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The Relative Economics of Sizing the Industrial Asynchronous Motor for Minimum Total Active Power Loss

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Abstract:

With the pervading environmental concerns as well as the threatening dearth of nonrenewable energy in the world today, more attention ought to be paid to the efficient use of energy,asone unit of energy saved is often said to be equivalent to two units of energy generated. The energy efficiency and economics of the induction motor drive system often turns out abysmal when an induction motor is uninformedly selected, such that it does not match its load appropriately. In the industries, a technical approach for minimizing the energy wasted by the motor, is by right sizing for an optimal motor loading experience. But sadly, many motors are usually operated at light loads where the running-efficiency and/or power factor is wastefully low; so that the overall energy consumed by the motor exceeds its design requirements. The extraneous energy wholly feeds various motor and line losses, and the life-span of the motor may just be shortened. For a constant torque application therefore, this paper considers the industrial operation of the squirrel cage induction motor (SCIM) at a load rate in which the total active power loss is deemed minimum, and then the energy efficiency and economics thereof was compared with those of various common motor resizing scenarios. At least, 60% of the economic evaluation metrics employed show that this SCIM loading technique appears quite profitable and cost-effective in the midst of the other investigated motor sizing strategic plans.

Keywords **—SCIM sizing, Active power loss, Load rate, SPP, PW, BCR, LCC, Energy saving.**

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I. INTRODUCTION

Electric motors which are arguably the most important electric load [1], consume most of the world's electrical energy yearly, and induction motors are the most common type of motors used in industries as they are robust, simply structured, reliable, affordable, and easy to maintain [2]. Therefore, these loads should be treated as priority in Demand Side Management (DSM) programs designed to achieve cost-effective electricity consumption.

Energy is a necessity for sustainable development and economic growth, and the demand for energy is increasing rapidly because of the rising levels of automation, industrialization and urbanization [3]. Future economic growth strongly depends on the long-term availability of energy, and so, for sustainable development there is the need to keep devising energy efficiency measures [4].

In order to make the motor operate economically, it must be chosen in the appropriate type and capacity that will ensure that the mechanical characteristic of the motor matches the load [5]. The declared efficiency and power factor of a motor are affected by its loading [6], so that motors that are matched to the load profile usually result in optimum energy use [7]. Motor service lifetimes could be prolonged, typically beyond 10 years, when the unit is properly matched to its driven load and operated under the design power supply specifications [8]. As a general rule, SCIMs that are undersized and overloaded have a shortened useful life with a greater probability of unanticipated downtime, resulting in economic losses. On the other hand, motors that are oversized and thus lightly loaded do waste energy and suffer both efficiency and power factor reduction penalties from the utilities [9], [10].

In the industry, due to factors like conservative system configurations, allowance for scale up in the future, requirement for safety margins to accommodate variations in load power and supply voltage, standardization of the machine power ratings, etc.; most three phase squirrel cage induction motors (SCIMs) are oversized [11], [12], [13]. However, while conceding the reality of the extra capital investment of the oversizing of direct-on-line, fixed-speed induction motors; their part-load efficiency could still be higher than the full-load efficiency of well sized smaller motors, because in general, the nominal efficiency usually increases with the rated power [14].

To ensure efficiency benefits associated with motor downsizing are achieved, it is important that the motor matches the power supply, environment, load, reliability, and business demands. Though some situations may require oversizing to make room for peak loads, but [15] suggests that motors be selectedto present a load factor between 75% and 80%. And [7] recommends that all the motors that are operating below 50-65 % loading should be considered for appropriate downsizing; as long as the motor is not continuously overloaded to a surge in current consumption, to overheating of the turn insulation, to thermal wear, to incomplete breakdowns, and eventually, to complete inter-turn short circuits and failures of the motor [16].

It is pertinent to note that when selecting a motor for a particular application, factors such as cost, availability, service and popular brand name; usually sway more users than the operating efficiency - the initial cost being often considered as the most important factor [1]. The economic evaluation of energy savings is often strongly imparted by the price of energy and its time variation, while the profitability depends on factors such as annual motor operating hours, its residual value, the initial cost of acquiring an efficient motor etc. [17], [18]. Often, theeconomic feasibility evaluation methods recommended by the manufacturers or consulting entities themselves, focus on simple payback time and do not consider all the influential factors [19]. The methods that are not based on discounted cash flow are severely limited in terms of effectiveness and precision [17].

In line with various established findings e.g., in [5], the operational efficiency and the power factor are both important technical indicators of the induction motor's energy efficiency. Whereas, the operational efficiency portrays the size of the power losses from the motor itself, the power factor reflects the power losses which are caused by the motor's reactive current flowing in the supply lines. The key to the realization of economic operation of the 3phase induction motor may not be quite distant from the proposed industrial culture in which the motor operational efficiency and power factor are regarded as indispensable cofactors for guiding motor procurement and replacement decisions.

This article compares the economics of various downsizing and oversizing replacement options for a failed/lossy three phase SCIM, vis a vis the economics of operating at an empirically determined load rate that presents the lowest overall active power loss for a chosen rating; and thus ascertain the relative suitability or otherwise of the latter as a practicable energy saving and economically viable replacement option for the industrial motor managers.

II. METHODS

The study assumes that the SCIMs are largely constant speed and invariably loaded machines driving a production line whose production target depends on the operating hours, which in turn is stiffly coupled to the rotor mechanical speed. The motor managers are also assumed to be on the verge of an inevitable motor replacement decision thathinges on right sizing, or they are just proactively arming up for such eventuality.

First, as a follow up to the validation section of a cognate treatise in [20], in which the concept of a distinct kind of load rate was introduced, the derivation of same is repeated hereunder:

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

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

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

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

Also, from [21], for an active power input P_{in} and power factor angle $\emptyset_i$ at a particular load point L_i, the reactive powerQ_i in *KVAR* units at a given point *i* is given as;

$$Q_i = P_{in} tan\emptyset_i. \quad (3).$$

Where, the corresponding real power demand for a horsepower output of P_{oi} is:

$$P_{in} = \frac{0.746 P_{oi} L_i}{Eff_i} \text{ (in kw)} \quad (4).$$

By leveraging on [22], and given the efficiency Eff_i and active power output P_i at that particular point i, it may be accepted that the active loss:

$$\Delta P_i = P_i({}^{1}/_{Eff_i} - 1) \quad (5).$$

At pf_i (power factor at L_i) for instance, equation 6 gives the power factor angle as:

$$\emptyset_i = cos^{-1}(pf_i) \quad (6).$$

And according to the analyses in [5], equation 7 gives the reactive loss as:

$$\Delta Q_i = K_Q Q_i \quad (7)$$

Where, K_Q (in kW/KVAR) is the economic equivalent of the reactive power for the case in view where the motor is taken as directly connected to the generator bus.

From equations 3, 5 and 7, the dimensionless *integratedpower loss argument*P_{arg} at load point L_i, was then derived as:

$$P_{argi} = ({}^{1}/_{Eff_i} - 1) + K_Q tan\emptyset_i \quad (8).$$

For the sole purpose of comparing the energy use of different SCIM sizes when delivering the same output, P_{arg} tries to approximate the total per unit active loss due to the motor, including the line loss caused by absorbing reactive power from the grid. The thrust here is to explore the P_{arg}/L_r curve and determine L_{omin} i.e., the load rate that presents the minimum P_{arg} value. This curve was developed for a 50HP and 75HP SCIM as shown in fig 1.

The economics of the operation of the 50HP SCIM at L_{omin} was then compared with that obtainable from other suitably resized SCIMs, all of which were made to output the same production load requirement P_{load}.

$$P_{load} = \frac{0.746 P_o L_{omin}}{Eff_{opt}} \text{ (KW)}. \quad (9).$$

Where, P_o = 50HP and Eff_{opt} is the operational efficiency declared at L_{omin}.

The annual energy savings as in [9], [20], [23], [24], for all investigated machine sizes outputting P_{load}($\approx$ 20KW) was computed as:

$$E_s = \left(\frac{P_f T_f}{Eff_f} - \frac{P_{load} T_r}{Eff_r}\right) \text{ in kwh.} \quad (10)$$

Where, T is the annual operating hours, P is the KW output and Eff is the operational efficiency declared per SCIM when it outputs constant P_{load}. Subscripts f and r respectively indicates the parameters for the failed or retiring SCIM (assumed to be a 30HP SCIM operating at full load and was bid for rewinding after failure), and its supposedly right sized replacement (assumed to be a new purchase). Each machine has a different power rating and hence at P_{load}, each machine would expectedly have a different load rate. The retiring SCIM is assumed to have a negligible scrap value of the metal. The cost savings C_{sav} which was structured to capture the penalty for power factor violation, was computed with equation 11:

$$C_{sav} = C_1 E_s + C_2 P_D + C_3 P_D (pf - pf_{ref}) \quad (11).$$

The KW demand savings is given in equation 12:

$$P_D = \left(\frac{P_f}{Eff_f} - \frac{P_{load}}{Eff_r}\right) \quad (12).$$

Where, C_1 (\$0.08) is the average energy cost per kwh, C_2 (\$100) is the annual demand charge per KW and C_3 (\$10) is the charge for a 1% violation of the utility power factor target (pf_{ref}). pf is the power factor of the SCIM under consideration while outputting P_{load}. The cost of rewinding the failed SCIM C_f was taken as \$700 and for the relative costs, the authors were duly guided by [24], [25]. This is case A.

With the assumption that the budget constraint precluded the adoption of more than one SCIM size per case by management, and that profit maximization was not a priority in this SCIM replacement drive; there arose the need to consider the cash flows representing the benefits and costs associated with the acquisition and operation of the SCIMs, so as to select the most cost-effective alternative that will also satisfy energy efficiency needs. The authors have however assumed for ease of economic comparison of SCIM sizes under exactly the same conditions of acquisition, operations and disposal, that:

- costs and benefits are invariably measurable in terms of cash, and that taxes are not applicable.
- projected cash flows are known with certainty and are independent of inflation or deflation.

The measures, as in [24]and[26], employed for comparison are as follows:

A. *The Simple Payback Period (SPP)*

$$SPP = \frac{\Delta C}{C_{sav}} \quad (13)$$

Where, ΔC is the difference between C_f and C (the purchase plus installation cost of the newly procured SCIM). It was also assumed that management had set the benchmark SPP for 4 years and that all SCIM sizes considered, incurred equal and negligible maintenance costs over their service lives, withall having the same installation costs.

B. *The Present Worth (PW)*

$$PW = C_{sav}\ (P/A_{,rt,yr}) + C_{salv}\ (P/F_{,rt,yr}) - C\ . \quad (14)$$

The PW of Annual savings is given as:

$$C_{sav}\ (P/A_{,rt,yr}) = C_{sav} \frac{(1+rt)^{yr}-1}{rt(1+rt)^{yr}} \quad (15).$$

Also, the PW of salvage valueis given as:

$$C_{salv}\ (P/F_{,rt,yr}) = C_{salv}(1+rt)^{-yr} \quad (16).$$

Where, rt is the constant discount rate (15%), yr is the anticipated useful life of the SCIM (10 years) and C_{salv} is the SCIM salvage value (taken as 50% of C) at the end of yr.

C. *The Benefit-Cost-Ratio (BCR)*

$$BCR = \frac{C_{sav}\ (P/A_{,rt,yr})}{C - C_{salv}(P/F_{,rt,yr})} \quad (17)$$

D. *LifeCycleCosting (LCC)*

$$LCC = C + C_4\ (P/A_{,rt,yr}) \quad (18).$$

Where, the operational cost is given as:

$$C_4 = C_1 E_c + C_2 P_c - C_3 P_c (pf - pf_{ref}) \quad (19).$$

And the annual energy consumed in kwh is:

$$E_c = P_c T_r \quad (20)$$

Where, KW demand $P_c = \frac{P_{load}}{Eff_r}$. (21)

In order to establish the replicability of the results from case A, and possibly bring out any significant patterns or trends; the entire procedure was repeated in case B, with slightly different set of machines and data. For instance, assuming management values the expected stream of future savings over today's money in hand, the discount rate was reduced to 8%. Also, P_{load} was changed to 37.3KW, and the rewound SCIM rating was changed to 50HP. Details are shown in table 1 and 2, with the motor operational data obtained from well validated Matlab/Simulink simulations.

All experimental machines are 6-pole SCIMs running on a 50 Hz 400V supply, except the 100HP SCIM, which has 8 poles (slightly more expensive design). Since the latter is a slower shaft speed machine, it was then assumed to be capable of making up for the expected deficit in the production target by working for an extra 100 hours annually – the motor being a factor of production (physical capital). The initial dollar costs are more of relative amounts than their actual market value, as reached with the guidance of [24]&[26].

III. RESULT

The result from the initial step of determining L_{omin} for the reference resized SCIMs of cases A and B is shown in fig 1, with the respective L_{omin} points marked on the curves.

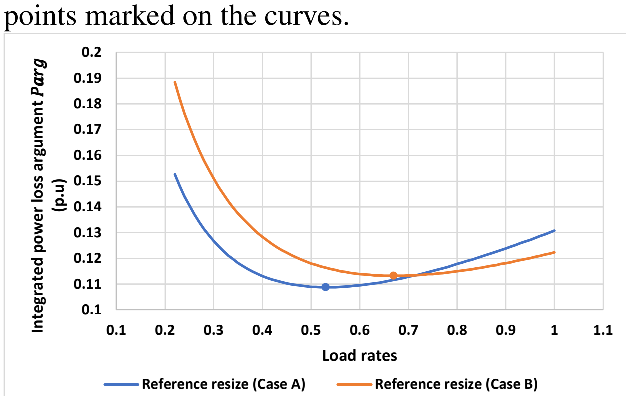

Fig 1: Determination of the L_{omin}

It may be observed from fig 1 that the minimum value of P_{arg} i.e., the minimum overall active power losses due to the flow of real and reactive power in the lines feeding the SCIMs as well as in the SCIMs themselves; tend to occur at about 53% and 67% loading (L_{omin}) for case A and case B respectively. This is also noted in tables 1 and 2.

TABLE 1: RESIZE PERMUTATIONS AND OPERATIONAL DETAILS FOR CASE A

SCIM Description	HP rating	Load rate %	Operational Efficiency	Operational power factor	Hours of operation	Initial Cost in USD
Rewound	30	100	0.91	0.83	6000	700 (Rewinding)
1st resize	35	76	0.90555467	0.82357547	6000	1,112.21
2nd resize	40	67	0.91405284	0.82695552	6000	1,308.70
Reference resize	50	*Lomin* = 53	0.92362791	0.80242736	6000	1,759.67
3rd resize	75	36	0.92640163	0.53061722	6000	2,420.64
4th resize	100	27	0.91555291	0.46712014	6100	3,752.85

Tables 1 and 2 show that the rewound SCIM serves only as a common base for evaluating the savings in energy and utility bills for the five resized variants so that they could be compared amongst themselves. The efficiency and power factor values are those declared at the respectively indicated load rates, with all SCIMs outputting roughly the same power (P_{load}). Of course, we expect P_{load} for cases A and B to be different.

TABLE 2: RESIZE PERMUTATIONS AND OPERATIONAL DETAILS FOR CASE B

SCIM Description	HP rating	Load rate %	Operational Efficiency	Operational power factor	Hours of operation	Initial Cost in USD
Rewound	50	100	0.9	0.83	6000	700 (Rewinding)
1st resize	*50	100	0.90235694	0.8408364	6000	1,759.67
2nd resize	60	84	0.91454534	0.84620835	6000	2,107.80
Reference resize	75	*Lomin* = 67	0.92498899	0.73699829	6000	2,420.64
3rd resize	100	50	0.92892912	0.67297728	6100	3,752.85
4th resize	125	40	0.9302459	0.70236496	6000	3,770.00

**Not quite a resize but a new purchase with slightly better efficiency and power factor than the rewound variant of same size.*

It may also be observed from tables 1 and 2 that as long as the motor isn't oversized to operate at a critically low load rate where efficiency trends precipitously, the major demerit of oversizing the SCIM appears to be a drastic and lossy drop in the operational power factor (indicative of energy wastage), besides the higher initial cost. The effect of this may become more evident in the analyses that follow hereafter.

A. *Kilowatt hour (KWH) Savings*

The first move at establishing the economics of operating the SCIM at L_{omin} could be observed in fig. 2. While case A operates the 50HP SCIM at

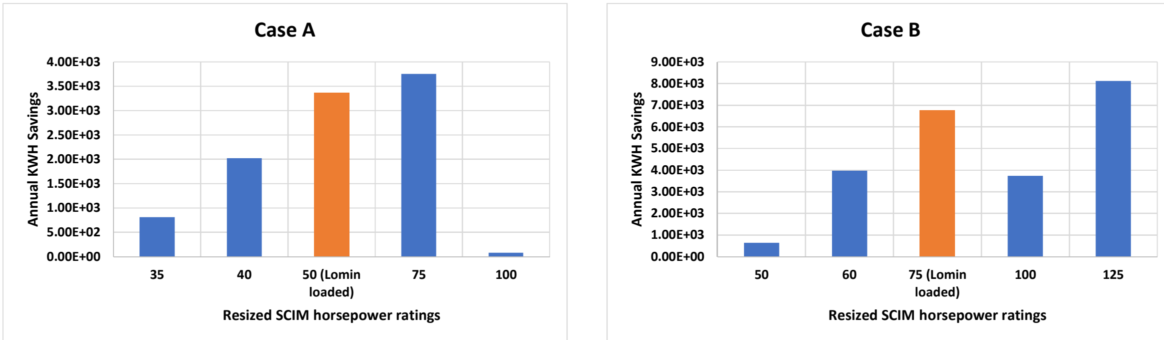

Fig. 2: KWH Savings.

L_{omin}, the 75HP SCIM is the one operated at L_{omin} in case B. These two machines are for the purpose of discussion termed the reference resize (RR). The savings in the units of electricity consumed annually would have been the highest in the RR of cases A and B, but for the slightly larger savings declared by the 75HP and 125HP SCIMs respectively. This is because the KWH savings computation does not capture the I^2R losses due to the flow of reactive power, but considers just the active power demand over time. The efficiency curves of these machines that are closely trailed by the RR's would most likely have a smaller range of precipitous sloping, as their impressive light load efficiency values suggest in tables 1 and 2. Perhaps, this efficiency stability under load is due toimproved design, better materials, or improved manufacturing techniques; besides being largercapacity motors.

These seemingly superior motor resizes however appear somewhat an overkill in terms of spare capacity. In [8] and[14], these kinds of good quality SCIMs were alluded to. Some reasons why management may prefer these machines (the 75HP and 125HP SCIMs) to the RR options in spite of their higher initial costs, may be for longer winding insulation and bearing lifetime, more tolerance for poor power quality and/or to pre-empt the eventuality of a sizeable future load growth.Perhaps, the merits of the foregoing reasons, in the wisdom of management, tend to outweigh the burden of a relatively high initial purchase price of these good SCIM designs (including the added cost associated with larger circuit breakers, starters, power cable gauge etc.). Otherwise, the RR is in both cases A and B, the choice eco-friendly and economic option. Also, comparing each SCIM size in both cases, it appears that except in the case where the load rate was pegged at 100%,the amount of saved energy for each SCIM size seems to increase with the motor load.

B. Utility Bill Savings

Unlike the KWH savings which was largely influenced by the active power flow over time due to the SCIMs, the utility billing in this study was structured, like is the custom in many utilities; to penalize poor values of operating efficiency as well as power factor. The bill savings is portrayed in fig. 3.

Fig. 3 shows that the trend in fig. 2 isn't strictly maintained. The RR option of case A appears the most economical in terms of bills; while in case B, the RR option closely trails the 125HP gilt-edged SCIM. However, the metric of dollar savings in utility bills by itself does not quite convey sufficientrelevant economic information because we are yet to find out the bill savings of whose SCIM presents the best justification for the incremental cost of motor replacement by resizing.

C. Simple payback period (SPP)

In this study, the cumulative cash flow equals zero at the point where cash savings from utility bills

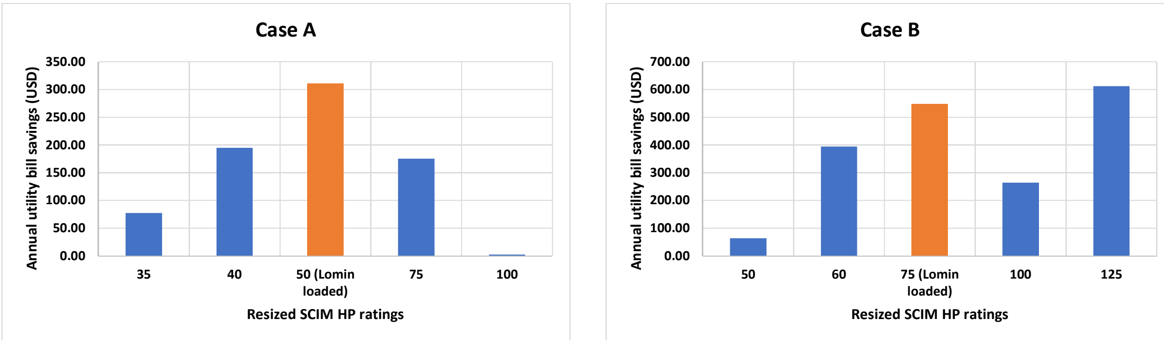

Fig. 3: Savings in utility bills.

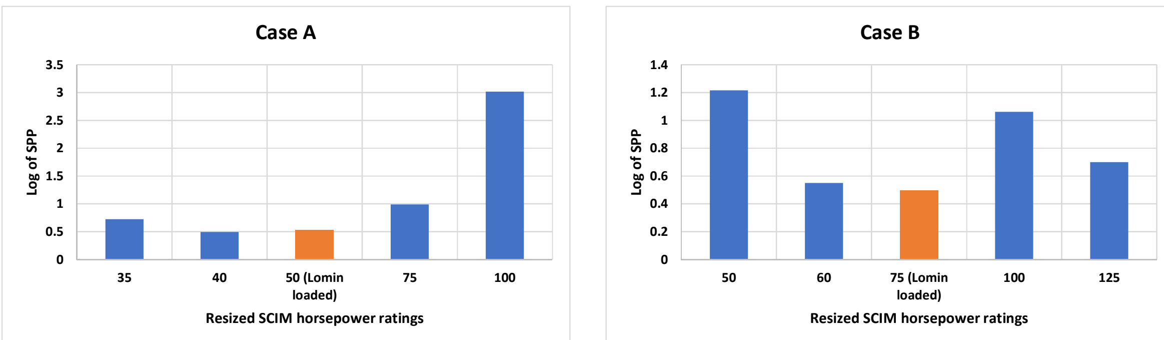

Fig. 4: Simple payback period (SPP)

exactly match or pay back, the cash outflows occasioned by the SCIM replacements. In fig. 4, the logarithms to base 10 of the SPP's were compared so as to minimize the dispersion among them, making for better presentation. The SPP for the RR's is the shortest amongst all the SCIM sizes, but for case A, where only the SPP for the 40HP SCIM is about 3 months shorter. Also, it is to be observed from tables 1 and 2, as well as fig. 4 that the RR's for both cases turn out to have shorter SPP than even the respective least expensive sizes of SCIMs.

Note also, that in both cases, only two SCIM sizes are able to pay back their incremental costs in about $3\,{}^{1}/_{2}$ years (0.55 in log form) or less, and the SCIM loaded at L_{omin} is one of these two; thereby satisfying the benchmark SPP of 4 years. These observations seem to show that the RR options merit strong considerations by management. However, because the SPP does not consider the time value of money, it is used cautiously and in combination with the following methods that explicitly considers the time value of money.

D. Present Worth (PW)

Again, for better presentation, the signed logarithms to base 10 of the unsigned PW of the SCIMs were plotted for comparison. In both cases A and B, the PW of the SCIMs loaded at L_{omin} (i.e., the RR's); was the most positive. In fact, in case A, the only positive PW was that of the RR. These may be observed in fig. 5.

This trend which shows strong replicability, is suggestive of the fact that for their respective discount rates, the L_{omin}-loaded SCIMs are the most cost-effective replacements – even the only economically feasible for case A. Therefore, for case A and at a discount rate of 15%, only the RR merits management's consideration and most likely would be the only economically acceptable option. In the same vein, at a discount rate of 8% as in case B, only 3 of the 5 SCIMs qualify for management's consideration and again, the RR, more than any other SCIM size, stands the best chance of acceptance.

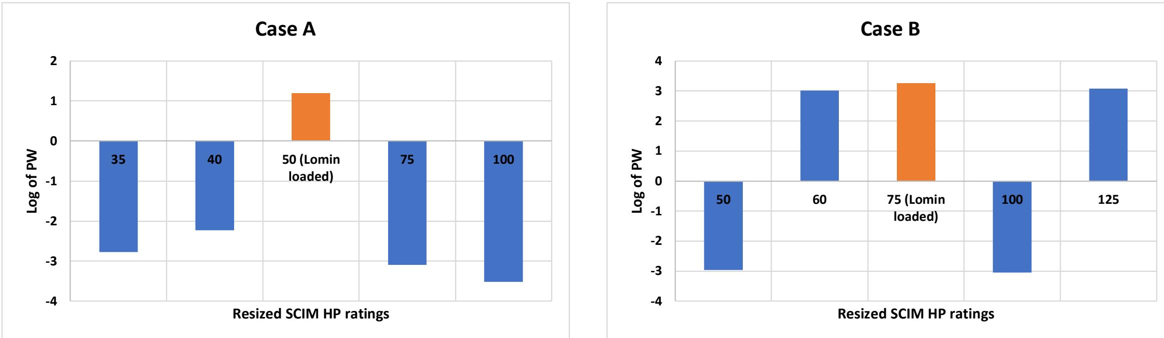

Fig. 5: Present worth (PW).

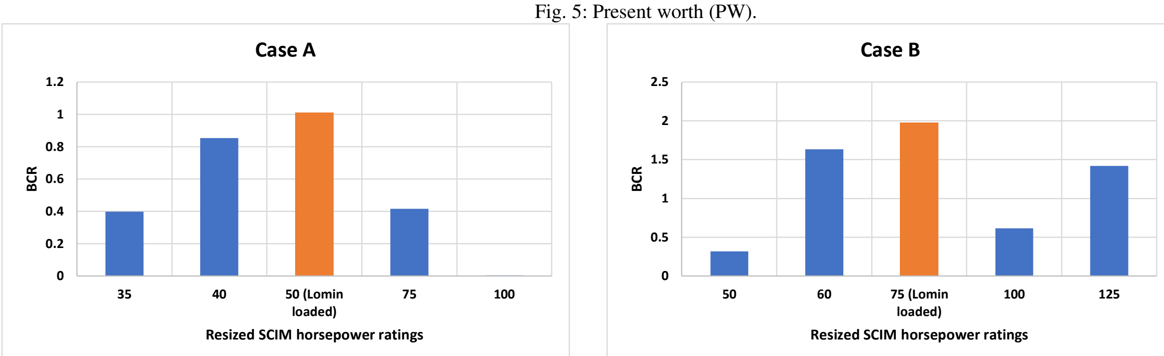

Fig. 6: Benefit-cost ratio (BCR).

E. Benefit-cost ratio (BCR)

The trend observed in the PW analysis seems maintained herein; further buttressing the superiority of the economics of the RR's in both cases A and B; since the BCR computation was done on the basis of the present value of the discounted benefits and costs.

It may be observed in fig. 6 that the BCR of investing in each SCIM was compared, and in case A, only the BCR of the RR exceeds unity at the chosen discount rate. Again, in case B, of all 3 SCIMs whose BCR's exceed unity, the BCR of investing in the RR appears clearly the greatest at case B discount rate.Even though the ratio itself is not a perfect indicator of the size of the profit but it is here giving support to the relative economic feasibility observed earlier with the PW discourse. For their economic attractiveness, management's decision is again most likely going to tilt in favour of the SCIMs loaded at L_{omin} (i.e., the RR's).

F. Life Cycle Costing (LCC)

One of the core needs of most stakeholders in the motor-run business is low-cost design that meets stated requirements.As we move from case A to case B, it may be noticed that the projected LCC of the RR's more or less maintains middle ground. The LCC of the RR is one of the lowest in case A and displays central tendency in case B. Overall, the projected LCC of the SCIMs appears weakly correlated with any single machine parameter or attribute, but rather seems to depend on many motor-related factors that include the initial purchase cost as well as ownership costs. The latter factor in turn will most often depend on usage patterns, maintenance, inherent qualitative factors that affect operating cost etc.

The SCIMs loaded at L_{omin} (i.e., the RR's) may not have declared the minimum long-term cost of ownership, but they reasonably prove to be one of the most cost-effective alternatives over their anticipated useful lives. On the basis of the LCC, the RR'sappear to be likely candidates for management's consideration.

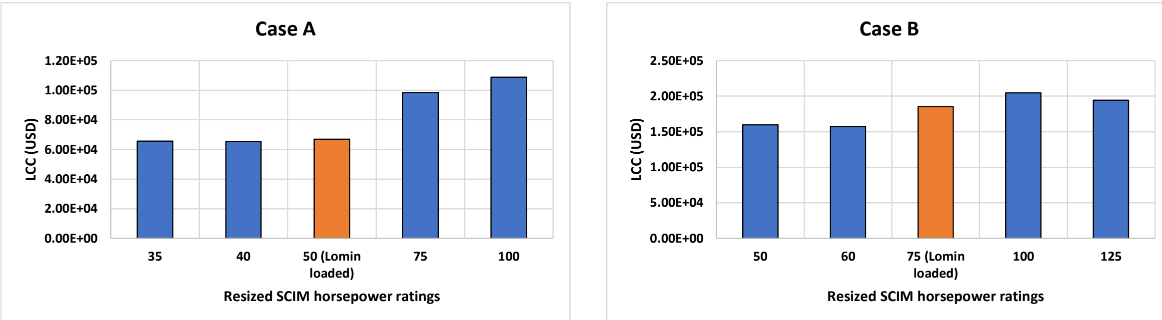

Fig. 7: Life Cycle Costing (LCC).

In sum, the foregoing results for case A show that virtually all the economic assessment tools project the SCIM loaded at L_{omin} (i.e., the RR) as best performing, except the SPP and LCC – where the RR gave the top performers a run for their money. About same goes for case B. The RR for case B is as well the best overall economic sizing, except for annual utility bills saving, where it finished in second place behind a larger gilt edge SCIM. The LCC also projects the RR of case B as second runner up. Also, for both cases and for the LCC, PW & BCR assessment methods that considerthe time value of money as well as the service life of the SCIMs; the SCIMs loaded at L_{omin} remain projected as the most profitable and cost-effective SCIM size by the PW and BCR assessments.

IV. CONCLUSION

The success or failure of engineering projects is known to be closely tied to economic factors, so it is critical for engineers to understand how their decisions affect outcomes. It is becoming ever more important that engineers and business managers understand the energy use and energy cost implications of their SCIM replacement decisions in order to continue to fulfill their roles sustainably and economically. This study emphasizes that computations regarding the cost-effectiveness and energy savings of motor purchase/replacement activities in the SCIM-driven business, appear more true-to-life when the chosen load rates accommodate a compromise between high operating efficiency and high power factor of the SCIM sizes under consideration. In the absence of a greener and more rewarding motor sizing strategic plan, the engineers in business are hereby encouraged to customarily determine the L_{omin} for the SCIMs in their production lines, and advise management accordingly to procure SCIM sizes that present in operation, the least overall active power losses in the system; in accordance with the results of this study. Some likely benefits of this energy management plan include: reduced energy costs, reduced emissions, reduced risk of energy price fluctuations, competitive advantage from green credentials, improved productivity etc. However, the domains of sustainability, performance, cost, schedule, and risk should ultimately align with the budget of the business.

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