INVESTMENT RECOVERY PERIOD IN ELECTRIC MOTOR OF HIGHER EFFICIENCY IN PUMPING FOR IRRIGATION

**JOÃO L. ZOCOLER[1], MAURÍCIO A. LEITE[2], JOÃO C. C. SAAD[3],
RAIMUNDO L. CRUZ[4], JOÃO G. ZOCOLER[5]**

ABSTRACT: In this study, it was adjusted a mathematical model to measure the effect of electric motor efficiency on pumping system costs for irrigation on the tariff structure of conventional electricity and green horo-seasonal , and also to calculate the recovery period of the invested capital in higher efficiency equipment. Then, it was applied to a center pivot irrigation system in two options of electric motor efficiency, 92,6% (standard line) and 94,3% (high efficiency line), and the acquisition cost of the first corresponded to 70% the of the second. The power of the electric motor was 100hp. The results showed that the model allowed us to evaluate if a high efficiency motor was economically viable compared to the standard motor in each tariff structure. The high efficiency motor was not viable in the two tariff structures. In the green horo-seasonal tariff, would only be viable if its efficiency was 4.46% higher than the standard motor. In the conventional tariff, it would only be viable if the efficiency overcame 2.71%.

KEYWORDS: conventional tariff, green horo-seasonal tariff, high efficiency.

PERÍODO DE RECUPERAÇÃO DO CAPITAL INVESTIDO EM MOTOR ELÉTRICO DE MELHOR RENDIMENTO NO BOMBEAMENTO PARA IRRIGAÇÃO

RESUMO: Neste trabalho, ajustou-se um modelo matemático para quantificar o efeito do rendimento do motor elétrico sobre os custos de um sistema de bombeamento para irrigação na estrutura tarifária de energia elétrica convencional e horo-sazonal verde, bem como calcular o tempo de recuperação do capital investido no equipamento de maior rendimento. Em seguida, o mesmo foi aplicado a um sistema de irrigação tipo pivô central em duas opções de rendimento do motor elétrico: 92,6% (linha padrão) e 94,3% (linha alto rendimento), sendo que o custo de aquisição do primeiro correspondeu a 70% do segundo. A potência do motor elétrico era de 100 cv. Os resultados mostraram que o modelo permitiu avaliar se um motor de alto rendimento era viável economicamente em relação ao motor-padrão em cada estrutura tarifária. Nas duas estruturas tarifárias, o motor de alto rendimento não foi viável. Na tarifa horo-sazonal verde, somente seria viável se seu rendimento fosse 4,46% superior ao do motor-padrão. Na tarifa convencional, somente seria viável se o ganho de rendimento superasse 2,71%.

PALAVRAS-CHAVE: tarifa convencional, tarifa horo-sazonal verde, alto rendimento.

---

[1] Engº Agrônomo, Prof. Adjunto, Departamento de Fitossanidade, Engenharia Rural e Solos, Faculdade de Engenharia de Ilha Solteira, FEIS/UNESP, Ilha Solteira - SP, Fone: (018) 3743-1143, zocoler@agr.feis.unesp.br
[2] Engº Agrônomo, Prof. Doutor, Departamento de Fitossanidade, Engenharia Rural e Solos, FEIS/UNESP, Ilha Solteira - SP, mauricio@agr.feis.unesp.br
[3] Engº Agrônomo, Prof. Adjunto, Departamento de Engenharia Rural, Faculdade de Ciências Agronômicas, FCA/UNESP, Botucatu - SP, joaosaad@fca.unesp.br
[4] Engº Agrônomo, Prof. Adjunto, Departamento de Engenharia Rural, FCA/UNESP, Botucatu - SP, cruz@fca.unesp.br
[5] Graduando em Engenharia Mecânica, FEIS/UNESP, Ilha Solteira - SP, jgzocoler@hotmail.com

INTRODUCTION

The amount of electricity demanded in the world in 2008, according to the IEA (2010), was 19,694 TWh, equivalent to 13.8% of the total global primary energy. In Brazil, the power currently installed is 113,986,520 kW, according to ANEEL (Electric Energy National Agency) (2011), however, it still imports from neighboring countries, especially Argentina and Paraguay, 6.69% of the electricity consumed.

In Brazil, the INEE (Energy Efficiency National Institute), quoted by LYRA (2005), estimates that the waste will reach 50% in some sectors, whether in procedures, facilities or equipment. The industrial sector, which accounts for 47% of electricity consumption in the country, is the main responsible for the waste. Of its total consumption, almost half refers to motors. Moreover, about 40% of consumption of sanitation companies (water and sewer) is wasted because of low efficiency of their machines and equipment.

Since 1996, Brazil manufactures electric motors with service factor greater than the unity, following the values prescribed in the standard. The technical literature about motor sizing for activation of hydraulic pumps indicates the need to adopt increases in engine power. Both the service factor as the increase in power are safety factors for the sizing, and they have the function of supplying higher power demand due to changes in working conditions, such as curves characteristic of the pump or motor, and power quality, such as oscillation and imbalance of signal voltage. OLIVEIRA FILHO et al. (2010), when evaluating 12 motors with power from 0.5 to 125 hp, concluded it should not be used an increase in power in the motor sizing with service factor greater than the unity, leading to overestimation from 44% to 88%.

RAMOS (2009) analyzed 86 cases of motor replacement of standard type for high efficiency motors in an industrial group in the food sector, and the motors had power from 7.5 to 125 hp, for a total of 3,870 hp. The replacement has generated annual savings of 720.32 MWh, and the time of the investment return was 27 months.

OLIVEIRA FILHO et al. (2004) found that the replacement of a standard electric motor (efficiency of 92.82%) with a high efficiency motor (efficiency of 95.79%), both with a 250 hp, loading of 80% and operating 2,800 h annual, would provide an annual saving of 2.77% (R$ 1,030.59) of electricity, with a time of investment return of 4 years and 4 months. However, the rate of consumption and demand of off-peak electricity considered in the assessment were R$ 0.4936 kWh^{-1} and R$ 5.949 kW^{-1}, respectively.

In Brazil there are three possible types of tariff for consumers: the conventional tariff, green horo-seasonal tariff (Green HST) and horo-seasonal blue tariff (Blue HST). The conventional tariff has only one price for energy and one for power. Horo-seasonal tariffs have four different energy prices depending on the time (on-peak or off-peak) and the time of year (wet or dry) of use. However, not all consumers may choose these three tariff modalities. Only consumers connected at medium voltage (voltages below 69 kV) and with contracted demand of less than 300 kW may choose the best, among the three, which depends on the load factor and the modulation factor of the consumer. Those treated at medium voltage and with contracted demand less than 300 kW may opt for one of the two horo-seasonal tariffs, while others must, necessarily, hire the Blue HST (FUGIMOTO, 2010).

Given the above, this paper adjusted a mathematical model to quantify the effect of the electric motor efficiency on the costs of a pumping system for irrigation in the tariff structure of conventional electricity and green horo-seasonal, as well as to calculate the recovery time of the invested capital in equipment for higher efficiency. Then, the model was applied to a pumping system in two options of electric motor efficiency. Finally, sensitivity analysis of the model was made in relation to the variation in motor efficiency, tariff prices and annual operation time of the system.

MATERIAL AND METHODS

The total annual cost of an elevating system may be obtained by the equation:

$$C_{ta} = C_{fa} + C_{va} \tag{1}$$

In which: C_{fa} - fixed annual cost of the system ($); C_{va} - variable annual cost of the system ($).

The fixed annual cost of the system may be obtained by the equation:

$$C_{fa} = A_a + R_a \tag{2}$$

In which: A_a - annual amortization of invested capital ($); R_a - annual remuneration of invested capital ($).

The annual amortization of invested capital corresponds to a fund that must be filed annually (adjusted for current tariff) to recover the invested capital in each equipment after its useful life. It may be calculated by the equation:

$$A_a = \sum_{i=1}^{I}\left[\frac{V_i\left(1+M_i\right)\left(1-R_i\right)r}{\left(1+r\right)^{Pa_i}-1} \right] \tag{3}$$

In which: V_i - initial value (new) of the i-th equipment ($); M_i - fraction of the initial value of the i-th equipment spent in its assembling system ($); R_i - fraction of the initial value of the i-th equipment after amortization period; r - annual interest rate; Pa_i - amortization or useful life period of the i-th equipment (years).

The annual remuneration of the invested capital, which means how much the entrepreneur would receive for his financial investment in another alternative, may be calculated by the equation:

$$R_a = \sum_{i=1}^{I}\left\{ \frac{V_i\left(1+M_i\right)\left[\left(1+r\right)^{Pa_i}-1\right]}{\left[\sum_{n=1}^{Pa_i}\left(1+r\right)^n\right]+1} \right\} \tag{4}$$

In which: n - polynomial exponential.

The variable annual cost of the system may be obtained by:

$$C_{va} = C_{amr} + C_{ap} \tag{5}$$

In which: C_{amr} - annual cost of maintenance and repairs ($); C_{ap} - annual cost of pumping ($).

Repairs and maintenance correspond to the annual cost required to maintain the capital asset in working condition. In practice, it is customary to calculate the annual maintenance costs as a mean percentage fraction of the purchase price of the equipment considered, i.e.:

$$C_{amr} = f_i\, V_i \tag{6}$$

In which: f_i - fraction of the initial value of the i-th equipment spent annually on maintenance and repairs.

The annual cost of pumping is obtained by the equation:

$$C_{ap} = F_d + F_c + A_j \tag{7}$$

In which: F_d – annual income of demand ($); F_c - annual income of consumption ($); A_j - annual adjustment referring to the power factor ($).

If planned the purchase of a capacitor banks to correct the power factor to the minimum value required by the distribution utility of electricity, for this tariff exemption, eq.(7) shall consist only of the demand and consumption income.

The annual cost of pumping of the system depends on the tariff structure that it fits on the electric utility, i.e., the conventional or horo-seasonal (green and blue) tariffs. The equation adapted from F_d and F_c, developed based on eq.(7) in the green horo-seasonal tariff structure, is presented below. In this tariff, it is considered that the motor and electrical equipment are exclusive to activate the hydraulic pump.

Green horo-seasonal tariff

The horo-seasonal tariff (blue or green, if there is a choice of the consumer) is compulsorily applied to consumer units from A Group served in voltages lower than 69 kV and with power demand equal or higher than 300 kW. It is also optionally applied to consumer units of A Group served at voltages lower than 69 kV and with power demand between 30 and 300kW. The tariff structure is as follows: 1) Demand (kW): a single price, 2) Consumption (kWh): 2a) A price for the on-peak hours in wet period; 2b) A price for the off-peak hours in wet period; 2c) A price for on-peak hours in the dry period; 2d) a price for off-peak hours in the dry period. The on-peak period corresponds to three consecutive hours (defined by the distribution utility) between 5pm and 10pm from Monday to Friday, while the off-peak period corresponds to the hours that complement the on-peak period, plus the total of hours on Saturdays and Sundays. In regions that produce hydroelectricity, the dry period is composed of seven consecutive months from May to November, while the wet period consists of five consecutive months from December to April.

Considering that the demand contracted with the distribution utility of electricity is not less than 10% of demand measured (A4 Subgroup), which gives the user the non-charging for the demand excess, then the annual income of demand for Class IV (rural) is obtained by the equation:

$$F_d = \sum_{z=1}^{12} Dm_z \, Tgd + 0.10 \, d \, Dc \, Tgd \tag{8}$$

In which: Dm_z - demand (kW) measured in the z-th measurement cycle (period between two consecutive readings, at intervals of approximately 30 days, subject to a minimum of 27 and maximum of 33 days, with a total of 12 cycles in one year contract with the Distribution Utility of Electricity) of the year; Tgd - green demand tariff ($ kW^{-1}); d - number of complete cycles per year that the elevating system is off, and, therewith, the demand income occurs corresponding to 10% of the demand contracted, Dc - power demand (kW) contracted with the electric utility. NOTE: Every 12 months, from the date of contract signing, it should be verified, by time segment, the measured demand not lower than the demand contracted in at least 3 full cycles of income, or, otherwise, the licensee may charge in addition, in the invoice for the 12th cycle, the positive differences between the three higher contracted demands and their measured demands, in accordance with Resolution 90/2001 (ANEEL, 2001). Thus: $0 \leq d \leq 9$.

Demand measured in the z-th year cycle (kW) is obtained from equation:

$$Dm_z = \sum_{y=1}^{Y} \frac{Q_y \, H_y \, \gamma}{1000 \, \eta_{Py} \, \eta_{EMy}} \tag{9}$$

In which: Q_y - flow of the y-th hydraulic pump in the z-th cycle of the year (m^3 s^{-1}); H_y - manometric height of y-th pump in z-th cycle of the year (m); γ - specific weight of water, considering 9,800N m^{-3}; η_{Py} - efficiency of y-th pump in z-th cycle of the year; η_{EMy} - efficiency of y-th electric motor in the z-th cycle of the year.

Annual income of consumption to Class IV (rural - irrigant) is obtained by the equation:

$$F_c = Cm_{wp}\,Tgc_{wp} + Cm_{wofp}\,Tgc_{wofp} + Cm_{wst}\,(1-dfgt)Tgc_{wofp} +$$
$$Cm_{dp}\,Tgc_{dp} + Cm_{dofp}\,Tgc_{dofp} + Cm_{dst}\,(1-dfgt)Tgc_{dofp} \qquad (10)$$

In which: Cm_{wp} - annual consumption measured (kWh) in the wet period during on-peak hours; Tgc_{wp} - green consumption tariff in the wet season and during on-peak hours ($ kWh^{-1}); Cm_{wofp} - annual consumption measured (kWh) in wet period during off-peak hours; Tgc_{wofp} - green consumption tariff in wet period during off-peak hours ($ kWh^{-1}); Cm_{wst} - annual consumption measured (kWh) in wet period during special time for irrigation (from 9:30pm to 6:00am of the following day); dfgt - discount factor on the green tariff during off-peak hours; Cm_{dp} - annual consumption measured (kWh) in dry period during on-peak hours; Tgc_{dp} - green consumption tariff in dry period during on-peak hours ($ kWh^{-1}); Cm_{dofp} - annual consumption measured (kWh) in dry period during off-peak hours; Tgc_{dofp} – green consumption tariff in dry period during off-peak hours ($ kWh^{-1}); Cm_{dst} - annual consumption measured (kWh) in dry period during special time for irrigation (from 9:30pm to 6:00am the following day).

The annual consumption measured in each horo-seasonal segment (wet period during on-peak hours; wet period during off-peak hours; dry period during on-peak hours; and dry period during off-peak hours) is obtained by:

$$Cm_{hss} = Dm_{hss}\,t_{hss} \qquad (11)$$

In which: Dm_{hss} - demand measured in the horo-seasonal segment (kW); t_{hss} - operating time of the elevating system in the horo-seasonal segment (h).

Once the tariff modality for electricity is green horo-seasonal, the user should not operate the pumping system during on-peak hours, either in the dry or wet periods, because every advantage in income compared to conventional modality can be lost or even get worse. Given this assertion, the equation (10) may be simplified:

$$F_c = Cm_{wofp}\,Tgc_{wofp} + Cm_{wst}\,(1-dfgt)Tgc_{wofp} + Cm_{dofp}\,Tgc_{dofp} + Cm_{dst}\,(1-dfgt)Tgc_{dofp} \qquad (12)$$

When selecting an electric motor, we are looking for a model that provides the lowest cost. Thus, the variation in the total annual cost of pumping system for consumers of A4 Subgroup (rural – irrigant), faced with two options of income and with acquisition cost of the electric motor, may be calculated by the equation:

$$\Delta C_{ta} = \frac{V_{m_2}\left(1+M_{m_2}\right)\left(1-R_{m_2}\right)r}{\left(1+r\right)^{Pa_{m_2}}-1} - \frac{V_{m_1}\left(1+M_{m_1}\right)\left(1-R_{m_1}\right)r}{\left(1+r\right)^{Pa_{m_1}}-1} +$$

$$\frac{V_{m_2}\left(1+M_{m_2}\right)\left[\left(1+r\right)^{Pa_{m_2}}-1\right]}{\left[\sum_n^{Pa_{m_2}}\left(1+r\right)^n\right]+1} - \frac{V_{m_1}\left(1+M_{m_1}\right)\left[\left(1+r\right)^{Pa_{m_1}}-1\right]}{\left[\sum_n^{Pa_{m_1}}\left(1+r\right)^n\right]+1} +$$

$$f_{m_2}\,V_{m_2} - f_{m_1}\,V_{m_1} + \left(\frac{1}{\eta_{m_2}} - \frac{1}{\eta_{m_1}}\right)\frac{Q\,H\,\gamma}{1000\,\eta_b}\cdot\begin{bmatrix}Tgd\left(12-0.9\,d\right)+\\ Tgc_{wofp}\left[t_{wofp}+t_{wst}\left(1-dfgt\right)\right]+\\ Tgc_{dofp}\left[t_{dofp}+t_{wst}\left(1-dfgt\right)\right]\end{bmatrix} \qquad (13)$$

As for the electric motor 1 and 2, respectively: V_{m1} and V_{m2} - initial value of the motor ($); M_{m1} and M_{m2} - fraction of the initial value of the motor spent in its assembling in the system ($); R_{m1} and R_{m2} - fraction of initial value of the motor after the amortization period; Pa_{m1} and Pa_{m2} - amortization period of the motor (years); f_{m1} and f_{m2} - fraction of the initial value of the motor spent annually on maintenance and repairs; η_{m1} and η_{m2} - motor efficiency.

As can be seen in eq.(13), the first four terms calculate the difference between the fixed annual costs among the motors. The fifth and sixth terms calculate the difference in the annual cost of their maintenance and repairs; and the seventh term calculate the difference in the annual cost of pumping that they cause due to income levels. It is expected that, as $\eta_{m1} < \eta_{m2}$ and $V_{m1} < V_{m2}$, the effect of the seventh term is greater than the sum of the others, and if its signal is negative, the ΔC_{ta} will be negative. If not, it means that the efficiency gain of motor 2 is insufficient to compensate for its increase in fixed and maintenance and repairs costs. It is noteworthy that the difference in efficiency between the motors treated here is not enough to change the nominal power of the motor and of other electrical equipment of the system (start command, transformer, capacitor bank, and others), not affecting, consequently, its fixed, maintenance and repairs costs in the equation. Otherwise, the fixed and maintenance and repairs costs should be incorporated in the equations.

Finally, the recovery period (P_r - in years) of the invested capital in the acquisition of a model of high efficiency motor ($\eta_{m1} < \eta_{m2}$ and $V_{m1} < V_{m2}$) may be calculated by the equation, which is valid only if ΔC_{ta} is negative, as already explained above:

$$\Pr_m = \frac{V_{m_2} - V_{m_1}}{\left|\Delta C_{ta}\right|} \tag{14}$$

Conventional tariff

It is applied to consumer units from A Group served in voltages lower than 69 kV and power demand lower than 300 kW. The tariff structure is as follows: 1) Demand (kW): a single price, 2) Consumption (kWh): a single price.

Considering that the contracted demand with the distribution utility of electricity is not less than 10% of demand measured (A4 Subgroup), which gives the user the non-charging for the excess demand, then the annual income of demand is obtained by the equation:

$$F_d = 12\, Dc\, Tcd \tag{15}$$

In which: Tcd - conventional demand tariff ($ kW^{-1}).

The annual income of demand for the Class IV (rural) is obtained by the equation:

$$F_d = \sum_{m=1}^{12} Dm_z\, Tcd + 0.10\, d\, Dc\, Tcd \tag{16}$$

The annual income of consumption is obtained by the equation:

$$F_c = Cm\, Tcc \tag{17}$$

In which: Cm - annual consumption measured (kWh); Tcc - conventional consumption tariff ($ kWh^{-1}).

The annual consumption measured is obtained by:

$$Cm = Dm\, t \tag{18}$$

In which: t - operating time of the elevating system during the year (h).

The annual income of consumption to the Class IV (rural - irrigant) is obtained by the equation:

$$F_c = Cm\, Tcc + Cm_{st}\left(1 - dfgt\right)Tcc \tag{19}$$

In which: dfgt - discount factor on the conventional consumption tariff; Cm_{st} - annual consumption measured (kWh) during special time for irrigation (from 9:30pm to 6:00am of the following day).

Thus, the variation in the total annual cost of the pumping system for consumers from A4 Subgroup (rural irrigant), faced with two options of income and acquisition cost of the electric motor may be calculated by the equation:

$$
\begin{aligned}
\Delta C_{ta} = {} & \frac{V_{m_2}\left(1+M_{m_2}\right)\left(1-R_{m_2}\right)r}{(1+r)^{Pa_{m_2}}-1} - \frac{V_{m_1}\left(1+M_{m_1}\right)\left(1-R_{m_1}\right)r}{(1+r)^{Pa_{m_1}}-1} + \\[2mm]
& \frac{V_{m_2}\left(1+M_{m_2}\right)\left[(1+r)^{Pa_{m_2}}-1\right]}{\left[\sum_{n}^{Pa_{m_2}}(1+r)^{n}\right]+1} - \frac{V_{m_1}\left(1+M_{m_1}\right)\left[(1+r)^{Pa_{m_1}}-1\right]}{\left[\sum_{n}^{Pa_{m_1}}(1+r)^{n}\right]+1} + \\[2mm]
& f_{m_2}\,V_{m_2} - f_{m_1}\,V_{m_1} + \left(\frac{1}{\eta_{m_2}}-\frac{1}{\eta_{m_1}}\right)\frac{Q\,H\,\gamma}{1000\,\eta_b}.\left\{Tcd\left(12-0.9\,d\right)+Tcc\left[t+t_{st}\left(1-dfgt\right)\right]\right\}
\end{aligned}
\qquad (20)
$$

Finally, the recovery period (P_r - in years) of the invested capital in the acquisition of a model of high efficiency motor ($\eta_{m1} < \eta_{m2}$ e $V_{m1} < V_{m2}$) may be calculated by eq.(14), already discussed.

The use of the manual mode model, while fully possible, is time consuming due to the large number of data required. Therefore, and in order to speed up the calculations, it was developed an electronic spreadsheet in which eqs.(13), (14) and (20) were inserted, also allowing to carry out a sensitivity analysis on the model.

The mathematical model was applied to evaluate the variation in the total annual cost of the pumping system and the recovery period of the invested capital in an electric motor for high efficiency to supply an irrigation system of center-pivot in two modalities of electrical energy tariff: i) Conventional Tariff; ii) Green horo-seasonal Tariff. In both cases, the customer is classified as A Group, A4 Subgroup, Class IV (Rural), A Subclass - agricultural item 2 - pumping water service intended for irrigation (Normative Resolution 156/2005 of ANELL which amended Resolution 456/2000 of ANEEL).

The elevating system considered has flow rate (Q) of 0.0556 m^3 s^{-1} (200.0 m^3 h^{-1}) and manometric height (H) of 79 m, and the hydraulic pump is in 73% efficiency. It also has the following operational characteristics: i) Daily operating time: 20 h (switched on 30 minutes after the end of on-peak time and switched off 30 minutes before the beginning of on-peak time), ii) Number of operating days during the dry period of the year (May to November): 100; iii) Number of operating days during the wet season of the year (December to April): 20; iv) Total operating time in the special time for irrigation (for the benefit of Resolution 207/2006, ANEEL): 8.5 hours (maximum possible), v) Number of months without operating the system in the year: 4.

The electricity tariffs used (tariff prices of electricity practiced in the distribution utility CPFL for the A4 subgroup, according to Resolution 961/2010 ANEEL) were:

A) Green horo-seasonal : i) demand tariff: R\$ 5.73 kW^{-1}; ii) consumption tariff in the dry period during off-peak hours: R\$ 0.14325 kWh^{-1}; iii) Consumption tariff in the wet period during off-peak hours: R\$ 0.13137 kWh^{-1}; iv) Discount factor on green consumption tariff during off-peak hours for irrigation: 70% (Southeast Region), v) Federal Taxes (PIS/PASEP and COFINS), which make up 4% on average, were not included in the tariffs;

B) Conventional: i) demand tariff: R\$ 23.72 kW^{-1}; ii) consumption tariff: R\$ 0.14522 kWh^{-1}.

The financial variables used are: i) Annual interest rate: 8.75%; ii) Amortization period of the electric motor (equivalent to useful life): 15 years; iii) Fraction of the initial value of the electric motor after the amortization period: 10%; iv) Fraction of the initial cost of the electric motor spent in its assembling in the system: 2%; v) Fraction of the initial value of the electric motor spent annually on maintenance and repairs: 2.5%.

The electric motors used in the application of the mathematical model were:

Motor 1: W21 Model (Default), 4 poles, rated speed 1,775 rpm, service factor 1.00, efficiency (80% load) 92.6; power factor (80% load) 0.84; purchase price R$ 8,625.00.

Motor 2: High Efficiency Model, 4 poles, rated speed 1,780 rpm, service factor 1.15, efficiency (80% load) 94.3; power factor (80% load) 0.81; purchase price of R$ 12,321.00.

RESULTS AND DISCUSSION

Table 1 shows the results of applying the model in a pumping system to supply an irrigation system of center-pivot.

TABLE 1. Fixed and variable costs of the pumping system changed due to the use of electric motors 1 (DF) and 2 (HE) in the green horo-seasonal (Green HST) and conventional tariff modality.

Dependent Variables	Green HST		Conventional	
	1 (DF)	2 (HE)	1 (DF)	2 (HE)
Annual amortization cost (R$)	214.09	305.83	214.09	305.83
Annual remuneration cost of capital (R$)	691.28	987.50	691.28	987.50
Annual cost of maintenance and repairs (R$)	215.63	308.03	215.63	308.03
Annual cost of electricity demand (R$)	3,062.53	3,007.32	12,677.71	12,449.16
Annual cost of electricity consumption in the dry period (R$)	10,644.13	10,452.25	-	-
Annual cost of electricity consumption in the wet period (R$)	2,084.77	2,047.19	-	-
Annual cost of electricity consumption (R$)	-	-	12,913.49	12,680.69
Annual cost of electricity (R$)	15,791.44	15,506.76	25,591.20	25,129.85
Annual consumption of electricity (kWh)	152,707	149,954	152,707	149,954
Total annual cost (R$)	16,912.43	17,108.12	26,712.19	26,731.21
Capital recovery period (years) 1 versus 2	Impracticable		Impracticable	

According to Table 1, in both cases, i.e., the green horo-seasonal and conventional tariffs, the substitution of motor 1 (default - DF), whose acquisition cost is 70% of motor 2 (high efficiency - HE), for an increase of 1.7% in efficiency, showed no economic viability. Basically, this can be explained by the slight increase in performance provided by motor 2, insufficient to compensate for its increase in fixed and maintenance and repairs costs, i.e., to even equalize the total annual cost. The sensitivity analysis model, made below, revealed the minimum values of efficiency increase of motor 2 to make it viable within the limit of 15 years.

Sensitivity of the model in relation to the variation of motor efficiency

The eq.(13), green horo-seasonal tariff, and (20), conventional tariff, were applied considering increasing levels of variation of motor efficiency. For example, if motor 2 presented efficiency higher than motor 1 at levels that varied from 1 to 7%, maintained the other conditions of use and acquisition cost, how much would the total annual cost of the system with this motor be at each efficiency level considered? After obtained this value, it was applied equation (14) to calculate the recovery period of the capital, in years, in the efficiency level considered, noting that the annual cost of the system with motor 1 remains unchanged. Again, the use of an electronic spreadsheet speeded the procedure.

Figure 1 shows the results of the sensitivity analysis of the model. As can be seen, it would be feasible to replace motor 1 by motor 2 if the increase in the efficiency rate surpassed 4.46% in the green horo-seasonal tariff and 2.71% in the conventional tariff, which are the values on the abscissa axis when the line of 15 years cuts the curve "2,400 h Annual" (blue line). This difference in recovery period of the capital between tariffs is explained by the lower energy cost in the case of green horo-seasonal, which means more time to recover the costs of amortization, remuneration of capital and maintenance and repairs. It was also verify that the curves rapidly reduce the capital

recovery period as the efficiency gain increases, however this only occurs at strict levels, rarely higher than 4%.

Figure 1 also presents the sensitivity curves of the model under two conditions of operation of the irrigation system: i) Increase of 100% in the price of electricity tariffs, maintaining the others unchanged (curve "2,400h annual with tariff 100% higher" - red dashed line), ii) Increase of 100% in annual period of operation of the irrigation system, i.e., from 2,400 to 4,800 h annual, and decrease from 4 to 2 months without operating the system during the year, while maintaining the others unchanged (curve 4,800h annual - green dashed line).

In the first case, curve "2,400h annual with tariff 100% higher", it appears that the replacement of motor 1 by motor 2 remains impractical in the green horo-seasonal tariff, only allowed if the gain in efficiency surpassed 2.2%. However, the replacement of the conventional tariff would be feasible and the capital recovery period would be 8.4 years. A similar fact occurred in the second case, curve "4,800 h annual", i.e., replacement of motor 1 by motor 2 would remain impractical in the green horo-seasonal tariff, only viable if the gain in efficiency surpassed 2.4%. In the conventional tariff, the difference in efficiency of 1.7% caused the capital recovery period to be approximately 15 years.
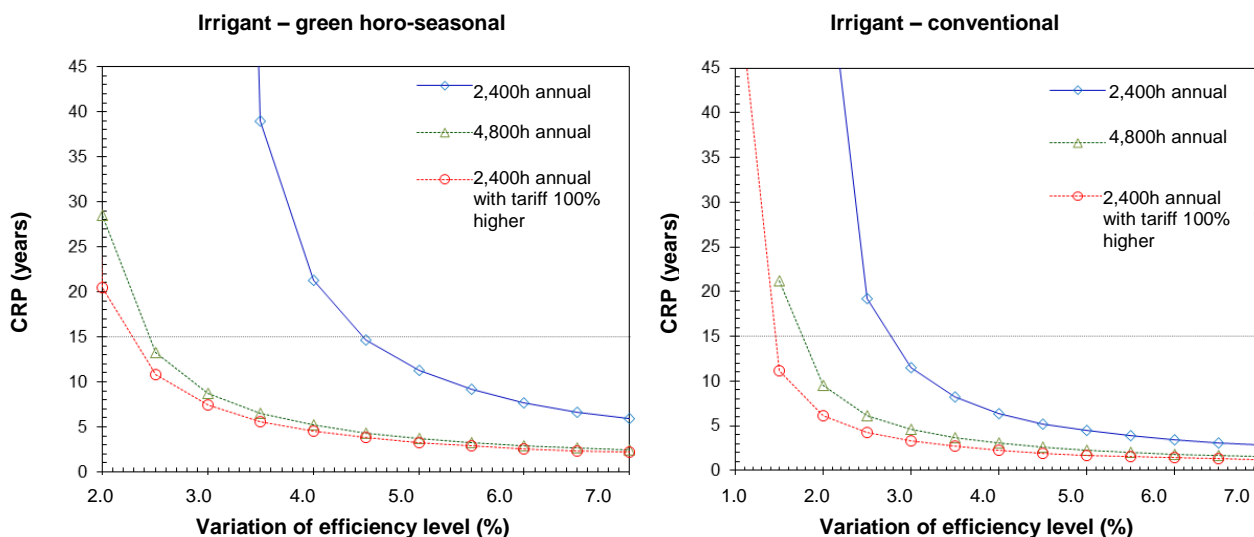

FIGURE 1. Capital recovery period (CRP) as a function of the efficiency variation of the interchangeable electric motors.

Sensitivity of the model in relation to the difference of acquisition cost of motor and efficiency levels

Similarly to the previous sensitivity analysis, it was applied the equations (13) and (20) considering increasing levels of percentage difference between the acquisition costs of motors and increasing levels of efficiency difference, maintained the other conditions. For example, if motor 2 presented acquisition cost higher than motor 1 at levels that varied from 5 to 45%, and efficiency differences levels that varied from 1 to 7%, how long would be the recovery period of the invested capital? Figure 2 shows the results.

It was verified that as the difference in acquisition cost between the motors increases, the greater the efficiency gain of motor 2 in relation to motor 1 so that the replacement becomes feasible (CRP curve below the 15 years line in Figure 2). The precise results of efficiency addition to enable the replacement of the motors within a maximum of 15 years were obtained using the electronic spreadsheet and are presented in Table 2.
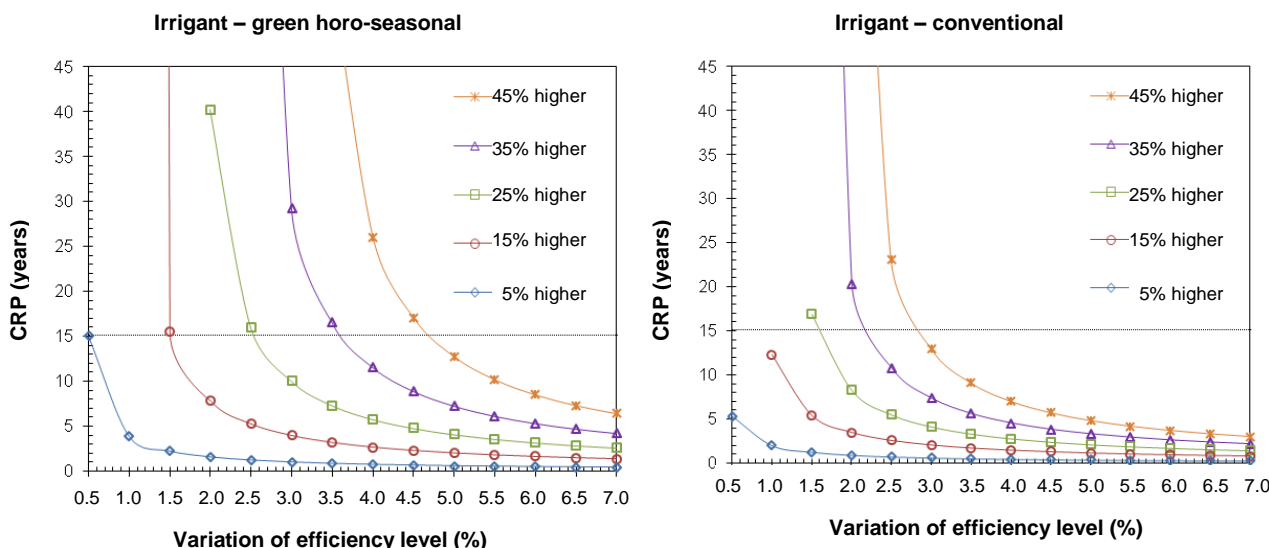
FIGURE 2. Capital recovery period (PRC) as a function of the percentage difference of efficiency, and percentage difference of the acquisition price of the interchangeable motors.

TABLE 2. Minimum increase of efficiency necessary to become viable the replacement of motor 1 (DF) by motor 2 (HE) in the green horo-seasonal tariff and conventional tariff in different variations of the acquisition price between the motors.

Tariff Modality	Percentage variation price of the motors acquisition				
	5	15	25	35	45
Green horo-seasonal	0.50	1.52	2.55	3.61	4.70
Conventional	0.31	0.93	1.56	2.20	2.85

According to Table 2, in the green horo-seasonal tariff the efficiency addition to enable was higher than in the conventional tariff, since the contribution to the energy cost on total cost is lower in this tariff modality. In the market, it is more common to find the acquisition price of the electric motor with high efficiency between 35 and 45% higher than standard electric motor for the same power level, which would require an increase in the efficiency between 3.61 and 4.70% in the green horo-seasonal tariff and between 2.20 and 2.85% in the conventional tariff. It should be emphasized that as increases in energy costs outweigh the increases in fixed costs of a pumping system, the increase of efficiency between the motors to enable the replacement tends to be lower.

Therefore, the feasibility of replacing a standard type motor for a high efficiency one depends on many factors, and the main ones are the effective efficiency gain, the difference of acquisition cost, the tariff modality of electricity and its prices and operation annual time of the pumping system.

CONCLUSIONS

The adjusted mathematical model allowed quantifying the effect of varying the electric motor efficiency in the variation of cost of a pumping system and the recovery period of the invested capital in the highest efficiency equipment;

The recovery period of the invested capital in high efficiency motor (efficiency 1.7% higher for an acquisition cost exceeding 42.9% higher) was not economically viable in both green horo-seasonal and conventional tariffs;

The replacement of motor 1 by 2 would only be economically viable if the efficiency gain surpassed 4.46% in the green horo-seasonal tariff and 2.71% in the conventional tariff;

As the difference in acquisition cost between the motors increases, the greater the efficiency gain of motor 2 in relation to motor 1 so that the replacement becomes feasible;

The main factors that influence the viability of replacing a standard type motor for a high efficiency one are: the effective efficiency gain, the difference of acquisition cost, the tariff modality and the prices of electricity and annual operation time of the system.

REFERENCES

ANEEL. AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. *Banco de Informações de Geração.* Disponível em: <http://www.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.asp>. Acesso em: 21 mar. 2011.

ANEEL. AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. *Resolução n. 456,* de 29 de novembro de 2000.

ANEEL. AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. *Resolução n. 90,* de 27 de março de 2001.

ANEEL. AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. *Resolução n. 156,* de 3 de maio 2005.

ANEEL. AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. *Resolução Normativa n. 207,* de 9 de janeiro de 2006.

ANEEL. AGÊNCIA NACIONAL DE ENERGIA ELÉTRICA. *Resolução 961,* de 6 de abril de 2010.

FUGIMOTO, S.K. *Estrutura de tarifas de energia elétrica análise crítica e proposições metodológicas.* 2010. 195 f. Tese (Doutorado em Engenharia) - Escola Politécnica, Universidade de São Paulo, São Paulo, 2010.

IEA. INTERNATIONAL ENERGY AGENCY. *Key world energy statistics 2010.* Paris: IEA Plubications, 2010. 78 p.

LYRA, J. O "nó" do setor elétrico. *O Jornal,* Maceió, 16 jan. 2005. Disponível em: <http://www.ojornal-al.com.br/16012005/opina04.htm>. Acesso em: 21 fev. 2008.

OLIVEIRA FILHO, D.; TEIXEIRA, C.A.; RIBEIRO, M.C. Dimensionamento de motores para o bombeamento de água. *Engenharia Agrícola*, Jaboticabal, v.30, n.6, p.1012-1022, 2010.

OLIVEIRA FILHO, D.; TEIXEIRA, C.A.; RIBEIRO, M.C. Racionalização energética de uma estação de pressurização de um perímetro irrigado. *Revista Brasileira de Engenharia Agrícola e Ambiental*, Campina Grande, v.8, n.1, p.135-143, 2004.

RAMOS, M.C.E.S. *Metodologia para avaliação e otimização de motores elétricos de indução trifásicos visando a conservação de energia em aplicações industriais*. 2009. 246 f. Tese (Doutorado em Energia) - Escola Politécnica, Universidade de São Paulo, São Paulo, 2009.