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Probing for the Energy-Conserving Load Rates of the Asynchronous Motor by Harnessing the Efficiency and Power Factor Synergy

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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Method Article

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ABSTRACT

In the light of the energy saving drive and environmental concerns in today's world, the technical and procurement staff of industries are encouraged to invariably take into consideration, motor efficiency as well as power factor in their motor load analyses prior to embarking on motor installation/replacement decisions. It is believed that with this practice, which hinges on a tradeoff between loading at high operating power factor and loading at high operating efficiency, the motor-driven business may stand a better chance of being run greener and more economical. This article proposes a method that engineers in research or in charge of the operations and maintenance of the 3-phase squirrel cage induction motor (SCIM) in business, may deploy to arrive at the energy efficient load range/rates for the machines of interest. The method was developed with the aid of the following motor curves viz: the load/efficiency curve, the load/compensated power factor curve as well as the load/kilovolt ampere reactive (KVAR) curve; and demonstrated on three different SCIM ratings, to determine their respective most energy efficient bounds of loading. Field data, z-score analysis and the power loss simulations were used for validating the proposed method. The

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energy efficient load range/rate was found to be machine-specific and the width of this load range seemed to be jointly governed by the high efficiency span of the load-efficiency curve as well as the load-wide profile of the power factor over the most part of the SCIM loading, up to full load. The mean optimal loading for the machines investigated, ranged from 66% - 73%, with standard deviations not exceeding 15.85%.

Keywords: Efficiency; power factor; load rate; energy conservation; SCIM; power loss.

1. INTRODUCTION

The efficiency and the power factor are key performance indicators of the squirrel cage induction motor (SCIM) operations. The efficiency indicates the size of power losses in the motor itself, while the power factor tells us the level of the line losses resulting from the motor's reactive current. In order to attain economic operation of an induction motor, the operational efficiency and the power factor of the motor has to be sufficiently high [1]. The efficiency and power factor should be jointly considered when determining the load rate of the SCIM because of the economic and environmental implications.

The authors in [2] emphasized that SCIMs are usually just a part of an electric drive system. The overall system efficiency depends on several factors such as motor sizing and operational efficiency, torque/speed control, mechanical transmission, maintenance practices, mechanical efficiency, losses in the supply system, power quality, etc. Several studies [e.g., 3-5] show that in practice there is a huge potential for boosting the overall system performance [2]. A salient part of this holistic approach is obviously the optimal loading of the SCIM.

Induction motors are the major consumers of electric energy in industrial applications [6]. In fact, about 60% of the electric power used in industries is consumed by three phase SCIMs [7]. This huge consumption is largely traceable to the relatively low efficiency and power factor of the SCIMs in operation [8], especially when they operate at light loads [9]. In [10], it was pointed out that their running costs could reach or exceed one hundred times the purchase price over their service life. About 90% of the life cycle cost of the SCIM is incurred via the energy it consumes. Cases of the suboptimal loading of the SCIM exist, seemingly due to the lack of knowledge and/or proper communication between the technical and managerial arms of industries [10]. Knowing that today, a huge volume of our primary energy reserves still comes from non-renewable and fossil sources, these could be conserved for future generations [11]. Sustainability surely requires the adoption of more energy efficiency measures.

The loading that commands peak efficiency can differ considerably from design to design, or from manufacturer to manufacturer [4,5,7-18]. Also, it should be noted that the power factor decreases with decreasing load rates, and except the reactive power is compensated, the additional line losses due to this reactive power, may in some cases, have to govern proper motor selection [12]. In [13-19], it was highlighted that the operating efficiency and power factor of a motor are affected by its loading. But Irrespective of the load, no-load losses as well as the reactive component of the motor always exist. The useful stator current, i.e. the phase current minus the no-load current of a normal SCIM, has a power factor as high as 0.9–0.95. But because of insufficiently high magnetizing inductance and/or too high series reactances in the motor, the power factor of the motor does not usually exceed 0.8–0.85 at full load. Thus, at loads lower than rated, with the magnetizing current remaining virtually the same, the power factor of the motor dips sharply. The efficiency, however, remains relatively constant for up to about 70% of load in view of the fact that the peak efficiency occurs at a load when copper losses equal the no-load losses [13].

This study therefore focuses on presenting to the engineers in the motor driven business as well as researchers, a practicable method of identifying for a given SCIM size, the block of energy efficient load rates from whence an optimal load rate could be conveniently arrived at in practice, subject to the technicalities of the load profile.

2. MATERIALS AND METHODS

An important objective for energy conservation and operating cost saving with respect to the 3 phase SCIM operation is to motor-size for a load rate that offers the highest possible values for both the efficiency and power factor for the better part of the production time. However, by the very nature of the 3-phase SCIM, its load rate/motor efficiency (Lr/Eff) curve does not increase all the way to full load; but somewhere around midway of the curve, it attains its peak and then begins a very gentle descent towards full load. On the other hand, the SCIM power factor is a lagging one and the load rate/power factor (Lr/PF) curve usually maintains a positive gradient from no load to full load, though the magnitude of this gradient diminishes as it approaches full load. Usually, the best (or highest) power factor presents itself at about full load. If we opt for the best (or highest) operating efficiency, we most times should look somewhere around the second trimester of the Lr/Eff curve – a region that usually does not present the most desirable power factor values. Here lies the dilemma in finding an optimal operating point, as the Lr/Eff and the Lr/PF curves ordinarily have no point of intersection at or prior to full load. However, this proposed method attempts to present a workable solution that hinges on a compromise between loading at high values of efficiency and loading at high values of power factor.

2.1 The Proposed Method

Besides the information on the nameplate, the author presupposes that the user of this method is an engineer with a good idea of the load profile and is fully armed with the relevant simulated or empirical data of the motor under consideration – at least the operating efficiency and power factor data at the strategic and feasible operating points, from no load to full load. With the duty cycle being assumed to be such that the motors operate under steady load conditions throughout the bulk of the production time, the method is outlined as follows.

Given a 3 phase squirrel cage induction motor (SCIM) with operating points, spanning from no load (subscript *n*) through full load (subscript *1*); the corresponding load rates *Lr* (the ratio of the output power to the rated output power) are given as:

$$\text{Lr} = [L_n, L_{n-1}, L_{n-2}, \dots L_1] \quad (1)$$

Also, the respective operating efficiencies *Eff* and power factors *PF* associated with the identified load rates are given as:

$$\text{Eff} = [Eff_n, Eff_{n-1}, Eff_{n-2}, \dots Eff_1] \quad (2)$$

And

$$\text{PF} = [pf_n, pf_{n-1}, pf_{n-2}, \dots pf_1] \quad (3)$$

The first step is to get the data of the reactive power Q in *kvar* drawn by the SCIM at each load point from no load to full load. For instance, at full load and from: [14].

$$Q_1 = P_1 tan\emptyset_1 \quad (4)$$

Where, the real power demand at for instance, full load (L_1) and for a horsepower output of P_{o1} is:

$$P_1 = \frac{0.746 P_{o1} L_1}{Eff_1} \text{ (in kw)} \quad (5)$$

Therefore, the reactive power in per unit drawn by the SCIM from L_n through L_1 is:

$$Q_{pu} = Q_{max}^{-1}[Q_n, Q_{n-1}, Q_{n-2}, \dots Q_1] \quad (6)$$

Where the subscript *max* indicates the maximum element of the array. And at pf_1 (power factor at L_1) the power factor angle is:

$$\phi_1 = cos^{-1}(pf_1) \quad (7)$$

Though the magnetizing current needed for excitation is almost always constant from no load to full load, the reactive power consumed by the leakage inductances varies in direct proportion to the load. This fraction of the reactive power component in the total power drawn by the SCIM at each load point, which is not needed for useful work, should be kept minimal. Therefore, the point of intersection QE between the $\text{Lr}/\text{Q}_{\text{pu}}$ and Lr/Eff curves serves as the upper bound for the Lr/Eff curve.

The second step is to identify the best power factor offered by the SCIM $pf_{max} = cos\emptyset$, and correct it to unity, while noting the correction factor

$$sin^2\emptyset = 1 - cos^2\emptyset \quad (8)$$

Then each element in PF is augmented by $sin^2\emptyset$.

The corrected power factor array will therefore be:

$$PF_{new} = \sqrt{(PF^2 + sin^2\emptyset)} \quad (9)$$

Since the input power factor offered at any point by the SCIM should be kept at maximum, then the point of intersection PE between the $\text{Lr}/\text{PF}_{\text{new}}$ and Lr/Eff curves serves as the lower bound for the Lr/Eff curve. In the final family of load-driven curves, all three ordinates (Eff, PF_{new}, Q_{pu}) are ratios of different power components occurring between L_n and L_1 , hence they are dimensionless quantities spanning between 0 and 1.

2.1.1 Method of validation

For the purpose of demonstration and validation, the proposed method, was deployed to find the range of energy efficient load rate for an 8 pole 72 stator/55 rotor slotted three phase 100HP SCIM, supplied from a 400V, 50Hz mains; and the result presented in Fig. 1. To observe how this method fares with other SCIM ratings, the foregoing procedure was repeated using the same mains supply, and the additional two SCIM ratings used were: a 75HP, 6 poles, 72 stator/55 rotor slotted machine, as well as a 50HP, 6 poles, 54 stator/41 rotor slotted machine. The results may be observed in Figs. 2 and 3 respectively. Table 1, presents the results obtained from this method and some suitable validation as follows:

Column 1 contains the investigated SCIM ratings.

Column 2 contains the energy efficient bounds as obtained by the proposed method.

Column 3 contains the average of the eco-friendly and commercially viable load rates that the author in [5] obtained from various industrial sectors, taking the case study of select countries in the European Union (EU); and Table 1 investigates if the mean load rates from this survey fall within the PE-QE bounds derived from this method.

Column 4 shows the computed load rates when the power loss computation was done to factor in the active power loss of the grid caused by the increase of reactive power i.e., the *comprehensive economic load rate (Lcr)* [1]*;* and Table 1 considers if each *Lcr* of the SCIMs lies within the PE-QE bounds derived from the proposed method. Given the no load active loss ΔP_o (kW), the economic equivalent of the reactive power (assuming the motor is directly connected to the generator bus) K_Q (kW/kvar), no-load reactive power Q_o (kvar), the rated reactive power Q_N (kvar), and the rated active loss, ΔP_N (kw), then from [1]:

$$\text{Lcr} \approx \sqrt{\frac{\Delta P_o + K_Q Q_o}{\Delta P_N - \Delta P_o + K_Q(Q_N - Q_o)}} \tag{10}$$

Column 5 considers the total KVA demanded by the SCIMs for each load rate within the PE-QE bounds; and shows how many of these KVA demands fall within one standard deviation below/above the mean of the critical load to full load KVA, i.e., how many have z-score units [15] of +/-1.0. The critical load rate being that below which the efficiency curve begins to fall sharply; which in this study is about 0.22. Given, the total power demand P_T (KVA) at any load rate, the mean power demand from critical load to full load $\overline{P_T}$ (KVA) and the standard deviation of the power demands from critical load to full load σ (KVA); then according to reference [16], the z-score of P_T for instance, may be computed as:

$$z = \frac{P_T - \overline{P_T}}{\sigma} \tag{11}$$

Fig. 4 illustrates equation 11.

For the last column of table 1, and leveraging on [17]:

Given, the efficiency Eff_i and active power output P_i at a particular load point i, the active loss

$$\Delta P_i \approx P_i({}^{1}/_{Eff_i} - 1) \tag{12}$$

Also, from [13], for an active power input P_{in} and power factor angle $\emptyset_i$ at a particular load point i, the reactive power at that point,

$$Q_i = P_{in} tan\emptyset_i \tag{13}$$

And according to the estimation in [1], the reactive loss

$$\Delta Q_i \approx K_Q Q_i \tag{14}$$

From equations 12 through 14, the *integrated power loss argument* P_{arg} at load point i, was then estimated as:

$$P_{argi} \approx ({}^{1}/_{Eff_i} - 1) + K_Q tan\emptyset_i \tag{15}$$

Equation 15 captures the total per unit active loss due to the motor, including the line loss caused by absorbing reactive power from the grid. Column 6 therefore, considers the P_{arg} at each load point and presents the load rate at which it turns out the minimum, L_{omin}.

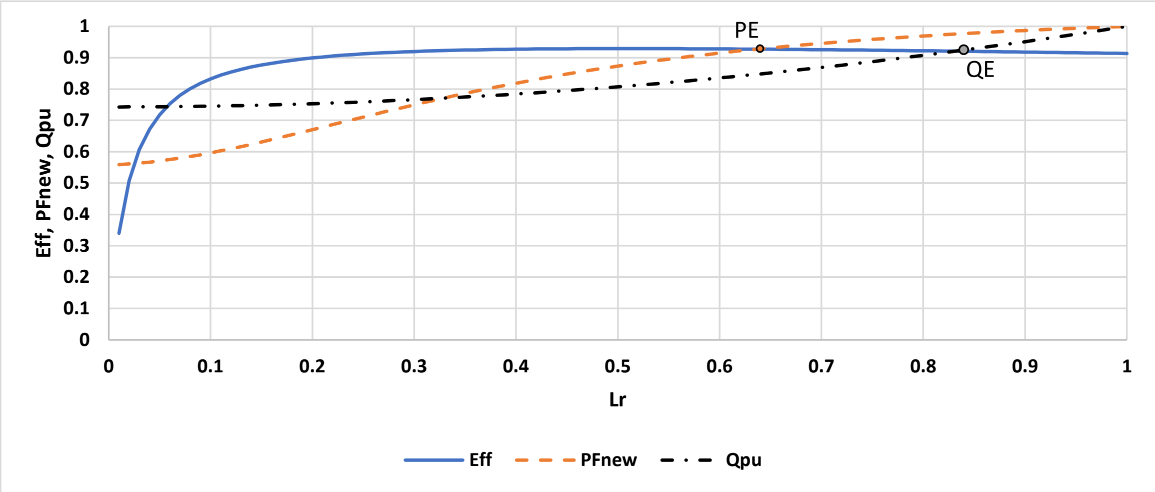

Fig. 1. Energy efficient load range by the proposed method (100HP SCIM)

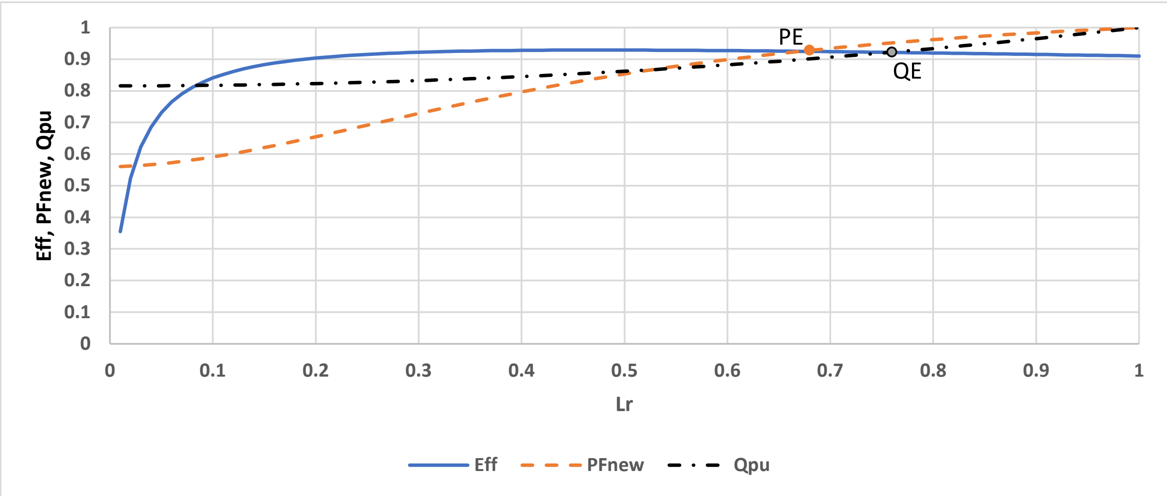

Fig. 2. Energy efficient load range by the proposed method (75HP SCIM)

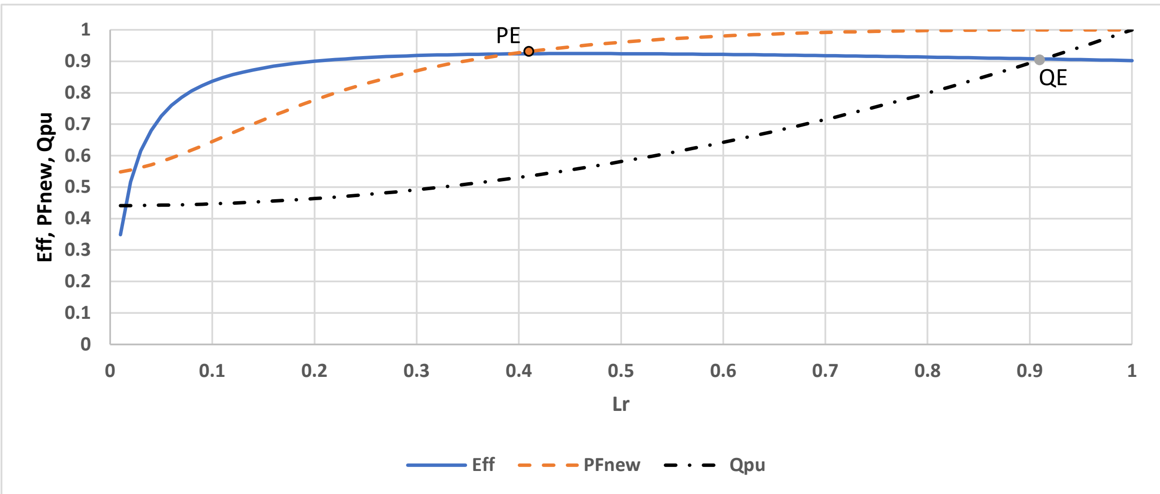

Fig. 3. Energy efficient load range by the proposed method (50HP SCIM)

3. RESULTS AND DISCUSSION

In Table 1 (column 3), it may be observed that the PE-QE energy efficient bounds obtained by the proposed method appears valid; since first, the mean value of the already commercially viable load rates that have been adopted by various SCIM-driven industries surveyed in the EU, for instance; fall within the energy efficient bounds got by the proposed method. In the EU, like in many advanced climes, energy saving measures have become effective in industries, being enforced via various forms of taxes on electricity bills [5].

Also, from Table 1(column 4), the *Lcr* as computed with the empirical formula (equation 10) obtained from [1], falls within the same PE-QE bounds identified by this proposed method. Equation 10 factors in the sum of the active power loss of the motor itself as well as the active power loss of the grid caused by the increase of reactive power.

A further validation as observed in Table 1 (column 5), shows that of all the KVA demanded at those practicable load rates (from critical load to full load), the KVA demand for each load rate within the PE-QE bounds seems to fall in the class of the closest to the mean KVA demanded $\overline{P_T}$. All the identified energy efficient load rates of the 100HP and 75HP SCIMs had a z-score of ± 1, (see Fig 4) except about 15% of those identified for the 50HP SCIM. Of course, with Fig 4, a workable load rate could be arrived at close to PE to avoid this 15%. The KVA z-score seems a good guide to identifying the section of the PE-QE bounds that has the least variability, in view of the fact that the deviations from $\overline{P_T}$ is expectedly maximum for lossy load rates.

A final validation as observed in Table 1(column 6), shows that for each SCIM, there is a load rate L_{omin} for which the total active losses due to the real and reactive power drawn by the SCIM assumes the minimum value; and the L_{omin} for each SCIM size all seem to lie within their respective block of the energy efficient load rates as prescribed by this proposed method. Fig 5 shows this trend.

It appears evident from Table 1 and Figs 1 - 3, that the size of the energy efficient band of load rates varies from machine to machine and appears to be proportional to the magnitude of the general power factor profile of the particular SCIM under consideration as shown in Fig 6 (LHS). For instance, the 50HP SCIM has the largest values of power factor at any given load rate (that's why PE occurs at the lowest Lr) and consequently, the largest mean power factor; and as such the largest range of energy efficient load rates. Though about 15% of the upper PE-QE bound for this SCIM may not be truly energy saving as implied by the z-score (Fig 4). The power factor also governs the reactive power (KVAR) level of the motor which was used to determine the upper bound of the energy efficient band of load rates. Also, as the SCIM ratings increase and the maximum to full load operating efficiency profile becomes more stable (small Eff/Lr slope), the more the location (typified by the median) of the block of energy conserving load rates shifts closer to full load. This is also supported in Fig 6 (RHS). Depending on the desired annual operating hours for the SCIM, the engineer may adopt any load rate within the PE-QE range as the SCIM operating point, to run that stable load profile, in view of profit maximization and energy conservation. For variable loads, the motor load rate could be made to alternate within the PE - QE range. If he decides to load too close to PE for the better part of the production time, he stands the risk of worsening the voltage dips and the available capacity in the upstream power system equipment feeding the SCIM - the losses due to reactive current rises and the utility costs in reactive power dependent bills or power factor penalty, rises.

Table 1. Results and validation for the proposed method

Rated output of the SCIMs (HP)	Energy efficient bounds from the proposed method	Commercially viable average from field survey [5]	Computed Optimal load rate (Lcr) by eqn. 10 from [1]	KVA within bounds and within z-score of +/-1 (%)	Load rate with the minimum Power loss (Lomin)
50	0.41 - 0.91	0.606	0.536	84.3	0.53
75	0.67 - 0.76	0.682	0.678	100	0.67
100	0.64 - 0.82	0.682	0.685	100	0.68

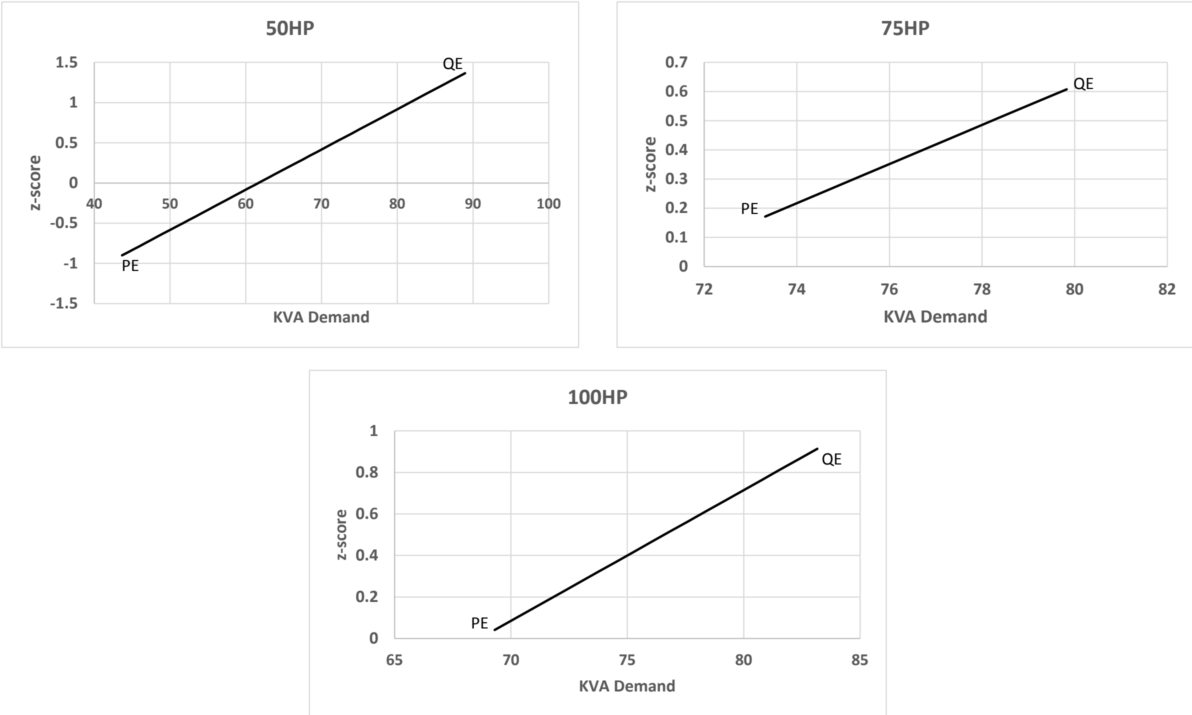

Fig. 4. Z-score vs KVA demanded within the PE-QE bounds

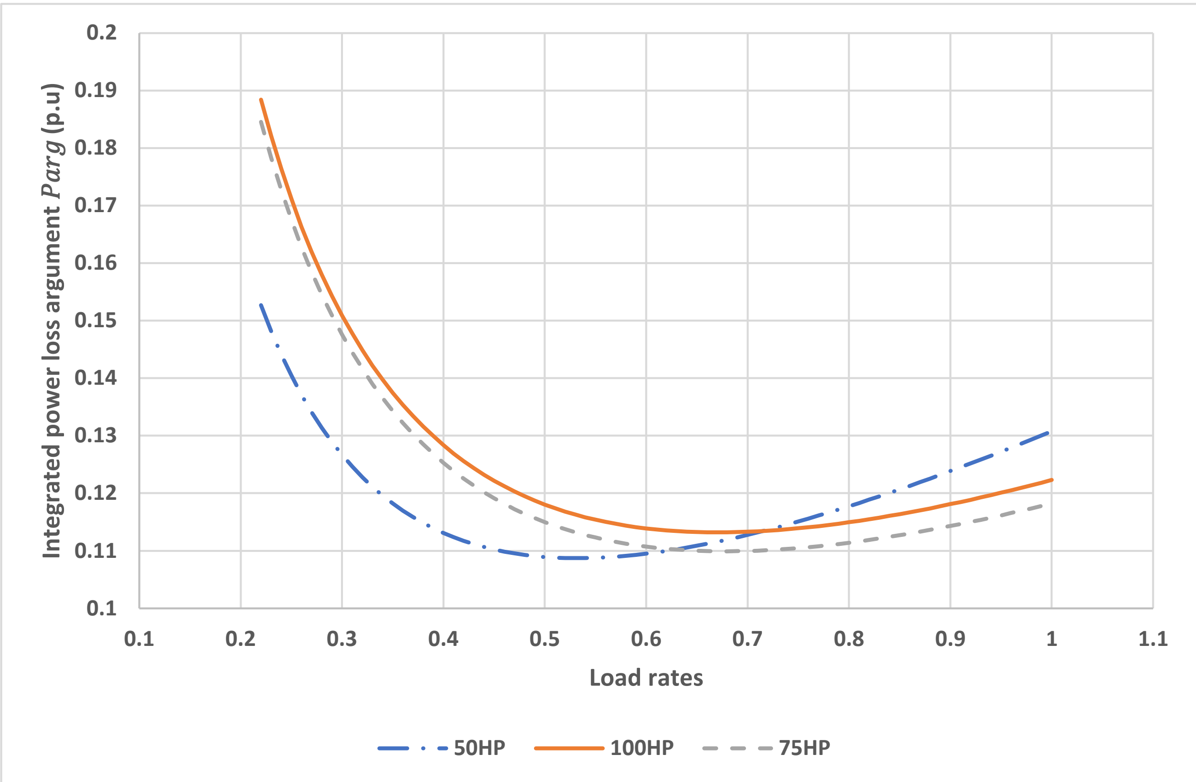

Fig. 5. Integrated power loss argument (P_{arg}) vs load rates

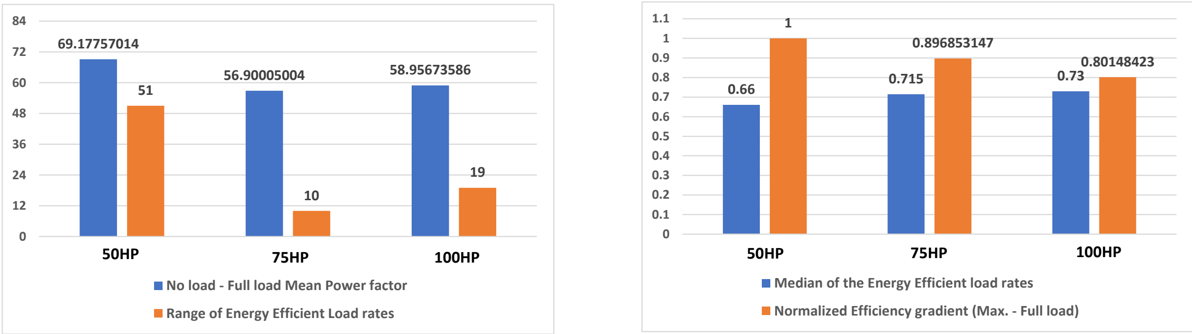

Fig. 6. Influence of power factor and efficiency on load rates

Alternatively, if he drifts towards QE, the motor begins to slip more and waste energy in motor losses with the attendant lower motor efficiency; thereby incurring more energy (kwh) charges accordingly. An eco-friendly and economic tradeoff sure exists between these extremes. However, if PE coincides with QE or virtually so, this point may be regarded as the mean load rate of a few closely dispersed energy conserving load rates. Armed with this knowledge of the PE-QE energy efficient load range, a cost saving and energy conserving motor-load match could be easier realized for that electric drive system of research or economic interest.

4. CONCLUSION

The utilization of optimal load rates for industrial SCIMs is an established way of contributing to the mitigation of operating cost and greenhouse emissions by aiding the reduction or elimination of unnecessary energy used or wasted. Even the benefits of using energy efficient motors may be overtaken if the load rate is uninformedly determined. The technical staff as well as the decision makers in the SCIM-driven industries need to be trained and made ever conscious of the energy use consequences of their motor loading configurations. From the foregoing results, we may observe that the total power demanded by a SCIM invariably increases with the load. Therefore, the most energy efficient load rate of a SCIM may not coincide with the lowest KVA demanded but will definitely present in operation, the best compromise between high values of power factor and efficiency for that machine rating; resulting in relatively low overall power losses per output, as typified by the relatively low z-score and P_{arg} values.

By harnessing the synergy between the efficiency, power factor and related data, this paper has therefore made a modest attempt at providing a workable guide to discovering the load rates that lie within the energy efficient load spectrum, and as such, facilitate the eventual decision regarding matching the mechanical characteristics of the motor with the load There perhaps now exist another method deemed reliable for guiding the researcher or the engineer in business towards arriving at that economic and greenhouse friendly SCIM load rate.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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