Design of an energy efficient motor for irrigation pumps operating under realistic conditions

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Abstract: The issues involved in the design of energy-efficient high-performance irrigation pump motors operating under typical field conditions are highlighted. Various factors deserving consideration, from the predesign survey to the final design stage, are discussed in detail. By resorting to optimisation techniques, suitable objective functions were evolved to arrive at an improved design, which is constrained by industrial practices and performance requirements. The new design is compared with the standard design, and its salient features are discussed to suggest useful guidelines.

1 Introduction

Energy conservation has become an important aspect of industrial development due to uncertainties in oil supply as well as fluctuating prices and depleting stocks of conventional fuels. Optimum utilisation of resources and reduction of wasteful energy have therefore become areas of growing concern for engineering designers.

Induction motors are the major energy guzzlers in industries contributing to more than 80% of the electromechanical energy conversion. However, from the available data their operating efficiency under field conditions is often far from satisfactory. The design of induction motors has therefore been an area of continuous interest as reflected in the literature on improved designs [1-12]. Being a nonlinear problem, the motor design for a given objective function requires considerable efforts in formulating the problem and finding a suitable solution, which involves many iterative procedures. Design optimisation of an induction motor uses an appropriate nonlinear optimisation technique by (a) clearly defining the objective function or the quantity to be optimised (such as cost, size, efficiency, etc.), (b) judiciously choosing the design parameters (variables) and (c) intelligently specifying the constraints.

Although reducing motor size for the same power has been the main objective of the motor designers over the years, the oil shock of the early 1970s changed the emphasis to energy efficient motors. At present, most of the work in design optimisation aimed at energy conservation in induction motors is invariably related to efficiency as the objective function, since, efficiency has direct bearing on power consumption [7-14]. The efficiency can be increased by loss reduction, which can be achieved through reduced flux density, increased cross-sectional area of conductors and improved materials [14]. Improved manufacturing technique also results in a compact motor with reduced losses. Mechanical parts designs to reduce mechanical losses are also attempted.

Part from the industrial sector, induction motors find extensive use in the agricultural sector to drive irrigation pumps. In an agrarian country like India, millions of induction motor driven pumpsets are in operation throughout rural electrification networks. Studies have been conducted in India by several governmental and nongovernmental agencies. Poor performance of induction motor pumpsets has been identified as a critical factor to be tackled to improve the rural energy scenario [13]. A study conducted by Gujarat Energy Development Agency (GEDA) in India has indicated that a 5% improvement in overall efficiency of pumpsets (i.e. motor and pump) would save enough electricity to avoid building a new power plant of a few hundred megawatts.

Besides maximising the efficiency, there are additional problems to be tackled in the rural sector. Rural distribution networks operate in far-flung areas away from power generating centers. Due to this fact, utilities are finding it very difficult to maintain the purity of power supply, mainly in terms of regulated voltage. Wide variation in supply voltage in rural areas is a common occurrence which affects motor performance. Realising this fact, the Bureau of Indian Standards (BIS) modified the motor standard [15] to achieve the satisfactory performance for voltage range from —15% to +6% of the rated value. Furthermore, since India is located geographically in a tropical region, seasonal variation in the groundwater table is large, which poses variable loads to the motor. According to the pump manufacturers in India, since the 'load and discharge' of the pump are

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interrelated, power demand of the pump from the motor varies from 40 to 100%. Thus the motor should give energy efficient and improved performance throughout this range of power. A proper matching of the pump size with that of the motor is yet another problem, since consumers tend to couple oversized motors (to avoid failures) resulting in poor power factor and efficiency.

In view of the above complex problems faced by agricultural pumpsets in rural India, the Central Board of Irrigation and Power (CBIP) of Government of India sponsored a project to the authors. It was aimed at carrying out detailed investigation to develop an efficient high-performance motor (tailor-made for pump applications) which can operate under these constraints and still be able to provide improved energy conservation and reliability.

This paper reports the outcome of this project, considered nationally relevant in India. It provides an account of the authors’ experience in the design of three-phase induction motors for irrigation pumps operating under typical field conditions. Design optimisation has been used as a tool to study the effects of choosing different objective functions of the motor design and consequently to select the best design for such applications in the present context. The paper is centered around the application of design optimisation to solve the present problem with a view to obtain a modified design. The problems, constraints and complexities involved at various stages in the motor design are elaborately discussed with useful guidelines. The proposed design is compared with the existing design and its salient features are highlighted. Finally, payback analysis of the new motor is carried out to show profitability to the user.

2 Problem formulation and method of solution

As detailed in the preceding Section, the aim is to design an improved motor tailor-made for irrigation pumps and satisfying the following criteria:

(i) It must be built in a standard frame size, using available materials and industrial infrastructure.

(ii) It must have maximum possible efficiency over a range of power output from 40 to 100%.

(iii) It must have minimum possible energy consumption over a range of power output from 40 to 100%.

(iv) It must operate reliably over a range of voltage, from \( V_{	ext{min}} = 85\% \) to \( V_{	ext{max}} = 106\% \), delivering the above power.

(v) It must match the torque speed characteristics of the pump.

At this stage of study all aspects are covered except the last one.

The largest number of motors presently employed in Indian irrigation pumping systems are 5 hp and 3 hp (1500 rev/min at 50 Hz) ratings. As an initial step, design of a 5 hp diecast squirrel cage motor in IEC 112M TEFC frame (NEMA equivalent 182 T) is considered and discussed in this paper. Relevant details of the motor under consideration are given in Table 1. The design is carried out for 0.5 mm thick S18 (AISI equivalent M43) laminations. Of late, demand for 2 pole, 3000 rev/min motors is increasing, and the design methodology discussed here can be extended to these ratings.

2.1 Problem formulation

Mathematically, the general nonlinear multivariable constrained optimisation problem can be stated as follows [16, 17]

Find \( X (x_1, x_2, ..., x_n) \) such that

\[ F(X) \text{ is minimum subject to} \]

\[ g_j(X) \leq 0 \text{ for } j=1,2,...,m \]

and \( X_l \leq x_i \leq X_u \)

where \( X \) \( (x_1, x_2, ..., x_j) \) is the set of independent design variables with their lower and upper bounds as \( X_l \) and \( X_u \), respectively.

\( F(X) \) is the objective function to be optimised and \( g(X) \) are the constraints imposed on the design. In the present work, the following design variables \( X (x_1, x_2, ..., x_j) \) are considered

(i) Stator stack length, \( l_s \)

(ii) Average air gap flux density, \( b_{avg} \)

(iii) Stator conductor area, \( a_{c} \)

(iv) Stator slot depth, \( s \)

(v) Stator slot width, \( w \)

(vi) Rotor slot depth, \( k_r \)

(vii) Rotor slot width, \( w_r \)

(viii) End ring height, \( h_e \)

(ix) End ring width, \( w_e \)

(x) Bore dia, \( d \)

(xi) Air gap length, \( l_g \)

The remaining design parameters can be expressed either in terms of these variables or assigned fixed values for a particular frame size.

\( g_j(C) \) are the set of 10 explicit constraints imposed on the design to make it feasible and practically acceptable. Relevant constraints are imposed to meet the starting, thermal and other performance requirements of the machine. These constraints are generally the specifications given by the customers and the norms set up by the manufacturing standards like NEMA, BSS, etc.

It is a known fact that the motor for centrifugal pumps does not need to have a large starting torque. Data received from the pump manufacturers show that the pump to be used with the motor has a squared speed characteristic and that it requires a starting torque of 0.4 p.u. and a pullout torque of 1.5 p.u. rated motor torque. As such, the starting torque is not considered as a constraint on the design.

Table 1: Details of the motor under consideration

<table>
<thead>
<tr>
<th>Winding type</th>
<th>Stator material</th>
<th>Rotor material</th>
<th>Stator slots</th>
<th>Rotor slots</th>
<th>Pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>copper</td>
<td>aluminium</td>
<td>number</td>
<td>type</td>
<td></td>
</tr>
<tr>
<td>slots</td>
<td>36</td>
<td>24</td>
<td>flat bottom</td>
<td>semiflushed</td>
<td>1-8</td>
</tr>
</tbody>
</table>

Frame: IEC 112M, power: 5 hp, poles: 4, volts: 415, frequency: 50 Hz, insulation: B, enclosure: TEFC

As the present design is restricted within the given frame, the outer diameter of the stator is fixed. Furthermore, the various dimensions considered for modifications are limited within their respective lower and upper bounds as per the requirements of the frame and feasibility of the design.

22 Optimisation technique

The sequential unconstrained minimisation technique (SUMT) has been used widely in the design optimisation of induction motors. Direct search methods in conjunction with SUMT have been found to be the best suited to rotating machine design optimisation problems. In this paper, SUMT with interior penalty function approach by employing a direct search method, namely Rosenbrock’s Method of rotating coordinates has been used [5, 7, 8, 16, 17]. The selection of the numerical programming technique has been made by especially keeping in view the simplicity in formulation and familiarity of the authors with the technique, details of which have already been reported [7].

The developed optimisation package uses design procedure based on time tested and reliable formulae to estimate the model parameters and performance. The effect of magnetic saturation on reactance, torque, losses, etc. has been incorporated through an iterative procedure; while stray load losses and effect of other secondary phenomena have been estimated with certain empiricism, which has been evolved from the experience of working with machines in production over a period of time.

3 Results and discussion

Characteristics of the standard motor are shown in Fig. 1. Increasing full load efficiency and reducing input kVA of the motor are required. It can be seen that, at voltages other than rated, performance of the motor varies considerably. Further, performance at part loads is much poorer than that at rated load. Thus a motor with an improved design should perform better than this standard motor in all the aspects mentioned above.

Since the problem addresses realistic conditions, the choice of the objective function (OF) needs a systematic study. Energy conservation in rural networks means reduction in total consumption of electricity. One may have a resort to a ‘systems’ approach to tackle the problem. There are losses in the motor which need to be minimised and hence, the choice of efficiency as an objective function for design optimisation of energy efficient motor, in general, is valid. But poor motor power factor aggravates losses in the motor winding and distribution/transmission lines, which reduces utilisation of generating unit capacity and necessitates installation of power factor improvement devices. Hence a choice of input kVA to the motor as an objective function becomes an interesting case for investigation.

To arrive at a suitable design for the present problem, optimum designs are obtained to tackle each aspect individually (as mentioned in Section 2) and to compare them with the standard design. Based on the observations made from these individual designs, a final design is evolved which is a proper mix of individual designs.

3.1 Design I

Fig. 2, shows characteristics of an optimum design with full load efficiency as the objective function. Although the full load efficiency of the motor is higher and the effect of voltage variation is slightly lower than that in standard
motor, it draws much higher kVA. Furthermore, considerable difference still exists between part load and full load efficiency.

3.2 Design II
If input kVA is taken as an objective function, the resulting motor has the characteristics shown in Fig. 3. Here, the overall efficiency and input kVA at rated and higher voltage levels are better than that of the standard design, but performance of the motor at lower voltage is dismal.

3.3 Design III
An attempt is made to improve the characteristics of the motor at lower voltages by designing the motor for full load efficiency (OF) at 85% of the rated voltage. The characteristics of such a motor is shown in Fig. 4. The motor has uniformly higher efficiency at lower voltages, but it performs poorly at higher voltages.

3.4 Design IV
To have uniformly high efficiency of the machine over a range of load, a design is attempted by taking maximization of efficiency at 50% rated load as the objective function. As seen from Fig. 5, although it is possible to achieve almost a flat efficiency characteristics of the motor for rated and higher voltages, it has highly deteriorated performance at lower voltages.

3.5 The proposed design
It is seen that designs solely based on individual aspects do not give performance which can be considered superior to the standard design in all the required aspects. However, a closer observation reveals that there are mutually exclusive advantages for each individual design. If now a proper mix of these designs is obtained, it would give the desired performance.

To arrive at such a design, a mixed objective function is used, which is in the form

$$ \text{OF} = k_1 \cdot \text{OF}_1 + k_2 \cdot \text{OF}_2 + k_3 \cdot \text{OF}_3 + k_4 \cdot \text{OF}_4$$

where $k_1, ..., k_4$ are weightages given to different objective functions, OF$_1$ to OF$_4$ used in the four designs discussed above.

A number of trials were made for different combinations of ks to arrive at the final objective function. Based on this, $k_1 = 0.125$, $k_2 = 0.1$, $k_3 = 0.2$ and $k_4 = 0.6$ have been chosen. Discussion will be focused on some detailed observations of the optimum design obtained for this mixed objective function.

3.5.1 Performance: Fig. 6 shows characteristics of the final design based on the mixed objective function. Here, a uniformly high efficiency over the range of load is noticed. The effect of voltage on the performance is reduced compared the case of the standard motor. Further, the kVA requirement of the machine is reduced by more than 3% at rated load and voltage, and the efficiency is increased by 2.3%.

Most of the energy efficient designs reported in the literature belong to the category of Design I (where full load efficiency is the objective function). With Design I, a full load efficiency of 86.2% is achievable as compared to 83.7% for the standard design and 86% for the proposed (mixed) design. As compared to Design I, the input kVA
of the proposed design is reduced over 10%, while the efficiency is at almost the same level. Furthermore, effect of variation in load and voltage on the performance of the motor with the proposed design is much reduced. Thus, suitability of motor design based on the mixed objective function is justified for driving irrigation pumps in typical field conditions of varying load and voltages.

3.52 Design details: Table 2 gives design details of the standard design and the proposed optimum design. It can be seen that the proposed motor has a larger core length, deeper and wider slots, larger end rings and a reduced air gap length. Furthermore, the new machine uses fewer stator conductors but they are of thicker gauge. The machine operates at lower air gap flux density and lower current density.

3.5.3 Cost aspect: Although the design is restricted within a standard frame, the proposed design requires more active material and is 15% more expensive than the standard motor.

The designs discussed so far are without any cost constraint. Now an attempt will be made to determine the effect of constraining the design with mixed objective function by cost. Cost is introduced as an additional constraint in the list of constraints shown in Section 2.1. Different optimum designs are worked out for different values of cost. Further, an additional design is worked out using minimisation of cost as the objective function.

Fig. 7 shows variation of full load efficiency and kVA of these designs at rated voltage for different costs. Here, A corresponds to an optimum design with minimisation of cost as an objective function. B, C and D correspond to designs with the proposed objective function but with a cost 100, 105 and 110%, respectively, of the standard motor cost. E corresponds to the proposed design which is not constrained by cost. The efficiency and kVA for these designs are drawn taking corresponding values of standard design as a reference (i.e. 83.7% and 5.223 kVA, respectively).

It can be seen that there is a gradual improvement in the performance of the motor as the cost is gradually relaxed from Design B to Design E. Although the cost

Table 2: Design details of the standard and the optimum motor

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Standard design</th>
<th>Optimum design</th>
</tr>
</thead>
<tbody>
<tr>
<td>stator stack length, l</td>
<td>125.00</td>
<td>140.00</td>
</tr>
<tr>
<td>average air gap flux density, b_g</td>
<td>0.724</td>
<td>0.664</td>
</tr>
<tr>
<td>stator conductor area, a_s</td>
<td>36.83</td>
<td>46.56</td>
</tr>
<tr>
<td>stator slot depth, h_s</td>
<td>17.25</td>
<td>17.81</td>
</tr>
<tr>
<td>stator slot width, w_s</td>
<td>3.09</td>
<td>3.69</td>
</tr>
<tr>
<td>rotor slot depth, h_r</td>
<td>17.30</td>
<td>17.66</td>
</tr>
<tr>
<td>rotor slot width, w_r</td>
<td>5.58</td>
<td>6.19</td>
</tr>
<tr>
<td>end ring height, h_e</td>
<td>22.00</td>
<td>26.20</td>
</tr>
<tr>
<td>end ring width, w_e</td>
<td>11.00</td>
<td>12.98</td>
</tr>
<tr>
<td>bore dia, d_b</td>
<td>103.00</td>
<td>103.01</td>
</tr>
<tr>
<td>air gap length, l/</td>
<td>0.33</td>
<td>0.30</td>
</tr>
<tr>
<td>number of conductors per stator slot, N</td>
<td>58 (64)</td>
<td>56 (64)</td>
</tr>
<tr>
<td>standard wire gauge, SWG</td>
<td>21 (20)</td>
<td>19 (18)</td>
</tr>
<tr>
<td>efficiency</td>
<td>83.70</td>
<td>86.00</td>
</tr>
<tr>
<td>power factor</td>
<td>0.84</td>
<td>0.85</td>
</tr>
<tr>
<td>kVA</td>
<td>5.233</td>
<td>5.061</td>
</tr>
<tr>
<td>Cost (Rupees)</td>
<td>1920</td>
<td>2288</td>
</tr>
</tbody>
</table>

b_g is in Tesla, while linear dimensions are in mm; **SWG-British Standard Wire Gauge number, figures in brackets pertain to near equivalent American Standard Wire Gauge number (AWG) and ** 1 UK £ = 40 Indian Rupees (approx.)
optimised design A is found to save over 15% of the active material cost, its performance is much poorer than that for the standard motor.

![Diagram](image_url)

**Fig. 7 Effect of cost on performance of motor**

(Numbers within brackets show material cost for different designs as percentage of that of standard design)

5.4 Payback analysis

Commercial success of an energy efficient motor depends on its profitability to the user in terms of early payback of the extra cost involved. An analysis [14] carried out gives a "payback period of about 8 months. This corresponds to rated operating conditions of the motor for 5000 h/year at a power cost of Rs. 1.25 per kWh.

In the present application, since the motor is to operate over a wide range of voltage and load, the operating efficiency and hence, the payback period will vary accordingly. Calculation shows that the payback period of the proposed motor is the least for 85% operating voltage at rated load. It is an interesting result since most of the target users are in rural areas where voltage level is generally low.

4 Conclusions

A detailed study on design modification of a three-phase 5 hp induction motor for improved performance in typical field conditions has been carried out. Design optimisation is resorted to, to obtain designs that are constrained by industrial practices and performance requirements. The optimum designs for different objective functions are critically examined and choice of suitable objective functions for the given application has been proposed.

The optimum design based on the proposed mixed objective function gives a motor having uniformly high efficiency over a wide range of load and supply voltage. It is seen that, within the same frame size, the full load efficiency of the new motor is about 2.5% more than that of the standard motor, and that its input kVA is 3% less than that of the standard motor. The active material cost of the proposed design is 15% more than that of the standard motor, but the extra cost is paid back within a reasonable period, which is calculated to be less than a year for the prevailing cost structure.

Although matching the motor to the pump has not been considered (which the authors intend to offer for publication at a later stage), effectiveness of the technique adopted has been demonstrated as can be seen from the results.

5 References

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