Application of methodology for the adequacy of the electrical motor's power sizing: permanent and transient analysis

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Abstract

The suitability of the motive force contributes to the efficient use of electrical energy. On the other hand, the inadequate size of electric motors is directly connected to increased investment and running costs. This article presents the theory and mainly the application of a methodology for the adequacy of the motive power. The research was conducted at the Federal University of Viçosa dairy factory. This methodology consists in measuring motor rotation, acquiring technical information from the manufacturer's manual, and identifying the type of motor load. In addition, it uses the linearization method to estimate the resistance torque in steady state. This step is achieved without the need for using additional equipment or sending the motor to a laboratory for measuring the torque. In this sense, the studies can be made during the production process. Thus, this relevant methodology has the advantage of allowing the studies to be carried out at the agro-industry facilities. After getting all the information described above, it was possible to determine whether each motor at the factory was oversized. Then, the suitable motor was selected according to the load type. The application of the methodology described herein could provide around 50.6% savings in the monthly electricity costs at the dairy factory, and an attractive internal return rate.

keywords: Energy efficiency, load management, demand side management, induction motor.

1. Introduction

The electricity production in Brazil in 2009 grew only 0.6 % compared to 2008, and 76.7% of that production came from hydro-power. Considering that a portion of the electrical energy that Brazil uses is imported from Paraguay also comes from hydro-power, this value increases to about 87.0% (Brasil, 2010).

Although Brazil is currently the third largest hydro-power producer in the world, the occurrence of blackouts is still a possibility. The electricity rationing declared in June 2001 is an example that the Brazilian power systems are not without risks. On that occasion, the rainfall was much lower than that expected during the biennium 2000-2001. Delay in the investments in generation, transmission and distribution systems, especially the gap between economic growth and the demand for the expansion of the electrical system, as well as the possibility of prolonged drought may contribute to the occurrence of new blackouts. Despite the fact that there are 13 hydroelectric power plants of medium and large sizes, either budgeted or under construction along the next 5 years, several experts assert that the country is not free from the risk of a new rationing. Presently, several reservoir levels are low and the country's economic growth has led to an increasing concern with the reliability of energy supply. Moreover, the history of delays in construction schedules of dams does not guarantee the supply after the year 2014. Many of these delays are due to environmental hindrances (Vichi and Mansor, 2009).

According to the National Energy Balance (Brasil, 2013), despite an increase of 1835 megawatts (MW) in installed capacity of the hydropower park, the supply of hydraulic power decreased by 1.9% due to hydrological conditions, especially in the second half of 2012. The lowest water intake explains the decrease in the share of renewable energy matrix, 88.9% in 2011 to 84.5% in 2012.

For the second consecutive year due to unfavorable hydrological conditions observed over the period, there was a reduction in the supply of hydropower. In 2013 the decrease was 5.4%. The lowest water intake explains the decrease in the share of renewable energy matrix, 84.5% in 2012 to 79.3% this year, despite the increase of 1,724 MW in installed capacity of the hydropower park (Brasil, 2014).

The traditional energy planning strove to expand the energy supply, concerned only with aspects related to the availability, reliability and the optimal cost of distributed energy. However, this model leads to poor energy planning, compromising the environment and making the use of such energy inefficient.

In the past, there was a global trend to supply the load demand only with the expansion of the generation capacity. After the 1973 oil crisis, the energy planning began to consider the Demand Side Management (DSM) options due to the substantial increase in energy costs. Currently, energy planning is being integrated, and there are concerns on both the Supply Side Management (SSM) and the DSM. This new model has been called Integrated Resource Planning (IRP) (Teixeira *et al.,* 2005).

Electric motors are responsible for the highest electricity end use worldwide. Applications involving electric motors use around 24% of all the electricity consumed in the country (Haddad, 2006).

Oliveira Filho *et al.,* (2011) found a great technical and economical potential for the electricity load management in irrigation, considering the following options: (i) use of energy-efficient motors properly sized for the load application in each project, (ii) use of high efficiency motors, and (iii) optimization of the annual number of operating hours. Teixeira et al. (2005) conducted studies on the adequacy of the motive power in feed mills, with the potential to reduce the electrical energy expenses by 22.6% and 64.9% of the power demanded. Lopes (2002) developed a computer program in order to enable the realization of the adequacy of the motive power quickly and efficiently. According to the results, it was concluded that the program was able to satisfactorily determine the feasibility of the adequacy of the motive power. The following options for the motive power were considered: (i) standard motor in the current operating condition, (ii) high-performance motors with the same rate, (iii) standard motor properly sized, (iv) high-performance motors properly sized, and (v) relocation of existing motors in order to maximize the efficiency. However, these studies considered the appropriateness of the motive power only in the steady state conditions.

Bortoni and Santos (2006) split the methodology for the analysis of the characteristics of electric motors during their operation into two major groups: standard and empirical methods. The first method is more suitable for use in the laboratory, since special tools and test conditions are needed. The second group is more suitable for field work, as only a few variables can easily be measured, such as current, voltage and rotation. Other relevant information is usually available: nameplate and manufacturer's manuals. Therefore, with multimeter pliers and tachometer, it is possible to perform the motor loading analysis. To perform the adequacy of the motive power without stopping the plant production can be very advantageous from a practical and economical point of view.

The main objective of this research was to apply a methodology for the adequacy of the motive power in both transient and permanent regimes, through the loading analysis, estimated during full load operation.

2. Material and methods

This work was developed at the Energy Laboratories of the Agricultural Engineering Department (DEA) and the FUNARBE (Arthur Bernardes Foundation) dairy factory, both located on the Viçosa Federal University campus, Viçosa, MG, Brazil.

Four motors in the plant were chosen for the application of this methodology for the proposed adequacy of the motive power. For this, the speed was measured, and data from the plate, the application type, and each motor operating time data were gathered.

The adequacy of the motive power methodology follows the steps suggested in the algorithm described below:

1. Measure motor speed at full load;
2. Estimate the resistance torque in steady state by the linearization method;
3. Calculate the motor load factor;
4. If the motor is not oversized, check the next motor, starting at step 1. Otherwise, proceed to the next step;
5. Classify the load type by the resistance torque to verify that if the starting torque is relevant (constant load model or hyperbolic);
6. Select an H class (constant load) motor with less power than the current one, or with less than or equal power, with a lower starting torque, i. e., N category (linear or parabolic load), or lower power with high starting torque, i. e. category D (hyperbolic model).
7. Return to step 3.

Figure 1 flowchart represents the proposed adequacy of the motive power algorithm in a different manner. If the selected motor shows a load factor greater than 1, i. e., if the motor is undersized, go to step 5 and select a commercial power motor immediately higher in the later stages.

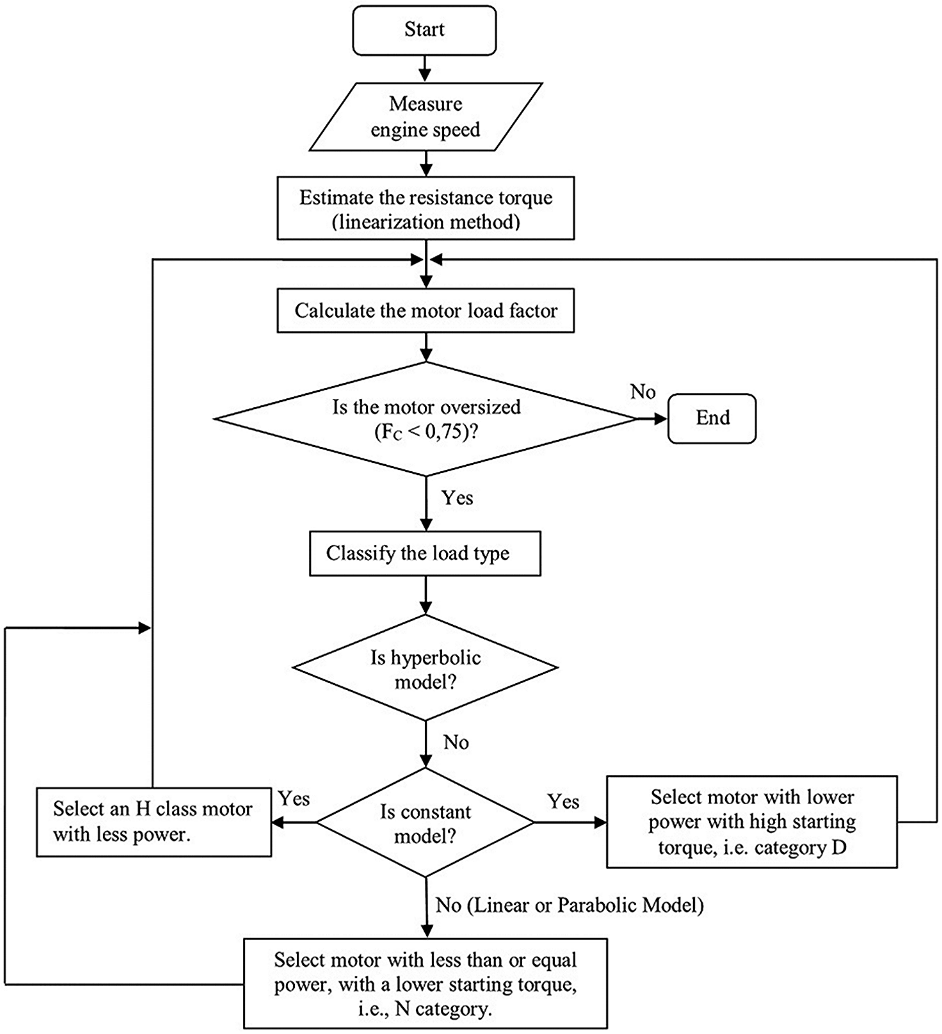

Figure 1
Flowchart of the algorithm
for the adequacy of the motive power.

2.1 Resistance torque in steady state

The linearization method was used on the resistance torque in steady state (torque) estimation due to its classification in the group of empirical methods, specifically for its simplicity and reliability (Bortoni and Santos, 2006). This method is based on the torque versus rotation curve (supplied by the motor manufacturer) that can be approximated to a straight line in the motor operation region. From this approach, the motor torque can be obtained from Equation 1.

$$M_t = M_N \left(\frac{n_s - n_t}{n_s - n_N} \right) \tag{1}$$

Where: M_t = Torque, N.m;
M_N = Nominal torque, N.m;
n_S = Synchronized speed, rad s^{-1};
n_t = Present speed, rad s^{-1};
n_N = Nominal speed, rad s^{-1}.

2.2 Loading factor

After estimating the torque, the motor load factor was calculated by Equation 2.

$$F_C = \frac{M_t n_t}{P_N} \tag{2}$$

Where: F_C = Dimensionless loading factor;
P_N = Nominal power, W.

Regarding the motor size, the following situations were taken into consideration:

1. A well designed motor will have a load factor higher than 75% because it will be functioning at an elevated efficiency level.
2. If the load factor is less than 75%, the motor is considered to be oversized.

2.3 Types of load

The load starting torque analysis was made based on the load type. Basically, all types of load can be described according to Equation 3.

$$M_C = M_0 + k_C\,(n_N)^x \qquad (3)$$

Where: M_C = Load resistance torque, N.m;
M_0 = Load torque at zero rotation, N.m;
K_C = Load dependent constant, decimal;
n_N = Motor nominal speed, rpm;
x = Load dependent parameter that can take on values -1, 0, 1, 2 and 3.

The values of the parameter "x" in Equation 3 identify the type of load behavior as a function of the motor speed. Table 1 shows a summary of the resistance torque equations and the power consumed by the load (P_c) as a function of speed, illustrating the types of load for each type of model. The critical case in relation to the starting torque happens in hyperbolic model because the load torque is maximum for zero rotation (Haddad, 2006).

X	Type of model	Resistance torque	Power	Examples
-1	Hyperbolic	$M_C = M_0 + K_C (n_N)^{-1}$	$P_C = k_c$	Paper Winder, Cloth Winder, logs Peeler, Lathes, wire Winders.
0	Constant	$M_C = M_0 + k_C$	$P_C = M_0 n + K_C n$	Piston compressor; Hoist; Cranes; Piston pumps; Crushers; Continuous carriers.
1	Linear	$M_C = M_0 + k_C n_N$	$P_C = M_0 n + K_C n^2$	Calender with viscous friction (calender paper); Centrifuge; Vacuum pumps.
2	Quadratic or Parabolic	$M_C = M_0 + k_C (n_N)^2$	$P_C = M_0 n + K_C n^3$	Centrifugal pumps, fans, Centrifugal compressors, Centrifugal mixers.

Table 1
Model type of the resistance torque, the power consumed by the load as a function of speed, and examples of loads.

2.4 Motors category

The motor category reveals some transient behavior characteristics, such as torque, slip, and starting current.

Table 2 shows the relationship of these characteristics in regards to the motor category, as defined in the Brazilian standard NBR 7094 (Bortoni and Santos, 2006).

Category	Starting Torque	Starting Current	Slip	Use
N	Normal	Normal	Less than 3%	Normal Loads such as pumps, operating machines, fans, among others.
H	High	Normal	Between 3 and 5%	Loads using greater torque as sieves at the start: carriers, high inertia loads, crushers, among others.
D	High	Normal	More than 5%	Loads with periodic peaks, lifts and loads requiring higher starting torque and limited starting current.

Table 2
Categories of triphasic induction motors.

The torque curves as a function of speed for the different categories. In the proposed methodology, the following relation between the model of the load resistance torque and the category of the motors was adopted:

1. Linear model or parabolic: Category N (High Efficiency - HE);
2. Constant model: Category H;
3. Hyperbolic Model: Category D.

When the exchange of an oversized motor for a category N one is warranted, choice should be given preferably to a high-performance motor (HE), especially in situations where the motor runs for several hours a day. However, Ferreira *et al*. (2009) and Teixeira *et al*. (2005) points out that the exchange of a standard motor by a similar one with high performance may be economically feasible depending on the a series of parameters such as: energy rates, motor costs and number of hours of work per year.

3. Results and discussion

Table 3 contains the data from each motor obtained through the proposed methodology. On it, we can observe that according to the methodology adopted, only motor 1 is well designed; that is, it is the only one with a load factor greater than 75%. Since the loads for motors 3 and 4 are parabolic, high performance motors with lower power of the N category were selected with enough torque to overcome the load torque in steady state. In other words, starting torque was not a concern in this case. As for the motor 2, a motor with less power and of the H category was selected because for this kind of load; the starting torque must be taken under consideration for sizing the motor purposes.

Table 3
Average speed (nt); synchronous (n_s) and nominal speed (n_N); nominal power (P_N); estimates for torque work (M_t) and the load factor (F_C);and load type for each motor.

Motor	Speed (rad.s^{-1})			P_N (kW)	M_t (N.m)	F_C (%)	Types of load
	n_t	n_s	n_N				
1	184.00	188.50	183.78	4.4	22.91	95.51	Piston air compressor
2	183.00	188.50	179.07	11.0	35.92	59.59	Piston air compressor
3	369.70	376.99	352.91	1.1	0.95	31.71	Centrifugal pump
4	187.10	188.50	179.07	2.2	1.82	15.47	Centrifugal pump
Total				18.76			

Table 4 shows the monthly expenditure on electric power for each motor in dollars (US$). For this, it was taken as basis that 1 kWh of electricity costs US$ 0.18 (price paid by the large electricity consumers in Viçosa, MG, Brazil).

Table 4
Monthly electrical usage for each motor according to: efficiency (η), active electrical power (P_{el}) and operating time (T)

Motor	η (%)$^{(1)}$	P_{el} (kW)	T (h.day^{-1})	Expenses (U$.moth^{-1}) $^{(2)}$
1	85.60	5.16	10	278.58
2	85.60	12.90	5	348.22
3	70.20	1.57	24	203.82
4	61.9	3.57	24	462.29
Total		23.20		1292.91

(1) Data provided by the operating manuals. (2) US$ 1.00 = R$ 2.23 in May 01, 2014.

Table 5 shows the required motor replacements for the adequacy of the motive power at the dairy factory, considering both the load factor and the motor category.

Table 5
Motors substitutions to suit the motive power.

Motor	Speed (rad.s^{-1})			P_N (kW)	M_t(N.m)	F_C	Category
	$n_t^{(1)}$	n_s	n_N				
1	184.00	188.50	183.78	4.41	22.91	95.51	H
2	184.35	188.50	179.07	7.36	18.07	90.04	H
3	361.91	376.99	352.91	0.37	0.65	93.13	N (HE) $^{(2)}$
4	177.94	188.50	180.12	0.37	1.82	88.28	N (HE)
Total				12.50			

(1) Speed obtained from the torque curve in function of the rotation, supplied by the manufacturer.

Table 5 shows that the installed power decreased by 33.33 %, i. e. from 18.76 kW (Table 3) to 12.50 kW. In addition, the load factor reached satisfactory values for this new situation. Therefore, the motors should have a higher efficiency level (HE) and, above all, consume less energy, as shown in Table 6.

Table 6
Motors monthly power usage after the adequacy of the motive power.

Motor	η (%)	P_{el} (kW)	Expenses (US$.month^{-1})	Investment (US$)	Payback time (month)
1	85.6	5.16	278.58		
2	87.0	8.45	228.41	493.27	4.1
3	71.0	0.52	67.17	112.11	0.8
4	74.3	0.49	64.19	112.11	0.3
Total		14.62	638.35	717.49	1.1

Tables 4 and 6 show that the adequacy of the motive power allows a monthly electricity savings of US$ 653.68. Table 6 also contains a simple calculation of the return on the capital timetable, showing that the replacement of oversized motors affords enough energy savings to pay for the investment in just 33 days. And lastly, it is important to note that the adequacy of the motive power never replaces the process adequacy, since the process optimization, for the most part, has the greatest potential for energy savings. Therefore, it is concluded that the adequacy of the motive power can always be performed, even when the industrial process in question is unknown.

4. Conclusions

Based on the results obtained in this work, it can be concluded that the application of the methodology for the adequacy of the motive power, when incorporating the torque evaluation, can provide savings of 50.6% in monthly energy costs at the UFV dairy factory, with a payback period of around 33 days. This work can support efficiently and easily the adequacy of the electrical motor's power sizing in other areas.

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