

INDUCTION ELECTRIC MOTORS OPTIMIZATION AIMING ENERGY EFFICIENCY IN INDUSTRIAL APPLICATIONS

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ABSTRACT

A methodology for assessment and optimization of induction electric motors aiming energy conservation is described, which works by means of replacing older motors with high-efficiency ones. The electric motor is an end-use equipment which is strongly present at industry, being subject to replacements that may have satisfactory results when the diagnosis is carried out in a consistent way, in accordance to coherent validation procedures. The adopted motor replacement methodology included an initial study, by means of measurements of electrical parameters. Afterwards, by using particular simulation software, operating conditions of the electric motor and the expected savings accruing from the use of high-efficiency motors were estimated. When necessary, the motor resizing analysis provides the best rated power for the drive. The motor substitutions carried out in this motor drives efficiency improvement program resulted in yearly savings amounting to 720 MWh.

KEYWORDS: Demand Reduction, Energy Conservation, Energy Diagnosis, High-Efficiency Motors, Induction Machines, Measurement & Verification, Maintenance Costs, Motor Resizing, Power Quality, Simulation Program.

INTRODUCTION

Electric power is present among us in many ways. Due to its ever growing and widespread availability and consumption since the previous century, new comfort and well-being patterns were made possible, making us highly dependent on this resource.

The options for electric power generation are related to the availability of primary energy resources, renewable or not, being this choice influenced by economic, environmental and technological conditions present where one intends to site a given power station (Reis, 2000).

Owning an installed capacity more than 115 GW, Brazil needs to invest not only in generation and transmission, but also in conservation and electric energy efficiency programs, fostering economic growth, environmental preservation and comfort for the population.

Through the restructuring of the electric sector, with the creation of the Brazilian Electricity Regulatory Agency and the privatization of electric power distribution utilities, new incentives were given to conservation programs, by means of a contractual clause according to which 1% of the net operational income of the electric power utility should be

spent in Research and Development and Energy Efficiency Programs.

The main advantage to making investments in energy efficiency programs is that they are cheaper than those in new power generation facilities.

Many industrialized countries prefer to adopt new technologies, regulations and price policies, giving impulse to the efficient use of electricity, which results in a lower increase in the total demand for energy.

In general, one can also observe, in most industries, much waste of electrical energy, due to the use of inefficient processes and equipment in terms of electric power, which comes as a heritage of a market that was once closed to international competition but nowadays, studies on substitutions, modifications and updates are necessary for companies to cut their internal costs and survive in an extremely competitive business scenario.

In Brazil, the industrial sector represents 46% of all electric power consumption. Out of this percentage, 55% comprises electric motor usage. Figure 1 illustrates this.

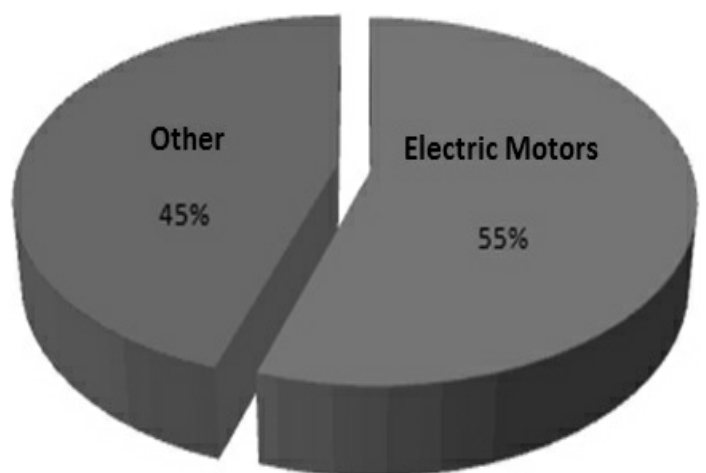


Figure 1. Percentage of electric motors in Brazilian industry.

The induction electric motor is an electromechanical converter based on electromagnetic principles, capable of converting electric power into useful mechanical energy.

The induction machine developed by Dolivo Dobrovolsky in 1890 is the most similar one to present motors. However, years before its formal appearance, the electric motor had already been studied, as seen in Figure 2.

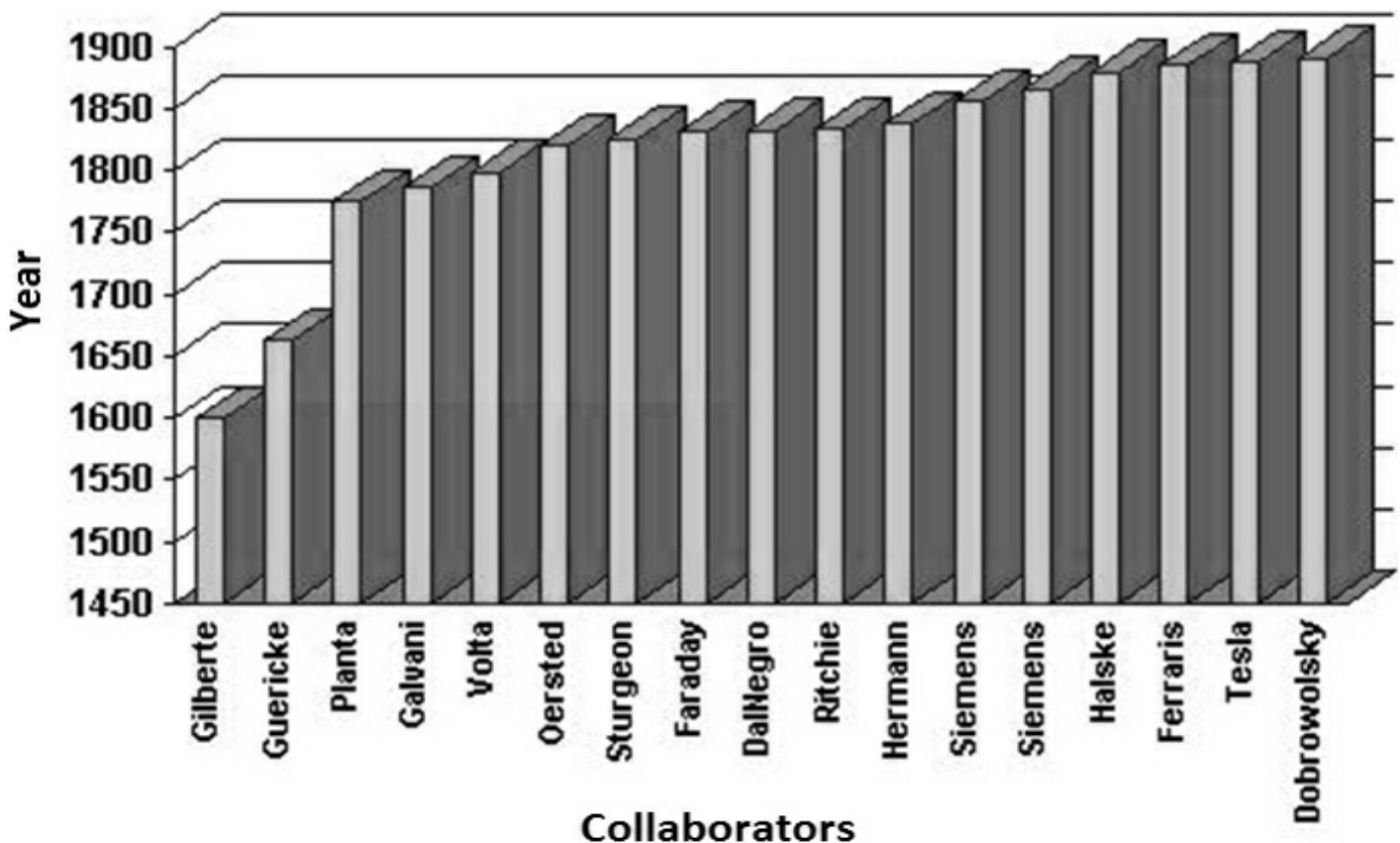


Figure 2. Contributions to the development of the electric motor.

Of the total installed electric motors, 25% are responsible for powering compressors, 22% for driving pumps, 16 % for fans and 2% for driving belts (Eletrobrás, 2003).

Since then, electric motors have been the object of innumerable improvements, its technology evolving along the years due to design modifications and new construction/manufacturing techniques.

Figure 3 presents the evolution of electric motors. One may see the reduction in mass, which the motor has been undergoing through the years.

This is credited to the development of new electrical dielectrics, materials with better magnetic properties and more efficient cooling systems (Eletrobrás, 2003).

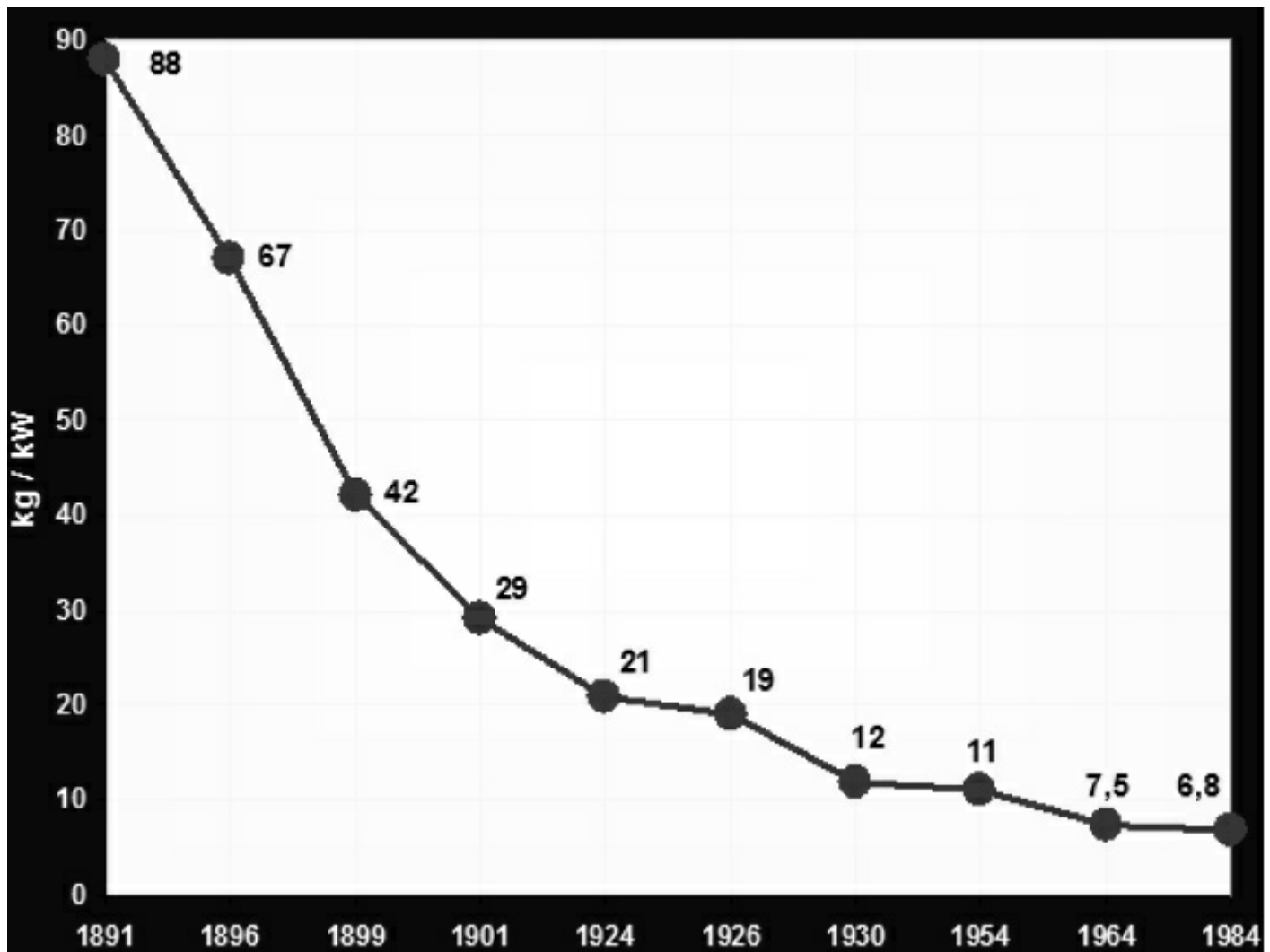


Figure 3. Evolution of electric motors.

The induction asynchronous motors can be ringed or caged. The ringed motor is made up of rotor coils with their terminals connected to rings fixed to the axis, electrically isolated from each other, and connected by a three-phase resistor that has a rotating cursor. The resistors are used only for starting motor operation, and the higher its value, the higher the starting torque for that given motor.

The squirrel-cage induction motor is the most widely used in industries nowadays.

The working of an induction motor is based on the principle of formation of a rotating magnetic field, produced in the stator due to electric current lead in its windings, the flow of which moves around the rotor due to the flux variation effect, generating induced currents on them which tend to oppose the rotating field and yet are dragged by it. If the motor is unloaded, the rotor develops an angular speed close to that of the rotating field, and this speed reduces as mechanical load is applied to its axis (Fitzgerald et al, 1991).

Since the electric motor is an energy converter that is based on magnetic principles, it is not possible for this conversion to be perfect, due to a series of losses which occur in the

interior of the machine. These losses are presented in Figure 4.

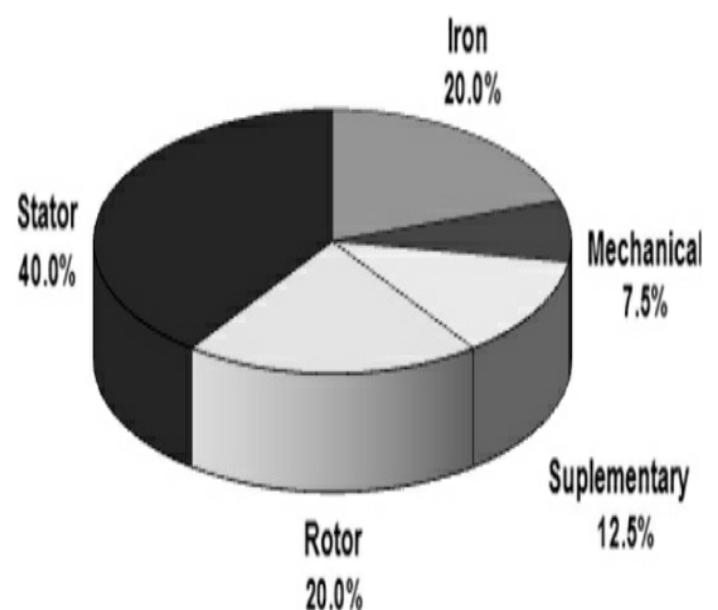


Figure 4. Main losses in an induction electric motor.

Losses in iron occur because the applied voltage is alternating, and the currents flowing in the stator windings generate a variable magnetic field in the ferromagnetic core, resulting in two types of losses: Eddy current losses and Hysteresis losses.

Eddy current losses occur due to induced currents in the interior of the magnetic material, generating losses as heat.

These losses can be determined by the Equation 1:

$$P_{FC} = K_{FC} \cdot f^2 \cdot B_M^2 \cdot e \cdot V \quad (1)$$

Where:

P_{FC} = Foucault losses [kW].

K_{FC} = coefficient that depends on properties of the material.

B_M = maximum core induction [Wb/m²].

f = voltage frequency [Hz].

e = thickness of the magnetic plate in the core [mm].

V = volume of the magnetic core [m³].

Hysteresis losses result from the alternating orientation of the magnetic field over the silicon steel laminated package.

These can be determined by the Equation 2:

$$P_H = K_H \cdot f \cdot B_M^n \cdot V \quad (2)$$

Where:

P_H = hysteresis losses [kW].

K_H = coefficient that depends the properties of the material.

B_M = maximum core induction [Wb/m²].

f = voltage frequency [Hz].

n = exponent to determine hysteresis losses.

V = volume of the magnetic core [m³].

Hysteresis and Eddy current losses occur in the stator as well as in the rotor.

Hence, the iron losses can be determined according to the Equation 3:

$$P_{FE} = P_{FC} + P_H \quad (3)$$

Where:

P_{FE} = iron losses [kW].

P_{FC} = Foucault losses [kW].

P_H = hysteresis losses [kW].

Mechanical losses in induction motors are related to friction in bearings, aerodynamic drag caused by the fan and irregular geometry of the rotor (Temiz et al, 2006).

Stray load losses can be divided into two groups: stray load losses in windings and in the iron core. In coils, losses occur mainly due to the skin effect, and can increase depending on the layout of the conductors in the grooves. In the iron core, stray load losses occur especially due to the air gap region, where the stator and rotor grooves generate high-frequency magnetic fields which cause further losses.

Joule losses in stator and rotor coils result from the flow of electric current and vary with the square of the r.m.s. current, being accountable for almost 60% of total losses. The service life of an electric motor depends on the heating of coils in the windings, and if this heating goes beyond standardized limits, it will accelerate the wear of the insulation, up to the point where insulation no longer withstands rated voltage and motor short-circuit ensues (Brown, 1927).

OPERATING CONDITIONS

Losses in an electric motor can be represented by the difference between input power and power actually converted into work.

Heat dissipates in a motor from its frame to the environment. In the case of enclosed motors, this dissipation is made by a fan connected to the motor axis. However, for good ventilation to be performed, the motor must have a good ventilation project, so as to be able to move a great deal of air and thus efficiently exchanging heat from its surface to the environment (Ramos et al, 2002).

An efficient cooling system is the one which can dissipate a larger amount of heat for a smaller dissipation area.

Figure 5 displays the percentage of power reduction in an electric motor as a function of the local environment temperature.

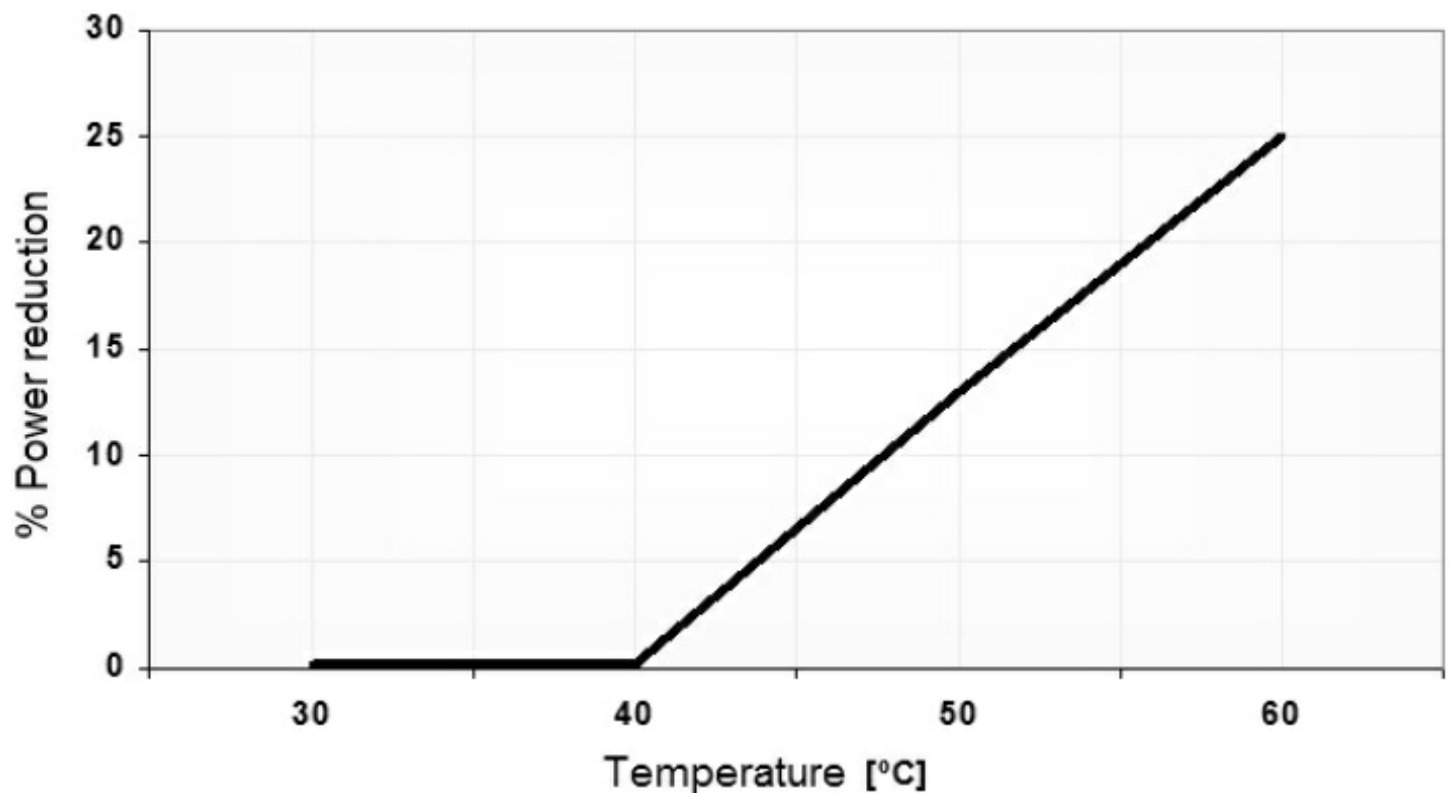


Figure 5. Percentage of power reduction as a function of the local environment temperature.

The life cycle of an electric motor depends on the insulation conditions, and this factor is extremely affected by temperature, moisture and corrosion. Some studies show that an increase of 8 to 10 degrees above the maximum allowed temperature is enough to cut the lifetime of a given electric motor in half.

In terms of permanent temperature regime, insulation of electric motors undergo a process known as fading, which is the gradual aging and a consequent drying of the material, so as to lose its insulating properties up to the point that it does not stand the applied voltage anymore, eventually giving rise to a short-circuit and subsequent motor damage (Guilbert, 1934).

The verification of an electric motor winding temperature can be done by the use of thermocouples. However, it is uncertain if the place to be chosen for measurement ought to be near the area of the motor which usually undergoes most intense heating or not. There are several more accurate methodologies to measure the temperature of electric motors, deployed only for the purpose of motor testing, where one can determine winding temperature by measuring its electric resistance, before and after it works (Gray, 1989).

HIGH EFFICIENCY MOTOR

The high-efficiency motor, also called premium, has as its main feature being an improved energy conversion equipment, as compared to standard motors, especially in areas where most losses are concentrated.

In the Brazilian market, these motors are on average 10% to 30% more expensive than the standard ones, a point that needs to be considered in feasibility studies for technology substitution. Some studies show that, when compared to standard motors, premium motors can present superior efficiency, from about 2% to 6%. This increase is due to a lower amount of losses for the same mechanical power (NEMA, 1998).

To obtain a higher efficiency, energy efficient motor design should include in its guidelines:

- Increased amount of copper in stator windings, in order to reduce Joule losses.
- Oversized rotor bars, thus reducing Joule losses.
- For improving thermic dissipation and cooling, rotor bars are to be accordingly reshaped.
- Reducing the magnetic flow density, by means of deploying larger volumes of magnetic materials.
- Use of good quality magnetic plates, to decrease iron losses and minimize magnetizing currents.
- Use of appropriate bearings.
- Optimized design for the cooling fan, to decrease friction and losses.
- Narrower air gap, in order to reduce stray load losses.
- Improved insulation.
- Improved thermic treatment.
-

As advantages, one can name extended service life, better performance under intermittent operation, larger power reserve and lower maintenance costs.

The decision on choosing between more expensive motors with lower operating costs and cheaper motors with higher energy consumption can be backed by a financial criterion of capital returns. This criterion uses the number of hours the motor should run per year as its main parameter.

However, it must be stressed that any advantage in purchasing a high-efficiency motor is lost if it is coupled to an inefficient equipment or is oversized for a given usage - thus raising energy consumption -, which happens to be a common situation, either on purpose or by misknowledge, usually under the allegation that excess rated power could increase drive reliability (Tupiassú et al, 2002). But an oversized induction motor presents low power factor and efficiency, varying with applied loads. Among several reasons for running an oversized and underloaded motor, one may name lack of knowledge on methods of characteristics and operation point assessment, expectation of an increase in load, lack of knowledge about motor service factor, substitution of damaged motors by others of higher rated power, unavailability of motors rated at the same power, and reduced production levels (Cathey, 2001).

SIMULATION PROGRAM

In this study, a Simulation Program developed by the Centre of Research in Electric Energy of Eletrobrás, with a data bank with characteristics of more than 2,000 motors was used,

including 220V, 380V and 440V rated voltages and rated powers ranging from 0.25hp up to 500hp. For each motor, this program provides technical data, price and manufacturer warranty.

By means of comparison, one can verify the cost-benefit ratio between two motors, for instance, a new motor and a motor in use or assigned for maintenance. The program also allows comparisons between new motors, e.g., one standard motor and a high-efficiency one, of equal or different power ratings.

Invested capital is a function of the difference between purchase prices. For the motor in use, the cost is the price of the new motor, and for the motor to be repaired, the cost is the difference between this and the repair cost.

As a benefit, there is the reduction in electric energy costs, to be calculated accounting for an average electric energy tariff and a running period under constant load. Using data on electrical current intensity, speed or electric power, the motor load condition is estimated. This is of great help for motor resizing analyses. For motors assigned to serve for an extended lifetime, the program has option for calculation of efficiency loss, as a function of the quality of rewinding and maintenance services. Figure 6 presents the main simulator screen (BD Motor, 2003).



Figure 6. Main simulator screen.

The methodology used for replacing squirrel-cage induction motors includes an initial assessment through measurements of electrical parameters of the analyzed motor with the help of power quality analyzers. This equipment provides data on voltages, electrical currents, real powers, power factors and harmonics.

By inputting measured true power to the Simulation Program, operating condition of the motor is obtained and mechanical power required by the machine and its respective load is calculated. Motors with loads over 75% of their nominal values are considered as a good fit by the Simulation Program. In this situation, a high-efficiency motor with same power rating is selected.

For motors loads under this figure, the motor resizing procedure is applied, in order to ensure that it will develop enough torque to drive the machine up to its working speed in a time shorter than the locked rotor time. When motor resizing is needed, the following steps are followed to calculate acceleration time:

Original motor:

- a) Nominal torque calculation.
- b) Load torque assessment.
- c) Average accelerating torque calculation.
- d) Total inertia momentum calculation.
- e) Calculation of the moment of inertia of the machine.

Proposed motor:

- a) Nominal torque calculation.
- b) Average accelerating torque calculation.
- c) Total moment of inertia calculus.

d) Acceleration time calculation.

Acceleration times should be shorter than the locked rotor time, or the motor is bound to be damaged before the load is accelerated to its required rotation speed (Lobosco et al, 1988).

CASE STUDY

The case study was carried out under financial support of an energy efficiency program coordinated by the Brazilian Electricity Regulatory Agency, with financial resources provided by a fund fed with a fixed percentage of the net operational income of electric energy utilities (Law 9991, 2000).

The motor replacement carried out in this study summed up to 3,870hp, accruing 720MWh yearly savings. Two studies are to be presented next, the first on substitution of same power rating motors and the second on motor resizing.

This procedure was applied in drives where the standard motor load was above 75%.

In this case, substitution costs refer only to the purchase of a high-efficiency motor, as there was no need of adaptation by the use of standard sized motor frame.

Figure7 presents two identical drives with 100hp power rating motors, one standard and one a high-efficiency type.

These motors, both with 4 poles and 380V three-phase voltages, operate 8,000 hours/year driving centrifugal pumps in a water-cooling tower.

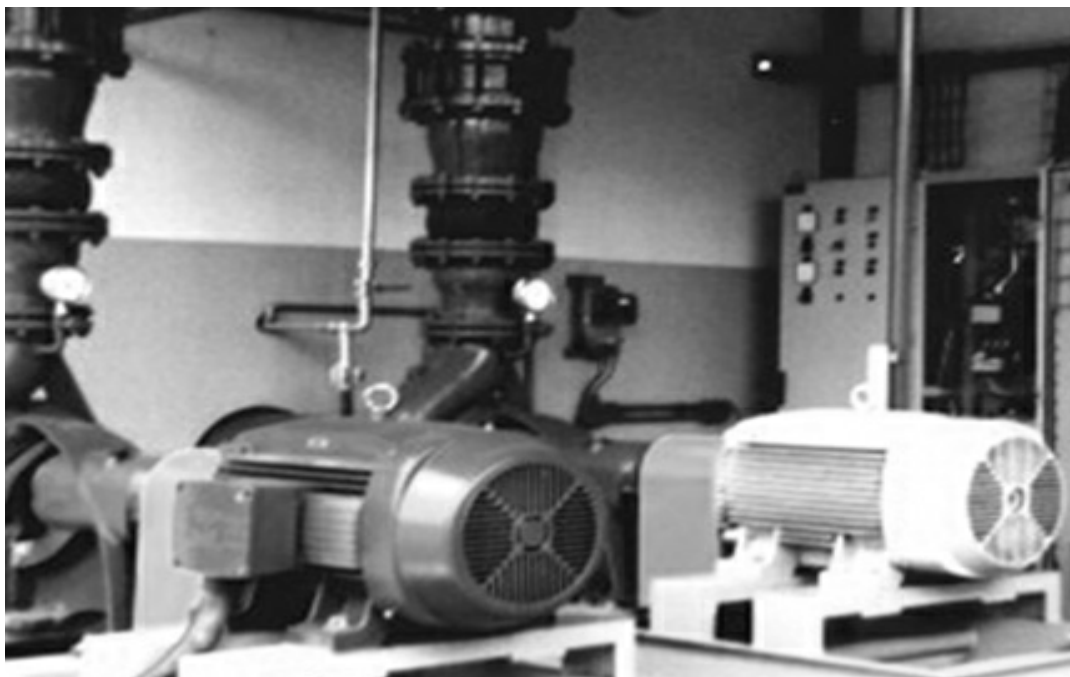


Figure 7. Identical drives with motors of rated power of 100 hp, high-efficiency and standard types.

Table 1 shows a comparison between the technical characteristics of each motor.

	Standard	High-Efficiency
Manufacturer	Weg	Weg
Size (hp)	100	100
Poles	4	4
Full Load Speed (rpm)	1775	1780
Voltage Rating (V)	380	380
Service Factor	1	1.15
Efficiency Full Load (%)	92.5	94.5
Amperage Full Load (A)	240	245
Power Factor Full Load	0.87	0.85
Torque Full Load (kgfm)	40.3	40.22
Weight (kg)	442	510

Table 1 - Technical characteristics

Figure 8 presents measurements taken in a standard motor (True power of 64 kW was obtained, with power factor of 0.85).

Summary Information		Voltage	Current
Frequency	59.81	RMS	378.5
Power		Peak	542.0
KW	64.02	DC Offset	-0.2
KVA	75.69	Crest	1.43
KVAR	-40.02	THD Rms	2.46
Peak KW	*	THD Fund	2.46
Phase	32° lag	HRMS	9.3
Total PF	0.85	KFactor	1.12
DPF	0.85		

Figure 8. Standard motor measurements.

The simulation program calculated an 80% loading for this drive. For a high-efficiency motor, the program calculated a 62.5kW true power.

Carrying out measurements in the high-efficiency motor, a 61.1kW 0.8 power factor reading was achieved, according to Figure 9.

Summary Information		Voltage	Current
Frequency	59.96	RMS	369.5
Power		Peak	519.3
KW	61.17	DC Offset	-0.4
KVA	76.72	Crest	1.41
KVAR	-46.10	THD Rms	2.05
Peak KW	*	THD Fund	2.06
Phase	37° lag	HRMS	7.6
Total PF	0.80	KFactor	1.08
DPF	0.80		

Figure 9. High-efficiency motor measurements.

Percentage deviation between predicted and measured figures in this case was 2%, showing the accuracy of this simulation program for energy efficiency calculations for motor systems.

In other simulations, deviations between predicted and actual figures ranged from 2% up to 7%, which are satisfactory figures if compared to the percentage deviations provided by the manufacturers: 2% for the power analyzer and 10% for the simulation program.

An 18-month return of investment period was estimated for those measurement results, accounting for the running period in hours and the average electrical energy cost. Motor resizing analysis was applied to drives where the load of the standard motor was under 75%.

In this case, substitution costs included, in addition to the high-efficiency motor cost, all machinery adaptations required

to fit different frame sizes. The second study was carried out on the exhaustor of a wood fed steam generating boiler operating 8,000 hours/year.

Table 2 shows a comparison between the technical characteristics of each motor.

	Standard	High-Efficiency
Manufacturer	Weg	Weg
Size (hp)	200	75
Poles	6	6
Full Load Speed (rpm)	1185	1180
Voltage Rating (V)	380	380
Service Factor	1	1.15
Efficiency Full Load (%)	93.1	93.6
Amperage Full Load (A)	500	188
Power Factor Full Load	0.83	0.82
Torque Full Load (kgfm)	121	45.5
Weight (kg)	987	453

Table 2 - Technical Characteristics (Motor resizing analysis).

The original fitted motor was a standard 200hp rated power, 6 poles, 380V, three-phase motor.

Measurements in the standard motor assessed a 62.5kW real power, and a 0.66 power factor.

Subsequently, the simulation program calculated a 37 % loading for this drive. In this case, it was necessary to replace it with a motor characterized by a lower power rating.

After installing a 75hp high-efficiency motor, it accelerated the load in 8 seconds, which is a satisfactory figure if compared to the 18-second locked rotor time provided by the manufacturer's brochure.

For this 75hp high-efficiency motor, the study assessed a 55.5kW real power and a 0.86 power factor. Calculated payback period for this substitution was 8 months.

Figure 10 shows the resized motor installed:

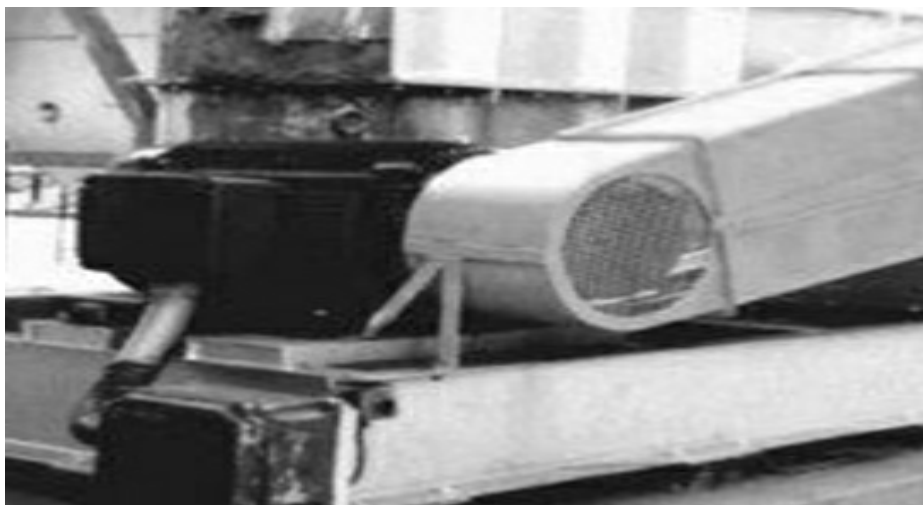


Figure 10. Resized 75 hp high-efficiency motor.

ECONOMIC ANALYSIS

Not only electric power consumption decreased after motor substitution, but it also lowered the required contractual demand. Measurements performed before and after motor replacements accounted for 720MWh yearly savings.

The capital investment for motor substitutions, including motor costs and freight fees, totaled US\$ 210,000.00.

Table 3 presents the results of an economic analysis for motor substitutions by a high efficiency model:

Installed Power (hp)	3870
Demand Reduction Benefit (US\$/Year)	36561
Energy Saving Benefit (US\$/Year)	55104
Revenue (US\$/Year)	91665
Capital Expenditure (US\$)	-210000
i (%)	10
Analysis Period (Years)	15
Net Present Value (US\$)	442925
Payback Period (Months)	27
Internal Rate of Return (%)	43

Table 3-Economic Analysis

The following photos illustrate the most significant electric motor replacements (standard motors replaced by high performance ones) carried out in the industrial food sector.

Figures 11 and 12 shows the cold water pump groups 1 and 2, before and after the replacement of electric motor substitutions:



Figure 11. Cold water pumps - Group 1

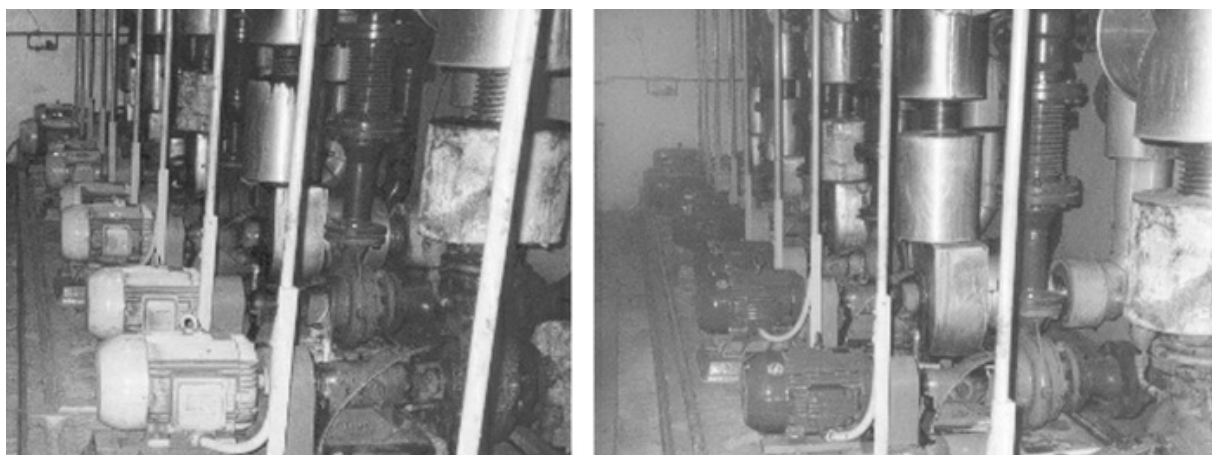


Figure 12. Cold water pumps - Group 2

CONCLUSIONS

Once the electric motor is an equipment of final use strongly present in industry, it is subject to replacement by more efficient technologies by carrying out energy efficiency studies. Energy Diagnosis in electric motors aims to provide the client with a decrease in electric energy costs, not only a decrease in demand, but also as a decrease in consumption.

Savings accruing from motor substitutions were in accordance to estimates calculated by the simulation program, which testifies for the accuracy of its predictions, as well as for its reliability for energy efficiency studies on drive systems.

Motor Resizing, for low load cases, allows for a rapid return of investment, even when accounting for mechanical adaptation costs. The motor power factor is improved and unnecessary expenditures on corrective capacitor installation are avoided.

Assuming a 15-year service life for an induction motor, the rapid return of investment made this project considerably attractive.

As an additional advantage, a significant reduction in maintenance costs was observed, due to a reduction in motor failure related machinery downtime. Moreover, the employees engaged in production and maintenance showed increased motivation, as they realized that the company was interested in investing in technological updating.

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