International Journal of Electrical and Computer Engineering (IJECE)
Vol. 7, No. 4, August 2017, pp. 1661~1670
ISSN: 2088-8708, DOI: 10.11591/ijece.v7i4.pp1661-1670

Economic Efficiency Measure of Induction Motors for Industrial Applications

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Article Info

Article history:

Received Jan 11, 2017
Revised May 25, 2017
Accepted Jun 10, 2017

Keyword:

Economic efficiency measure
induction motor
Fixed and operating cost
Refurbished motor

ABSTRACT

This paper, introduced an expression of Economic Efficiency Measure (EEM) to permit quick evaluation for replacement of faulty induction motor with alternative (new or refurbished motor) for lowest life-cycle cost based on efficiency and rated-load conditions. This approach, simplifies the process for evaluating the energy efficiency to mere proportionate factor called as EEM. During the operating phase, the motor losses correspond to extra energy consumption, based on various parameters like motor operating conditions, operating hours, operating costs, fault factor, depreciation factor and fixed costs. The approach is effective in addressing the global issue on replacement of the faulty motor that needs a comprehensive analysis and mathematical expression. Compared to other alternatives the EEM provides a simple but effective and reliable means to asses, the feasibility of replacing or refurbishing the faulty motor. A detail analysis here would establish how much the present approach is effective in determining the replacement for a faulty induction motor either by a new one or refurbished one of corresponding rating.

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1. INTRODUCTION

The induction motor is the main driven system in industries, which consumes 30-60 percent of total electrical energy. Energy is utmost need in every field to perform activities whether it is residential, commercial, industrial, agricultural and host of alike applications. The need for energy conservation is vital but the best practice principle while selecting induction motor begins with analyzing the life cycle cost of the motor. Life cycle cost is a financial principle for selection of motors as they consume more than half the energy used by the plant [1].

In general, 65 percent of the total load is industrial load in India and 90 percent of this industrial load is induction motor load. It is a well known fact that induction motor operating at full load offers good efficiency, even at relatively modest kW-rating. However, at lower values than rated loads, which is common condition that many motor experience for significant portion of their service, their efficiencies decreases and increases losses so energy consumption is more in industry [2]. The efficiency of a motor is determined by intrinsic losses (fixed losses and variable loss) that can be reduced only by changing the design of the motor.
It is evident that optimizing efficiency of induction motors would significantly address this issue but major task lays mostly in its difficult controllability, due to its complex mathematical model, its non linear behavior during saturation effect and the electrical parameter oscillation which depends on the physical influence of the temperature. When induction motors are operated without a proper control (drive), the motors are consuming large energy and the operating costs are high. These physical and operational disturbances often cause failure of the motor, often replacement of the motor is considered as a viable solution but often to reinstall a failed motor after refurbishing could be economically feasible. The most common cause of

induction motor failure is due to the motor windings, and which can often be resolved by rewinding the old motor with in permissible limits. Unfortunately, the motor rewinding process often results in a loss of motor efficiency, which is the prime challenge in focus whether it is feasible to replace with a new motor or refurbish the failed motor.

Here, focus has been drawn to a common cause of motor replacement i.e. problem with the motor windings, and the solution often used is either replacement of the existing motor with a rewind or new motor. Henceforth, the proposed EEM determines the best possible, economically viable and pragmatic solution in terms of replacement with the rewind or new motor. From the scenario it is evident that refurbishing a faulty motor, its fixed cost is low but operating cost is high while replacing a faulty motor with new one its fixed cost is high while operating cost is low. Operating cost largely depends on the energy consumed by the motor which can be saved, either by improving/optimizing efficiency of IM drive.

Before deciding whether to purchase a new motor or refurbish the fault one, consideration regarding cost difference EEM, and relevant operational cost should be given preference. It is general understanding that the rewound induction motor would not perform better with reference to the new motors because these windings of refurbished cause additional losses because they produce unbalanced flux. Further, different horsepower refurbished motors would be studied for different types of losses so as to determine the overall efficiency of the induction motors. Then, these efficiencies are compared with the efficiencies of new induction motors of different hp. After that, it would analyze different cases whether it is better to replace the rewound induction motors with the new ones or not in the proceeding paragraphs.

2. BACKGROUND

The induction motor is without doubt the most used electrical motor and a great energy consumer in industries. An analysis have been done by determine the efficiency and life cycle cost comparison. Induction motor efficiency improvement is one of the most important energy saving options. Rewinding a motor consume more energy than new motor [1]. The energy saving in inductries can be done by determine the efficiency of rewound motor and compare it with the rated efficiency of that motor [2]. Energy Auditing based on life cycle cost comparison of Induction Motor have been analyzed [3].

When a motor fails, the basic decision of whether to rewind or replace will depend on the availability of a new motor and a rewind, their relative costs, operating costs, and availability of expense versus capital funds [4]. A simplified equation and figure are presented to permit quick evaluation of motor purchase alternatives for the lowest life-cycle cost based on efficiency and rated-load speed differences [5]. An economical method have been proposed to take deision for replacing the inefficient motors to efficient ones [6]. The method focusses on the field efficiency of motors without needs for removing motors and measuring output power. A detail study illustrated in [7] which determines the losses and efficiency of motors. The motive of their work was to assist in interpretation of measured efficiency data and in guidliing mitigation measures to be taken to improve accuracy cost-effectively. An anlysis on life cycle cost of motors have done in [8-10].

The comparison between new and rewound induction motor on the basis of various parameters of induction motor with different rating and losses are calculated. Then the life cycle cost of new and rewound induction motor on the basis of efficiency is also calculated. After analyzing the rewound motors, a recommendation is made to save electrical energy. The payback period of new and rewound induction motors has also been calculated [12-14]. A novel technique for estimating refurbished induction motors' full-load and partial-load efficiencies from onlyno-load tests have been discussed [15].The technique can be applied in any electric motor workshop which eliminates the need for the dynamometer procedure. It also eliminates the need for the locked-rotor test. An estimation of the efficiency of the machines after the refurbishment process have been done [16] in the workshops, which in fact can affect numerous machines in the industry.Their method proposed for the purpose which requires only the no-load test.

It is evident that incorporation of efficiency improvement techniques often yield similar results in case of new and refurbished motors. Henceforth, it cannot be used as a measure to analyze whether replacing a burnt motor with a new motor would be efficient or simply replacing with a refurbished one. Thus, the economics as a measure is considered which play a vital role in estimating the life cycle cost of the motor and presents a measureable and comparable value.

3. ENERGY ECONOMICS

In current energy management scenario, energy economics deals with strategizing of adjusting and optimizing energy, which interns reduce energy requirements for given operation. The fundamental goal of energy economics are [10]

a. To reduce energy dependency thus minimizing the environmental effects.
b. To minimize energy costs / waste while enhancing production & quality thus maximizing the profits of corporate sector

The objective of Energy economic efficiency is to achieve and maintain optimum energy procurement and utilization, throughout the organization while maintaining enhancing production & quality of the products. In general with reference to induction motor, the economic efficiency of a motor depends on three major components i.e. motor efficiency, motor cost (fixed and operating), operating hours and loading factors.

Motor Efficiency: The motor efficiency [17], [18] is defined as the ratio of the output power to the input power and is of paramount importance nowadays due to increasing electrical energy demand, increasing economic turmoil in fossil fuel prices, and other socio-economic factors. Energy losses are the determining factor in motor efficiency. The losses in the induction motor are typically divided into a) copper loss (stator & rotor), b) iron loss, c) friction and windage loss, d) stray losses and e) additional losses. The combined copper, iron and stray loss contribute to 90% of total motor losses.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_c - P_{rc} - P_{scl} - P_{Al}}{P_{in}}$$

$$\eta = 1 - \frac{(motor\ losses)}{P_{in}}$$

where,‘ η’ is the motor efficiency, ‘P_{in}’ is power input, ‘P_{out}’is power output, ‘P_c’ is core losses, ‘P_{rc}’ is rotor copper losses, ‘P_{scl}’ is stator copper losses, ‘P_{Al}’is the additional losses of the inductor motor in general discussion. The efficiencies of New and Rewound Induction Motors at full load are tabulated in Table 1 after determining the above losses. The results can also be seen in Figure 1 which shows that for lower rating of induction motor (15 hp and 20 hp) there is not so much difference, but at higher rating of motor the variation of efficiencies increases.

Table 1. Efficiency of New and Rewound Induction Motors at Full Load

HP	Efficiency of New Motor	Efficiency of Rewound Motor
15	93.71	91.09
20	94.47	85.47
50	96.01	84.11
100	96.75	89.89

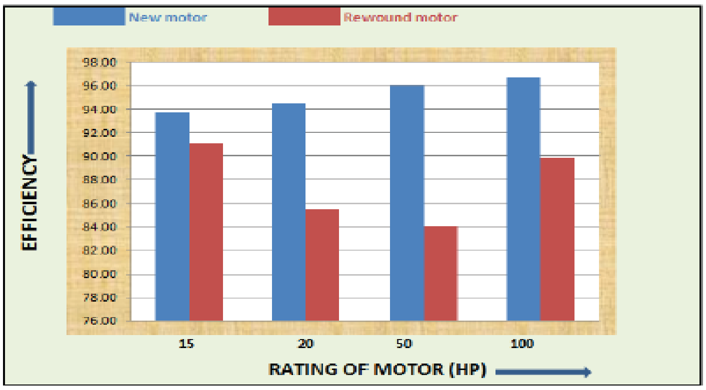


Figure 1. Efficiency vs Rating of New and Rewound Ims

The operating efficiency of any motor is determined by its original design, the quality of the construction or rewind, how heavily it is loaded and the quality of the power supply. If one were to relate to the manageability of the cost or potential cost savings, then the feasibility function constitutes a strategic area for cost reduction. The exact impact of motor efficiency will vary with the flux density of the original/rewinding winding and the motor load. Voltage unbalance can have a dramatic impact on motor efficiency. The rewound (or) refurbished induction motors would not perform better with reference to the new motors because the windings of refurbished cause's additional losses because they produce unbalanced flux as presented in Table 1 and corresponding efficiency is presented in Figure 1.

4. PROPOSED OBJECTIVE FUNCTION

Fixed and operating cost: The fixed cost is the bare cost of the induction motor (new/refurbished) in discussion and the operating cost is defined as the cost at which the motor is operated, it is critical to measure as it gives detail information about the motor operation. The operating cost is vital because they account for 90 percent of the power used by induction motor.

In addition, the costs of energy efficient motors are in general higher than those of regular common used motors due to several modifications in its construction which results in improved performance. The total feasible cost of induction motor is defined as the summation of the fixed and operating cost that will often be paid back rapidly in saving operating costs, particularly in new applications or end-of-life motor replacements [10]. To calculate total feasible cost, the price of new/refurbished induction motor is needed, its total operational hours, the current power tariff, motor efficiency and the load factor are given as;

$$T_{fc} = pp + TC * H * \eta * Lf \quad (1)$$

where,' η' is the motor efficiency, load factor 'Lf', 'H' is total number of operating hours, 'TC' is power tariff. The energy economics tends to provide the information about efficiency scenarios where existing motors have not reached the end of their useful life. The favorable economics of energy-efficient motors are based on savings in operating costs of the induction motor. Unfortunately, there may be certain cases which are generally economically ill-suited to energy efficient motors. These include highly intermittent duty or special torque applications such as, traction drives, hoists and cranes, punch presses, machine tools, and centrifuges. Further, the overall cost associated with induction motor of a plant is presented as below,

$$LCC = CP_p + CP_i + CP_o + CP_L + CP_d + CP_{Env} + CP_{Dec} \quad (2)$$

where, LCC =life cycle cost of the induction motor
"CP_p" = initial cost, purchase cost (motor, system, auxiliary services)
" CP_i" = installation and commissioning cost (including training)
"CP_o" = operating/energy costs (cost for system operation, including drive, controls, and any auxiliary services)
"CP_L" = operation labor costs and maintenance and repair costs (labor cost of normal system supervision)
"CP_d"= down time costs (loss of production)
"CP_{Env}" = environmental costs (contamination from pumped liquid and auxiliary equipment)
"CP_{Dec}" = decommissioning/disposal costs (including restoration of the local environment and disposal of auxiliary services).

Some parameters are introduced that would be considered in developing the objective function for new/rewound induction motor. This function will offer rewound and new motors Economic Efficiency Measure (EEM) that helps an industrial expert to decide whether to buy a new motor or refurbish the old one, it would wise to consider the cost difference between the as well as the relevant operational energy costs. In addition, analyze various scenarios whether it is better to replace the induction motor by rewound induction motors or buy new ones or not.

4.1. Initial/Fixed Cost Calculation

In general, the fixed cost is the price of induction motor (new/refurbished) but the price of the new motor reduces with time (i.e. depreciation factor) and in the case of refurbished motor the effect of depreciation factor is negligible (i.e. zero), hence forth the proposed fixed cost is presented as follows;

For New Motor

$$CP_p = pp_{new} * (1 + Dp) \quad (3)$$

For Rewound Motor

$$CP_p = pp_{rewound} \quad (4)$$

where,‘ pp_{new}’ is the purchase cost of new motor, ‘$pp_{rewound}$’ is the purchase of refurbished motor, ‘Dp’is the depreciation cost of the induction motor. The cost of different rating of induction motor (new/rewound) with depreciation factor of new motor for different hours are given in Table 2.

The operating cost of any motor is determined by its location of operation, operating hours, the motor efficiency, how heavily it is loaded and the quality of the power supply. In general, the location of operation and the quality of the power supply has significant impact on the failure rate of the induction motor. Since the refurbished motor and the new motor would be employed in same operating conditions and locations, we can ignore the failure rate of the motor as it would be the same.

Table 2. Costs for different ratings of Induction Motor

Rating (hp)	Depreciation Factor (%) 4hrs	8hrs	16hrs	24hrs	New Motor Price in Rs.	Rewound Motor in Rs.
15	18	30	50	100	66095	44284
20	18	30	50	100	77445	52090
50	18	30	50	100	205360	110895
100	18	30	50	100	461080	230596

4.2. Installation Cost Estimation

In general, the installation and commissioning cost of induction motor (new/refurbished) is cost of erecting machinery and the systemic interconnection for functionality of the motor to start the operations with the entire machinery running and all hands on their respective jobs. It is evident that the installation and commissioning cost of new motor (includes training) will be more than its cost for a refurbished motor.

4.3. Operating Cost Estimation

In general, the operating cost of induction motor (new/refurbished) is power used for the required work done but the operating cost of the new motor is low since the efficiency of the motor is high and in the case of rewound motor the operating cost is generally high as the efficiency of the motor would be low as presented in the Table 1, hence forth the operating cost ‘Fc’ is presented as follows:

$$Fc = TC * H * (1 - \eta) * Lf \quad (5)$$

where,‘ η’ is the motor efficiency, load factor ‘Lf’, ‘H’ is total number of operating hours, ‘TC’ is power tariff.

It is evident, that the motor efficiency vary with load. The maximum efficiency occurs where no-load losses equal load losses. The voltage at the motor terminals also has an effect on efficiency. The exact impact will vary with the flux density of the original design and the motor load. This unbalance between the motor efficiency and load factor can have a dramatic impact on motor operating cost. Hence forth the proposed operating cost function ‘Fc’ is presented as follows

$$CP_{o_{new}} = TC * \sum_i H_i * (1 - \eta_i) * Lf_i \quad (6)$$

or

$$CP_{o_{rewound}} = TC * \sum_i H_i * (1 - \eta_i) * Lf_i \quad (7)$$

Where,‘ $CP_{o_{new}}$ ’ and ‘$CP_{o_{rewound}}$’ are the total operating costs of the new and rewound motor respectively, ‘TC’ is power tariff (rupees per kWh), ‘H_i’total number of the operating hours when the loading factor is ‘Lf_i’ and the efficiency of the motor is ‘η_i’.

4.4. Labor and Maintenance cost

In general, the labor and maintenance cost of induction motor (new/refurbished) is cost of employed skilled personnel for the operation of the machinery and the systemic maintenance for smooth functionality of the motor during its operations. It is evident that the labor cost of new motor (includes training) will be more than its costs for a refurbished motor.

Unfortunately, the maintenance cost associated with new motor (includes regular checks) will be less than its costs for a refurbished motor. Henceforth, the authors consider the effect of labor and maintenance cost to have minimal to zero effect on choosing the induction motor i.e. new or refurbished.

4.5. Down Time Cost

In general, the down time cost is the loss in the production due to non-operational condition of the induction motor during the functional hours of the plant. It is evident that the downtime cost of new motor will be less than that of a refurbished motor. Further, the downtime cost is directly proportional to hours of operation. Hence, 8-15% loss is considered [11] as the difference in profit based on the number of operational hours.

4.6. Environmental Cost

In this paper, the environment cost of induction motor (new/refurbished) is considered which is same for new and refurbished induction motor.

4.7. Decommissioning/Disposal Cost

The decommissioning and disposal cost of induction motor (new/refurbished) is almost same for new and refurbished induction motor which consists of removal of the induction motor and transportation costs.

4.8. Proposed EEM

It is common understanding that simply replacing a faulted motor with a new motor rather than a refurbished (or rewound motor) could guarantee lower electricity bills. But the other factors as illustrated above have a potential impact in reducing the savings significantly. The potential savings have been presented as Economic Efficiency Measure (EEM).

$$EEM = (LCC_{new} - LCC_{Rew}) \quad (8)$$

Calculation for LCC_{new} and LCC_{Rew} is carried out on the basis of expression as below;

$$LCC = \left(CP_p + CP_o\right) * DTR_d \quad (9)$$

"DTR_d" is down time ratio for estimating the feasibility of the refurbished induction motor under different conditions. Further, EEM offers a simplified expression to determini the feasibility of new/refurbished motor. If (i) EEM is greater than zero, the rewound motor is best for consideration, (ii) EEM is less than zero, the only option is to prefer a new one.

5. RESULTS AND ANALYSIS

In this section, the results of the proposed objective function are presented considering various parameters and operating conditions to resolve the case of replacing the faulty motor with rewound/refurbished motor (or) new motor. The analysis has been carried out in steps, where each step analyzing a particular parameter in consideration in detail while the other parameters remain invariant. Further, during the entire simulations analysis some of the cost estimations are not considered as their contribution in the selection of economic feasible motor is limited or almost negligible.

Here, the operating hours of the motor and the costs are presented in Table 3 and 4 for 20 hp and 100 hp new and rewound induction motors.

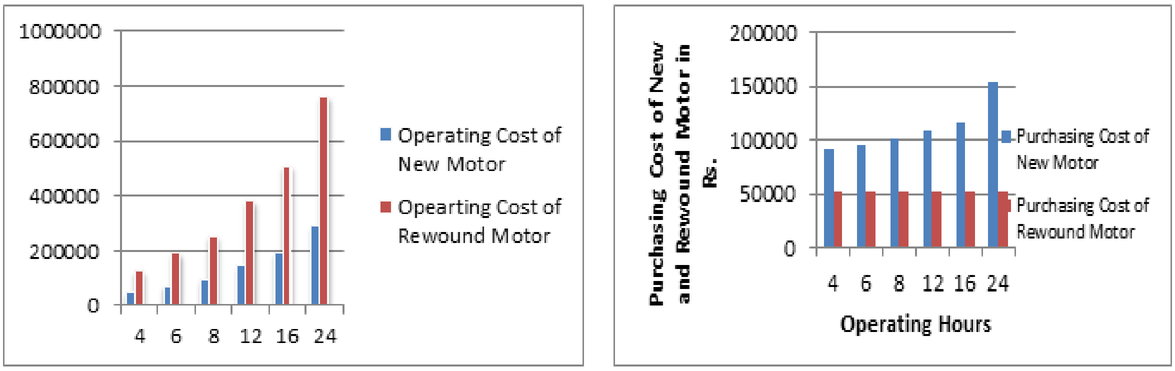
Table 3. The operating hours of the machine as the variable and the cost functions (20 hp)

Hrs	CP_o in Rs.		CP_p in Rs.	
	New	Rewound	New	Rewound
4	48443	127283	91385	52090
6	72664	190924	96032	52090
8	96886	254566	100679	52090
12	145328	381848	108423	52090
16	193771	509131	116168	52090
24	290657	763697	154890	52090

Table 4. The operating hours of the machine as the variable and the cost functions (100 hp)

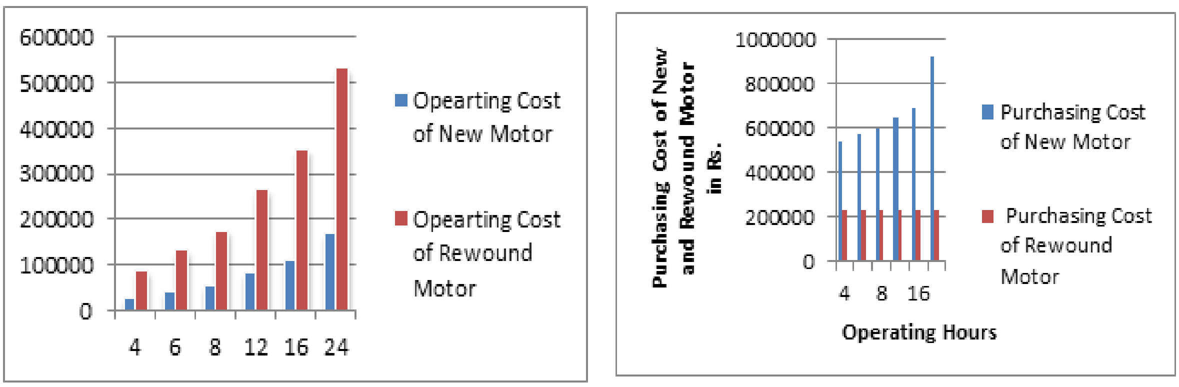
Hrs	CP_o in Rs.		CP_p in Rs.	
	New	Rewound	New	Rewound
4	28207	88564	544074	230596
6	42311	132845	571739	230596
8	56414	177127	599404	230596
12	84622	265691	645512	230596
16	112829	354254	691620	230596
24	169243	531382	922160	230596

From the results shown in Figure 2(a) and Figure 3(a) it is concluded that a new motor always operate at lower cost if properly designed, operated and maintained. Rewound motors have less efficiency, low power factor and operating costs are high. Henceforth, it is evident that the by applying optimizing algorithms and properly rewound with high quality materials could have a significant impact on the operation costs of the rewound motors rather than new motor. The difference between cost of new and rewound motor is very narrow in case of low hp induction motors as compared to the electricity consumption of low efficiency rewound motors. So, highly efficient motors should be install. Unfortunately, in case of high hp induction motors prices differences between the new and rewound motor is very large as compared to the electricity consumption of low efficiency rewound motors while operating for low working hours in operation.



(a) (b)

Figure. 2. (a) Operating cost of New and Rewound Induction Motor versus Operating Hours for 20 hp, (b) Purchasing cost of New and Rewound Induction Motor versus Operating Hours for 20 hp



(a) (b)

Figure 3. (a) Operating cost of New and Rewound Induction Motor versus Operating Hours for 100 hp, (b) Purchasing cost of New and Rewound Induction Motor versus Operating Hours for 100 hp.

From the results shown in Figure 2(b) and Figure 3(b) it is concluded that the depreciation value is always high for new motors in comparision with rewond motors. Further based on operating hour the value of depreciation increases which results is higher purchase price of the new motors operating at high operating hours. Henceforth, it is evident that the by applying optimizing algorithms for optimum operations and properly rewound with high quality materials could have a significant impact on cost of the motor.

For the further in-depth analysis, the EEM over tenure of 5years as the general lifetime of the industrial motor for 20 hp and 100 hp are shown in Table 5 and 6.

Table 5. The operating hours of the Induction Motors as the variable Vs EEM (20 hp)

Hrs	EEM 1st year	EEM 2nd year	EEM 3rd year	EEM 4th year	EEM 5th year
4	-52496.6	-141035	-229573	-318111	-406649
6	-94502.3	-229219	-363935	-498652	-633368
8	-137781	-319949	-502116	-684284	-866452
12	-227185	-506620	-786055	-1065490	-1344925
16	-320555	-701380	-1082205	-1463030	-1843856
24	-474786	-1050754	-1626723	-2202691	-2778659

Table 6. The operating hours of the Induction Motors as the variable Vs EEM (100 hp)

Hrs	EEM 1st year	EEM 2nd year	EEM 3rd year	EEM 4th year	EEM 5th year
4	233310	166150	98991	31831	**-35329**
6	224040	121970	19906	**-82161**	**-184230**
8	213880	76019	**-61842**	**-199700**	**-337570**
12	188900	**-22364**	**-233620**	**-444880**	**-656140**
16	161850	**-125780**	**-413420**	**-701050**	**-988690**
24	258780	**-176290**	**-611370**	**-1046400**	**-1481500**

During the analysis from Table 5, it is evident that the 20hp motor operating for 4, 6, 8, 12, 16 and 24 hours of operation per day for 5 years offers negative EEM (i.e.<0) proves that new motor is better suited in comparison with rewound motor for 5 years of operation.

Furthermore based on Table 6, the 100hp motor continuously offers positive EEM (i.e.>0) for the entire 24 hours in the first year, but it is positive for 4, 6 and 8 hours of operation in second year. For third year EEM is positive for 4 and 6 hours and in fourth year it is positive only for 4 hours operation. In the fifth year EEM is negative for all operation of hours.

Hence it is inferred that rewound motor is better choice in replacement for 1 year for 24 hours. As the year increases EEM decreases as shown in Table 6. The economic efficiency measure (EEM) provides a basic understanding wheather a new motor or rewound is the best fit for an application.

The EEM between refurbished and new motor characteristics for 20hp motor based on operating hour is per day and number of years the motor is operated is presented in Figure 4. The simulations anlayis show that formajor portion the curve offers EEM (<0) that indicates rewound motor is not suited while operation of low hp motor. While the EEM between refurbished and new motor characteristics for 100hp motor based on operating hour is per day and number of years the motor is operated is presented in Figure 5.The simulations anlayis show that formajor portion the curve offers EEM (>0) that indicates rewound motor is better suited while operating larger hp motor.

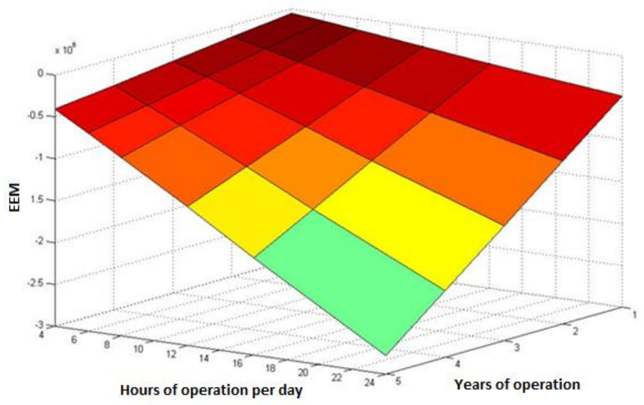


Figure. 4 EEM of 20 hp for 1-5 years “-ve” new motor and “+ve” rewound motor is the best replacement

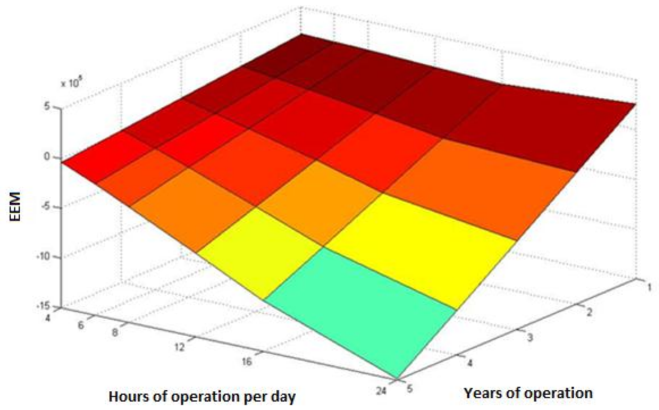


Figure 5. EEM of 100 hp for 1-5 years “-ve” new motor and “+ve” rewound motor is the best replacement

6. CONCLUSION

An EEM based analytical technique is introduced here to permit quick evaluation of replacing the faulty motor with alternative (new or refurbished) for lowest life-cycle cost based on efficiency and rated-load conditions. The technique includes modified parameters with reference motor operating conditions, operating hours, operating costs, fault factor, depreciation factor and fixed costs. The proposed technique effectively addresses the global issue of replacing a faulty motor under limited conditions and applications which are mentioned here in the preceding paragraph.

In this paper, EEM provides a simple but effective and reliable means to address the feasibility case of replacing or refurbishing the faulty motor. Based on the simulation analysis, it is concluded that the 20hp motor operating for 24 hours of operation per day for 5 years offers negative EEM (i.e.<0), while the 100hp motor continuously offers positive EEM (i.e.>0) for the entire 24 hours in the first year, for second year it is positive for 4, 6 and 8 hours of operation, in third year it is positive for 4 and 6 hours and it is positive only for 4 hours in fourth year. In the fifth year EEM is negative for all operation of hours.

Hence it is concluded that the 100 hp rewound in place of new motor of same rating offers an acceptable working conditions based on EEM. For first year EEM is positive in all operating hours of operation. Therefore it proves that the rewound motor may be feasible for replacement and it is best suited while operating as for 1 year. The information can then be used to guide future decisions regarding the investment in higher efficiency motors using payback period or present value analysis.

ACKNOWLEDGEMENTS

The authors would like thank and express their gratitude to Electrical Engg. Dept. and Computer Center of NIT Jamshedpur fore extending valuable technical support require to carry out this investigation.

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