Induction motors between the range of 0.37kW to 150kW are one of the most widely used motor range and the designing considerations of these motors are based on international standards but unfortunately there is no only one standard. Standards like IEC, NEMA (National Electrical Manufacturers Association) and JEM have their own designing considerations which differ over the range and many of the present standards had been prevailing for over 30 years and this has given manufacturers a little inconvenience for design changes other than to reduce costs and to increase efficiency [3].

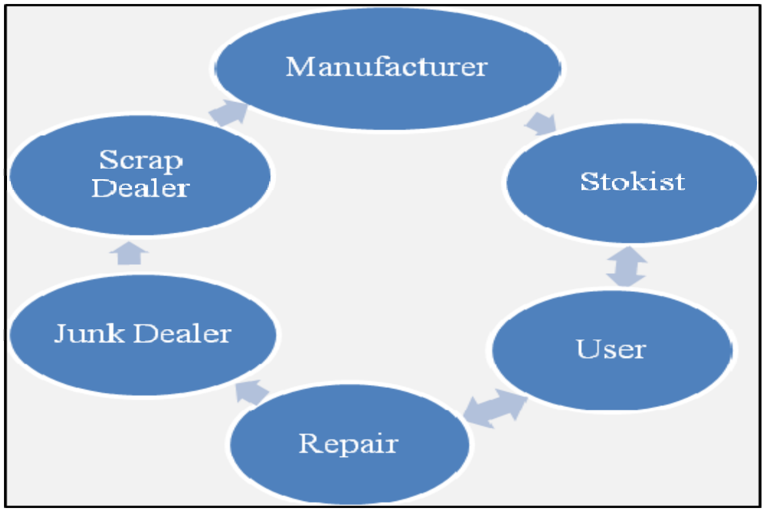

Fig. 2. Lifetime chain for motors

5. Motor Losses

A function of motor is to convert electrical energy into mechanical energy to perform useful tasks. Motor efficiency may be increased by reducing losses.

Motor energy losses can be divided into various categories, each of which is influenced by design and construction of the motor. One design consideration is the size of air gap between the rotor and the stator. Large air gaps tend to maximize efficiency at the expense of power factor, while small air gaps slightly compromise efficiency while significantly improving power factor. The losses may be categorized into two major areas viz. fixed losses and variable losses. These losses are described below and with the help of Table I; we can analyze these losses briefly.

5.1. *Fixed losses*

Fixed losses are independent of motor load it consists 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, structure of stator and rotor and with input voltage. Friction and windage losses are caused by friction in the bearings of the motor.

5.2. *Variable losses*

Variable losses depend upon motor load. It consists of resistance losses in the stator and in the rotor and miscellaneous stray losses. Resistance through which current flows in the stator and rotor results heat generation that is proportional to the resistance of the material and the square of the current and it is given by I^2R. Where R is the stator winding resistance for stator resistance (R_S) loss and for rotor resistance loss it can be used as rotor winding resistance (I_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.

Table I shows various losses in the motor and the factors affecting these losses. It is clear from Table I that no load losses such as core losses and friction and windage losses both are about 15% of the total losses that occur in the motor while under loaded condition stator I^2R_S loss consists of 25-40%, rotor I^2R_R loss 15-25% and stray load loss consists of 10-20% of the total losses occurring in the motor [12].

It is clear from Table I that no load losses depends upon the type and quantity of the magnetic material with selection and design of the fans and bearings while under loaded condition motor losses mainly depends upon the stator and rotor conductor size.

Table 1. Description of various losses in electrical motors

Fixed Losses	Typical Losses %	Factors Affecting These Losses
Core Losses	15-25	Type and Quantity of Magnetic Material
Friction & Windage Losses	5-15	Selection and Design of Fans and Bearings
Variable Losses		
Stator I^2R_S Losses	25-40	Stator Conductor Size
Rotor I^2R_R Losses	15-25	Rotor Conductor Size
Stray Load Losses	10-20	Manufacturing and Design Methods

6. Variation of Motor Efficiency with Load

Most electric motors are designed to run at 50% to 100% of rated load the maximum efficiency is achieved usually near 75% of rated load. Thus, a 10-hp motor has an acceptable load range of 5 to 10 hp with maximum efficiency is at 7.5hp. A motor's efficiency tends to decrease dramatically below about 50% of rated load. However, the range of efficiency varies with individual motors and tends to extend over a broader range for larger motors. A motor is considered under loaded when it is in the range where efficiency drops significantly with decreasing load.

Overloading of motors can decrease efficiency. Many motors are designed with a service factor that allows short time overloading. Service factor is a multiplier that indicates how much a motor can be overloaded under ideal ambient conditions. For example, a 10hp motor with a 1.15 service factor can handle an 11.5hp load for short periods of time without causing significant damage. Although many motors have service factor of 1.15, running the motor continuously above rated load reduces efficiency and motor life.

Fig. 3 shows a bar graph of the estimated and measured efficiency for the 10-hp motor as a function of load. As can be seen from the graph, the estimated value of the efficiency at full load is identical to the actual value but at the third quarter, half and one fourth of the full load value the estimated value is slightly greater than the measured value [5].

Measured efficiency can be calculated by the measurement of actual power by experimental setup whereas estimated efficiency is the efficiency calculated from the given condition through applied voltage and machine parameters.

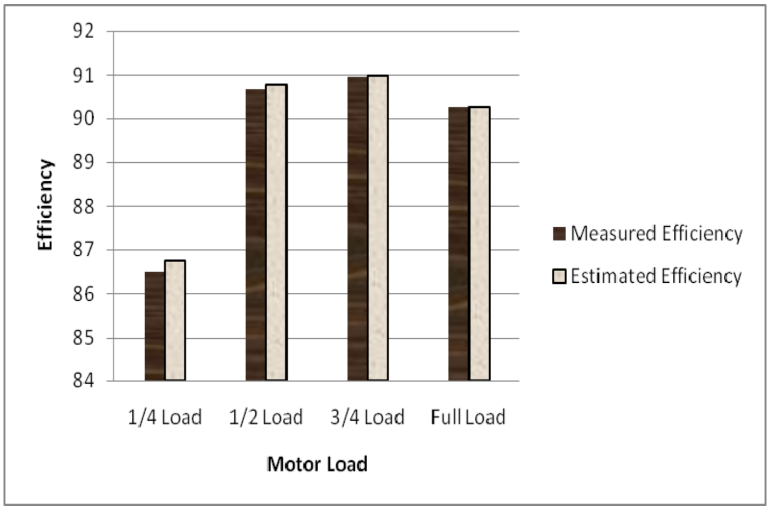

Fig. 3. Estimated and measured efficiency vs. load

7. Effect of Harmonics on Motor Efficiency

Harmonics are ac voltages and currents with frequency that are integer multiples of the fundamental frequency. In earlier years, harmonics were not prevalent in most of the industries due to balanced linear loads using three phase induction motors along with incandescent lighting, resistivity etc., but the rapid advancement of power electronics in industrial application makes industrial loads non-linear type. These non-linear loads draw non-sinusoidal current from the sinusoidal voltage waveform. The distortions thus produced in the voltage and current waveforms from the sinusoidal waveforms are called harmonic disorders.

7.1. *Condition of harmonics generation*

Harmonics are generated due to increasing number of non-linear loads as explained below-

(1) When the system voltage is linear but the load is non-linear, the current will be distorted and become non-sinusoidal. The actual current will become higher than the current measured by an ammeter or any other measuring instrument at the fundamental frequency.

(2) When the supply system itself contains harmonics and the voltage is already distorted, the linear loads will also respond to such voltage harmonics and draw harmonic currents against each harmonic present in the system and generate the same order of current harmonics.

(3) When the system voltage and loads are both non-linear (a condition which is more common) the voltage harmonics will magnify and additional harmonics will be generated, corresponding to the non-linearity of the load and hence will further distort an already distorted voltage waveform [9].

7.2. *Source of harmonics*

Harmonics are mainly generated due to different types of loads of non-linear nature. Few most important types are listed as:

(1) Rapid use of energy conservation devices in both domestic and industrial sector such as electronic chokes for tube lights, electronics energy controllers for motors and electronic fan regulators etc. inject harmonics substantially.

(2) Large use of shunt capacitors to improve power factor and stability has significant influence on harmonic level. Supply converters and traction motors are the major causes of Harmonics generation.

(3) Non-linearity of customer load also causes harmonics that affect the power quality.

7.3. *Effect of harmonics on induction motor*

Hysteresis and eddy current losses are part of iron losses that are produced in core due to alternating magnetic field. Hysteresis losses are proportional to frequency and eddy current losses vary as the square of the frequency. Therefore, high frequency voltage components produce additional losses in the core of AC motors, which in turn, increase the operating temperature of core and the winding surrounding the core. Application of non-sinusoidal voltage to motor result in harmonic current circulation in the windings of the motor and due to this circulation additional loss may occur and these additional losses may lead to decrement in the efficiency of the rotating machines [9].

8. Energy Efficiency and Environment

It is well known that environment and efficiency are closely interlinked with each other. Machine designers over many years have tried their best to respond to the need for improved efficiency of induction motors.

Real driver for the evolution of higher efficiency motor is to save the environment through reduction of energy consumption. An improvement in energy efficiency will lead to reduction of CO_2 emissions [7].

Today in India millions of the induction motors are manufactured every year and they combined to consume about 50% of the total energy generated. By improving the efficiency considerable amount of energy can be saved and it also leads to save environment because to meet the load of these machines power generating stations are releasing millions of tons of greenhouse gases into the atmosphere every year. There is requirement of sustaining the constantly increasing demand of energy and at the same time reducing environmental pollution, then automatic increase in the efficiency of energy conversion will have to substantially improve in order to produce more power from the same or less material.

It will not be sufficient to consider only the efficiency of energy conversion and the final work which is done by using the induction motor but full attention must be given to energy used and the pollutants generated during the energy conversion and the production of final product [13].

One of the main motives of increasing the efficiency induction motor is to save our environment through the reduction of energy consumption. An improvement in energy efficiency will lead to reduction of CO_2 emissions. Electric drive systems are largely responsible for the largest part of the electricity consumption. Therefore an increase in efficiency in motor will result in large energy savings and reduction in CO_2 emission into our environment [6].

So, for environment protection perspective and to have an increased output per unit volume the induction machine should consume less energy, be immune from the environment and must not pollute the environment.

9. Payback Period

Payback period is the length of time required for incoming returns to equal the cost of an investment (e.g. purchase of computer software or hardware, training expenses, or new product development), usually measured in years. Payback period takes essentially an "Investment" view of the action, plan, or scenario and its estimated cash flow stream. The better investment is the one with the shorter payback period. Payback period is sometimes used to compare alternative investments with respect to risk and the investment with the shorter payback period is considered less risky [10].

9.1. *Payback period analysis for motor*

For a new motor purchase, the simple payback is the price premium minus any utility rebate for energy efficient motor, divide by annual dollars saving [10]:

$$Simple\ Payback\,Period = \frac{Price\ Premium - Utility\ Rebate}{Annual\ Dollar\ Saving} \qquad (1)$$

When calculating the simple payback for replacing an operating motor, we must include the full purchase price of the motor plus an installation costs:-

$$Simple\ Payback\ Period = \frac{Motor\ Price + Installation\ Charge - Utility\ Rebate}{Annual\ Dollar\ Saving} \quad (2)$$

10. Annual energy savings and efficiency

By operating the motor at balance supply more energy can be saved and this saving is variable with the motor power and on the basis of the Fig. 4 it is clear that saving is highest for the range of 0.75-7.5 kW motors and minimum for the range of >75 kW motors. This saving for different range is also subcategorized into three parts

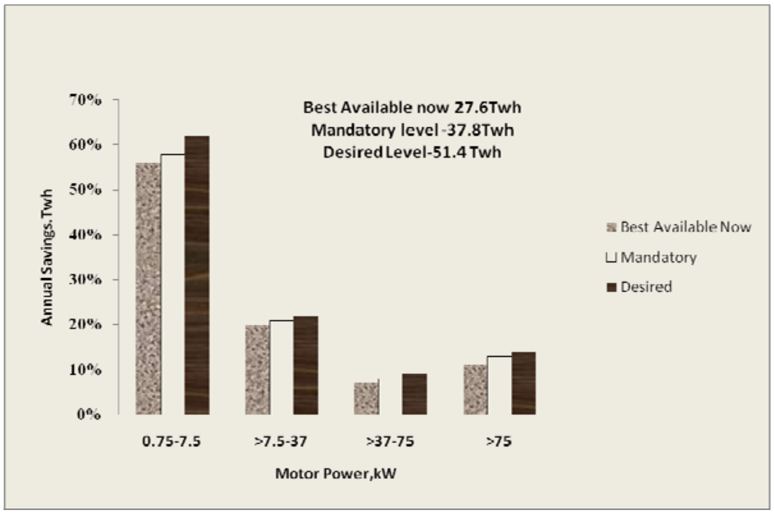

Fig. 4. Annual energy saving by variation of motor power

in which the desired efficiency level is highest among the best available level and the mandatory level [8].

10.1. *Determination of annual energy saving*

Energy efficient motors require fewer input kilowatts to provide the same output as a standard efficiency motor. The difference inefficiency between the high efficiency motor and a comparable standard motor determines the demand or kilowatt savings. For two similar motor operating at the same load, but having different efficiencies, the following equation is used to calculate the kilowatt reduction [10].

$$kW_{saved} = Rating\ of\ the\ Motor \times \left(\frac{100}{E_{std}} - \frac{100}{E_{HE}}\right) \quad (3)$$

Where:
E_{std} = Standard motor efficiency under full load condition
E_{HE} = Energy efficient motor efficiency under full load conditions

The kilowatt savings are the demand savings. The annual energy savings are calculated as follows.

$$kWh_{saving} = kW_{saved} \times Annual\ Operating\ Hours$$
$$Annual\ Saving(in\ Rs.) = kWh_{saving} \times Power\ Rate(in\ Rs.) \quad (4)$$

The above equations apply to motors operating at a specified load. For varying loads, we can apply the energy saving equation to each portion of the cycle where the load is relatively constant for an appreciable period of time. The total energy saving is then sum of the savings for each load periods.

For example let us compare two motors, one of which is standard efficiency motor and other is energy efficient motor both having same rating i.e. 3.7 kW. Efficiency of standard efficiency motor and energy efficient motor are 85% and 88.3% and cost is Rs. 7215, Rs. 9380 respectively. Both motors are working 16 hrs/day in 300 days a year with the power rate of Rs. 4.5/kWh. So

$$kW\ Saved = 3.7kW\left(\frac{100}{85} - \frac{100}{88.3}\right) = 0.1626kW \quad (5)$$

$$kWhSaving = 0.1626 \times 16 \times 300 = 780.48\ kWh \quad (6)$$

$$Annual\ Saving = 780.28kWh \times (Rs.\ 4.5) = 3512.2\ Rs./Year \quad (7)$$

Extra investment in purchasing energy efficient motor is Rs. 2615 so payback period for this investment is approximately 9 months [11].

11. Conclusion

A detailed analysis of the energy efficiency of the industrial motors has been presented in this paper. One part of the fixed losses may be reduced by using advances materials with smaller area of hysteresis loop and another part by using better stacking of the core and high resistivity material. Friction and windage losses may be reduced using better aerodynamic design of rotor and bearing with low friction.

The optimum design gives a motor having uniformly high efficiency over a wide range of load and supply voltage. It is seen that, within the same frame size, the full load efficiency of the new motor is about 2.5% more than that of the standard motor and the input kVA is 3% less than that of standard motor. The active material cost of the energy efficient motor is up to 15% more than that of the standard motor, but the extra cost is paid back within a reasonable period, which is calculated to be even less than a year for the prevailing cost structure. The motor tests described in this paper have demonstrated that energy efficient motor designs offer higher operating efficiencies than standard designs. In addition, the high efficiency motors operated closer to the peak efficiency over a wide range of loads than did the standard motors, so that the difference in the efficiency was even greater at less than full load, where many motors operate much of time. Due to the lower losses it shows better performance and life expectancy is more.

In the age when conservation of natural resources and energy saving is considered so important, the leading manufacturers of induction motors have contributed by progressively making available environmental friendly products. Thus by improving the efficiency of the induction motor we can also contribute in making the environment clean for all living-beings and today when global warming i.e. pollution is increasing day by day.

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