Application of Computer Simulation for the Assessment and Optimization of Induction Electric Motors Aiming to Energy Conservation

MÁRIO CESAR E. S. RAMOS[1], HÉDIO TATIZAWA[1], GERALDO F. BURANI[1], MÁRIO CESAR G. RAMOS[2]
[1]Institute of Electrotechnics and Energy
[2]Polytechnic School
University of São Paulo
1289 Luciano Gualberto Ave - São Paulo
BRAZIL
mcesr@uol.com.br http://www.iee.usp.br

Abstract: - This paper shows a methodology for the assessment and optimization of induction electric motors aiming to energy conservation, through substitution of older electric motors by high-efficiency ones, including motor resizing, aided by computer simulation. This study and its application were carried out through the Electric Energy Efficiency Program promoted by the Brazilian Electric Energy Agency. The methodology adopted for the substitution of these motors included an initial study, by means of measurements of electrical parameters, through the use of a power quality analyzer. Afterwards, by using a specific simulation software, the operating conditions of the electric motor and the expected economy obtained by 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 of 3.1 GWh, equivalent to 4.52% of the previously required energy.

Key-Words: - Electric energy conservation, power quality analyzer, high-efficiency motor, motor resizing, simulation software, payback period.

1 Introduction

In many ways, the electric power is present among us. Due to its ever growing and widespread availability and consumption, started in the previous century, new comfort and well-being patterns were made possible, making us highly dependent on this resource, thanks to the benefits made available, regardless of ones geographic situation or social level.

However, for electric energy production, financial investments are required many years before their return, and this capital is paid by the income from the sales of the generated energy. The options for electric energy 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 establish the power station.

Owning a installed capacity of 90 GW, Brazil needs not only to invest in generation and transmission, but also in conservation and electric energy efficiency programs, promoting economic growth, environment 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 used in Research and Development and Energy Efficiency Programs [1].

The main advantage of investing in energy efficiency programs is that this option is cheaper than to invest in the production of new energy.

Despite investing in energy efficiency technology also demands capital expenditures, however, the payback period is shorter than the time needed for generating more energy. This is because a company or utility produces the electrical power whereas and the consumer is responsible for the energy efficiency, both having different investment priorities and demanding different payback periods.

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 [2].

In general, one can also observe, in most industries, much waste of electrical energy, due to the use of inefficient processes and equipment concerning the electrical energy aspect, as an heritage of a market closed to competition but, in the present days, studies on substitutions, modifications and updates are necessary, aiming the companies to cut their internal costs and survive in an extremely competitive business scenario.

2 Electric Motor

The electric motor is an electromechanical converter based on electromagnetic principles, capable of transforming electrical energy in useful mechanical energy.
Since its origin, the electric motor has had countless improvements, evolving technologically through the years, due to design modifications, construction and manufacture.
Figure 1 presents the evolution of electric motors. We can 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 [3][4][5].

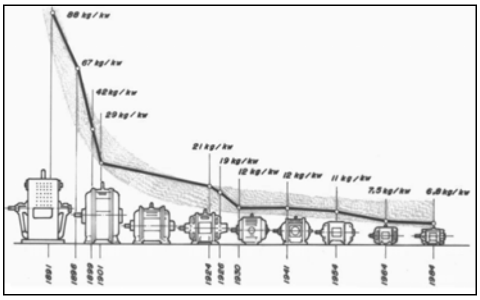

Fig. 1. Evolution of electric motors.

The squirrel-cage induction motor is the most widely used in industries nowadays.
Its rotor is formed by a set of interconnected bars through conductive rings, and its features are virtually constant with operating speed, varying slightly depending on the load applied to the axis.
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 2 [4].

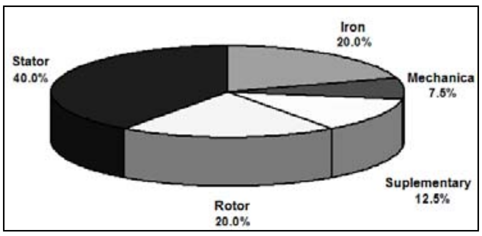

Fig. 2. Main losses in an induction electric motor.

Losses in iron occur because the applied voltage is alternating, and the currents that flow in the stator winding 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 in form of heat. Hysteresis losses result from the alternating orientation with the magnetic field over the silicon steel laminated package. Hysteresis and Eddy current losses occur in the stator as well as in the rotor.
Mechanical losses in induction motors are related to friction in bearings, aerodynamic drag caused by the fan and irregular geometry of the rotor [6].
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 skin effect, and can increase depending on the layout of the conductors in the grooves. In iron core, stray load losses occur especially due to the air gap region, where the stator and rotor grooves generate high-frequency magnetic fields, causing further losses.
Joule losses in stator and rotor coils result from the electric current flowing, varying with the square of r.m.s. current, and sum for almost 60% of total losses.
The service life of an electric motor depends on the heating of coils of windings, and if this heating is greater than the limits set by standards, it will accelerate the wear of the insulation, up to the point where it no longer withstands rated voltage, causing motor short-circuit to occur [4][6][7].

3 High Efficiency Motor

High-efficiency motor, also called premium or energy-efficient motors, has the main feature of being an equipment for energy conversion presenting improvements when compared to standard motors, specially in areas where most losses are concentrated [8].
In Brazilian market, these motors are on average 35% to 50% more expensive than the standard ones, a point that need to be considered in the feasibility study for the substitution of technologies [9].
Some studies show that, when compared to standard motors, the high-efficiency motor can present a superior efficiency, from about 2% to 6%, this increase due to a lower amount of losses for the same mechanical power [10].
To obtain a higher efficiency, the design of energy-efficient motors should consider:

- Increased amount of copper in stator windings, aiming at reduction of Joule losses.

- Oversized rotor bars, thus reducing Joule losses. For improving thermal dissipation and cooling, rotor bars are accordingly reshaped.
- Reduction of density of magnetic flow, through increasing of magnetic material volume.
- Use of good quality magnetic plates, to decrease iron losses and reduce magnetizing current.
- Use of proper bearings.
- Optimized design for the cooling fan, to decrease friction and losses.
- Smaller air gap region, reducing stray load losses.
- Improved insulation.
- Improved thermal treatment [11].

As advantages, one can name extended service life, better performance under intermittent operation, larger power reserve and lower maintenance costs.
The decision on choosing more expensive motors with lower operating costs or cheaper motors with higher energy consumption can be backed by a financial criterion of return of capital. This criterion considers the number of hours the motor should run per year as the main parameter.
However, it must be stressed the lack of any advantages in purchasing a high-efficiency motor, for coupling it to an inefficient equipment or making it work oversized, causing more energy consumption, a common situation, on purpose or by misknowledge, under the (false) allegation that in excess rated power could increase drive reliability.
But an oversized induction motor presents poor power factor and efficiency according to applied load, as shown in Figure 3 [12][13].

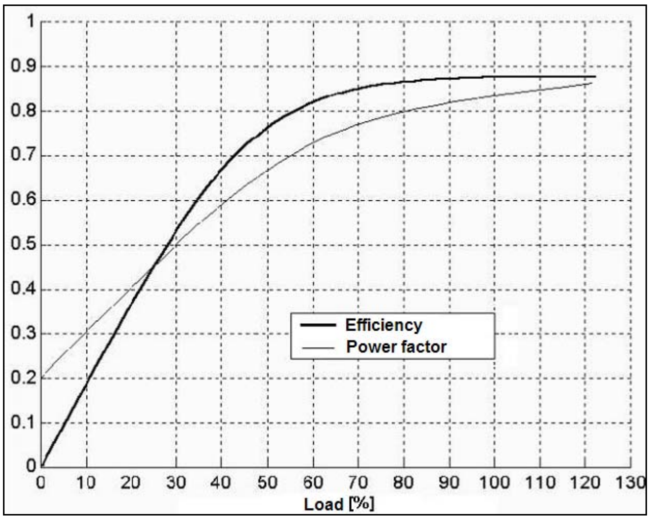

Fig. 3. Typical variations on efficiency and on power factor of induction motors.

Among several reasons for running a oversized and underloaded motor, we can name lack of knowledge for methods of determining its characteristics or operation point, expectation of an increase in load, lack of knowledge of motor service factor, substitution of damaged motors by others of higher rated power, unavailability of motors with same power, and reduction of production level.

4 Simulation Program

In this study a Simulation Program with a data bank with characteristics of 2,000 actual motors was used, considering rated voltages of 220V, 380V and 440 V and rated power from 0.25 cv up to 250 cv. For each motor, the program provides technical data, price and manufacturer warranty.
Through comparison, one can verify the cost-benefit ratio between two motors, for instance, a new motor and a motor in use or to be repaired. The program also allows the comparison of two new motors, e.g., one standard motor and one high-efficiency motor, of equal or different power.
The capital to be invested refers to the difference between the two prices of purchase. For the motor in use, the cost is the price of the new motor, and for the motor to repair, the cost is the difference between the new motor and the repair cost.
As a benefit, there is the electric energy cost reduction, considering an average electric energy tariff and a running period under constant load.
Using information concerning the electrical current intensity, speed or electrical power, the motor load condition is estimated, a helpful data for studies of motor resizing.
For motors with long term of use, the program gives option of efficiency loss, as a function of quality of rewinding and maintenance services.

5 Methodology

This proposed methodology for replacing squirrel-cage induction motors includes an initial study, through measurements of electrical parameters of the motor under consideration, by using power quality analyzers. With this equipment, voltage, electrical current, real power, power factor and harmonics data are provided.
By applying the measured true power to the Simulation Program, the operating conditions of the motor is obtained, the mechanical power required by the machine and the respective load.
Motors with loads over 75% are considered well fitted by the Simulation Program. In this situation, a motor with same rated power is selected, but high-efficiency type.

ISSN: 1790-5117

ISBN: 978-960-474-064-2

For motors loaded under this figure, the motor resizing procedure is applied, to verify if it would have enough torque to drive the machine up to its working speed, in a time shorter than the locked rotor time.
Through the Simulation Program, it was possible to select, for the same mechanical drive, motors with lower rating, resulting in lower electrical power required and higher loading.
This way, several simulations were carried out, and after all motors replacement, new measurements were taken for comparison with the figures previously estimated.
For cases of motor resizing (30% of total) the following steps were used to obtain the acceleration time [14].

Motor originally installed:

- Calculation of nominal torque.
- Verification of torque required by the load.
- Calculation of the average accelerating torque.
- Calculation of the total inertia momentum.
- Calculation of the machine´s moment of inertia.

Proposed motor:

- Calculation of nominal torque.
- Calculation of the average accelerating torque.
- Calculation of the total moment of inertia.
- Calculation of acceleration time.

Acceleration times should be less than the locked rotor time, to accelerate the load without causing damage to the motor.

6 Case Study

The case study was carried out under financial support of a energy efficiency program, under coordination of the Brazilian Electricity Regulatory Agency, with financial resources provided by a fund that fixed percentage of the net operational income of electric energy utilities.
The motors replacement carried out in this study summed 17,000 cv substituted, resulting in an yearly savings of 3.1 GWh, and corresponding to 4.52 % of the energy previously required, with additionally, an expressive drop in maintenance costs due to a reduction of failure rates, and reduced downtime of the machinery. Moreover, the employees engaged in production and maintenance showed increased motivation, as they realized the company was interested in investing in technological update.

Subsequently, two studies are presented, the first through the substitution of motors of same rated power, and the second using motor resizing.

6.1 Motors of same rated power

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.
Study 1 presents two identical drives with motors of rated power of 100 cv, standard and high-efficiency motor types.
These motors, with 4 poles and 380 V three-phase voltage, operate 8,000 hours/year driving centrifugal pumps in a water-cooling tower.
Through measurements in the standard motor, a true power of 64 kW was obtained, with power factor of 0.85.
With the simulation program, a 80% load was obtained for this drive.
For a high-efficiency motor, the program showed a 62.5 kW true power.
Carrying out measurements in the high-efficiency motor, 61.1 kW was obtained, with power factor of 0.8.
The percental deviation between predicted and measured figures in this case was 2%, showing the usefulness of this simulation program in studies of energy efficiency in motor systems.
In other simulations, the obtained deviation between predicted and actual figures ranged from 2% up to 7%, considered satisfactory if compared to percental deviations provided by the manufacturers, 2% for the power analyzer and 10% for the simulation program.
Considering the measurement results, the running period in hours and average electrical energy cost, a period of 18 months was determined for the return of investment, according to Equation (1)[15]:

$$TRI = \frac{\log\left[\frac{(EA)}{(EA) - i(PR)}\right]}{\log(1+i)} \tag{1}$$

Where:
TRI: payback period (years).
EA: yearly savings of electrical energy, referring to reduction in consumption and power (US$).
PR: price of motors (US$).
i: yearly interest rate (%).

6.2 Motor resizing

This procedure 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, the necessary modifications for adaptation to the machinery, due to differences in frame sizes.
This study was carried out in an exhauster for a wood-burning boiler for steam generation, operating 8,000 hours/year.
The original fitted motor was a standard motor 200 cv rated power, 6 poles, triphasic 380 V.
Through measurements in the standard motor, real power was determined as 62.5 kW, and power factor 0.66.
Subsequently, with the simulation program, 37% was obtained as the load for this drive.
For this same load driven by a high-efficiency motor, 200 cv, the simulation program presented power figures of 59.5 kW.
With the installation of a 200 cv high-efficiency motor, measurements showed 58 kW for real power and 0.54 for power factor. The Time for Return of Investment for this substitution was 31 months.
In case the system was driven by a 100 cv high-efficiency motor, the simulation program presented a 59 kW real power.
After installing the 100 cv high-efficiency motor, measurements showed 55.8 kW for real power and 0.8 for power factor. The Time for Return of Investment for this substitution was 12 months.
Finally, a study was carried out to verify if a 75 cv high-efficiency motor could have enough torque to accelerate this load from rest to operating speed, in a time shorter than locked rotor time.
The 75 cv high-efficiency motor accelerated the load in 6 seconds, a satisfactory figure if compared to the locked rotor time provided by the manufacturer's brochure: 18 seconds.
This way, with a 75 cv high-efficiency motor, the study showed 55.5 kW as real power and 0.86 as power factor. Payback period for this substitution was 8 months.
Figure 4 presents the obtained results, where the rapid return of investment shows the advantages of motor resizing.

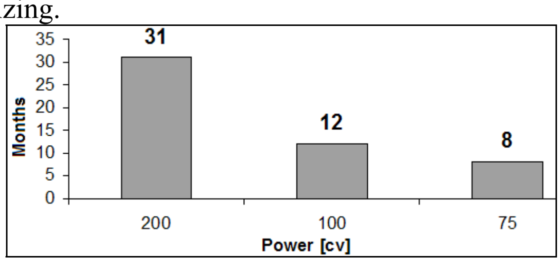

Fig. 4. Comparison of payback periods for different nominal powers.

7 Results

Not only has motor substitution provided a decrease in electric energy consumption, but it also resulted in a lower contractual demand.
Measurements performed before and after the motor substitutions showed a yearly saving of 3.1 GWh.
The capital investment for motor substitutions, including cost of motors and freight, summed a total of US$ 693,912.00.
Table 1 presents, for each manufacturing plant, the obtained results for energy demand reduction and energy saving.

Table 1- Demand reduction and energy saving

Manufacturing plant	Demand Reduction (kW)	Energy Saving (kWh/year)
1	99.19	781,403
2	127.32	735,048
3	35.20	283,293
4	37.88	294,910
5	10.45	76,339
6	32.27	208,381
7	55.50	420,808
8	46.11	331,204
TOTAL	**443.92**	**3,131,386**

Table 2 presents an economic analysis for the high-efficiency motor implementation.

Table 2 - Economic Analysis

Installed Power (cv)	16,889
Demand Reduction Benefit (US$/year)	105,262.00
Energy Saving Benefit (US$/year)	295,916.00
Revenue (US$/year)	401,178.00
CAPEX (US$)	- 693,912.00
i (%)	6
Analysis Period (years)	15
NPV (US$)	3,202,933.00
Payback period (months)	23
IRR (%)	58

8 Conclusions

The implementation of high-efficiency motors presented the following advantages:

- The savings provided by the substitutions agreed with the simulation program estimation, showing the accuracy of the predictions, allowing the use of this program in energy efficiency studies in drive systems.

- Motor Resizing, for low load cases, allows for a rapid return of investment, even considering the costs for adapting the motor to the machinery. The motor power factor is improved and unnecessary expenditures with correction by the installation of capacitors are eliminated.
- Assuming 15 years as the service life for the induction motor, the rapid return of investment turned this project considerably attractive [16].
- As additional advantage, a significant reduction in maintenance costs was observed, due to a reduction in machinery downtime caused by motor failure. Moreover, the employees engaged in production and maintenance showed increased motivation, as they realized the company was interested in investing in technological update.

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