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PROCESS & DESIGN OPTIMIZATION OF PTCR HERMITIC MOTORS

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ABSTRACT

The objective of this work is to present the correlation involving hermitic motor efficiency, voltage range, startability, motor cost and actual process optimization.

Motor Design is the delicate balancing of many independent variables to meet a number of design constraints. Motors designed for refrigerator hermitic compressors have to ensure that the system (compressor and load) shall start and run without overheating in the designed voltage range. In India for the last three years, hermitic compressor manufacturers are attempting to accept the PTCR motor designs for Refrigerator applications. The emergence of six sigma concepts has triggered lot of momentum in the process optimizations. Electrolux paid much attention in proving and practicing the PTCR designs in full-fledged way with optimization studies and implementations.

This paper presents how the process and designs were optimized at Electrolux Kelvinator Limited compressor plants in India. The work has been done with reference to Indian tropical and inherent power supply conditions with Startability, Wider Voltage Range, Efficiency and Value Additions as project requirements along with process optimizations.

INTRODUCTION

Objectives & Methodology:

In the field testing the initial SA PTCR compressors had given some tropicalization problems like inconsistencies in Startability and Operating Voltage ranges in comparison with the designed conditions.
Initial compressor performance tests were conducted at Electrolux research labs. A correlation between reported customer feedback and lab test results was established in order to make the design work acceptable for the final tests.

Lab tests identified inconsistencies in the test results i.e., voltage range varying from 170 to 260V instead of 160 to 260V and startability varying from 165 to 175V instead of designed 160V.

Along with the above requirements, inherent Indian power supply conditions ranging 160 – 260V, 50 Hz and 52°C ambient conditions emphasized the authors for thorough investigation and optimization studies. Since the overall parameters are not consistent, a project for improvement was accomplished.

In the initial optimization studies, we had reviewed the induction motor unbalanced magnetic pull forces of Sawhney [1] and also performance standards review was made from measurements as given by Koteswara Rao [4]. Frame PCDs, Rotor tapering, concentricity, Stator winding resistance specifications vis-à-vis samples were verified. A Quality Circle was formed for the estimations of process capabilities. Finally it was identified that manual air gap setting process resulting inconsistencies in the startability and operating voltage range.

Based on the different global engineering and performance standards of refrigerators, improved design simulations were conducted to finalize new PTCR motors.

**ANALYSIS**

**A. Process Optimization:**

Unbalanced magnetic pull is very large in induction motors. This is because, even a small eccentricity cause a fairly large unbalanced magnetic pull as the length of the air gap is very small. Every care must be taken to keep this air gap uniform around the rotor periphery. In Induction motors where the length of air gap is very small and therefore even a slight eccentricity may cause saturation.

The unbalanced magnetic pull due to p poles

\[ \frac{1}{4} u_0 B_m^2 D L \int_{\theta=0}^{\pi} \sin^3 \theta d\theta = 0 \]

Where

- \( B = B_m \sin \theta \)
- \( D = \text{Stator Bore} \)
- \( L = \text{Axial Length} \)

It is necessary to allow dimensional tolerances during the process of manufacture of hermitic motors. Dimensional tolerances are allowed for Frame, Rotor and Crankshafts. Tolerances results in variations in the length of the air gap which give rise to unbalanced magnetic pull, particularly in pull down tests at
high load conditions leads to starting ability variations. Unbalanced magnetic pull for the worst conditions found when the eccentricity is coincident with the axis of maximum flux density.

The uneven air gap setting motor is shown in fig.1.A. Also rotor displayed motor is shown in fig. 1.B.

**Feeler gauge CAN design:**

As per the motor design parameters a gap setting, ranging from 0.15 to 0.25 mm was allowed. A Can was used with 0.15 THK X 3 W X 12 NOS. feeler gauges around the air gap for setting. Considering the possible unbalanced magnetic pull and stator alignment disturbance with the available handling and transit practices and also peak conditions of pull down tests, a new can was designed with the below mentioned methodology [3].

Fig 2.a shows the stack out of squareness or face to bore measurement scheme. If face to bore squareness is checked near the bolt holes not at point 'B' then the new length, say AB’ must be taken into account.

For easier withdrawal of the Can a production concession of 0.040 to 0.050 max out of squareness was allowed. This was for manual withdrawal only. For machine withdrawal, the Pull should be set against a face and hence the dimension could be reduced.

\[
F_B = AB \sin \theta = A \ B \sin (\tan^{-1} x/Lc)
\]

\[
= A \ B \sin(\tan^{-1} (D_1-D_2)/Lc)
\]

A feeler Can of 0.23 THK X 3 W X 4 NOS. design finalized as shown in fig 2.B. With the above improvements, C_{pk} was observed as 2.85 from 2.15.

**B. Design Optimization:**

The main design objectives considered were to keep the performance same as that of existing motor and to improve the locked rotor torque and to optimize the copper content as much as possible. Therefore the operating flux was kept as exactly same as of existing motor.

The finalized motor definition & functional optimization parameters as follows:

- **Efficiency**: To keep same as that of existing
- **Torque**:
  - **Starting Torque (ST)**
  - **Break down Torque (BDT)**: Ratio improvement
- **Winding Temperature**: < 130°C
- **Starting Ability**: 3% below min design voltage (155V)
Harmonics : < 5%  
Cost reduction : $0.25

Refrigerator with double door 165 liters capacity was selected for the lab tests, as this product relates to higher end applications.

**Engineering standards of the refrigerators used for analysis:**

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Test</th>
<th>Conditions</th>
<th>Approval Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Short cycle start test</td>
<td>Ambient 43.3°C: 160-260V Most severe control cycle</td>
<td>Product shall start w/o tripping: &lt;3 trips/24 hrs</td>
</tr>
<tr>
<td>2</td>
<td>Pull down test</td>
<td>Ambient 43.3°C Soaking 16 Hours</td>
<td>Product must start at stabilized conditions</td>
</tr>
<tr>
<td>3</td>
<td>Short duration power interruption test</td>
<td>Three minutes run cycle &amp; 2 sec Off cycle &amp; Start</td>
<td>Compressor has to recover within 45 minutes</td>
</tr>
<tr>
<td>4</td>
<td>Ultimate trip test</td>
<td>Extreme high load –thermal load (blanketing condensor etc.)</td>
<td>Product must overload before 150 °C wdg temp</td>
</tr>
<tr>
<td>5</td>
<td>Extreme low voltage test</td>
<td>21°C ambient Voltage starts from 45 V</td>
<td>Winding temp should not exceed 190°C</td>
</tr>
</tbody>
</table>

**Compressor approval conditions on Calorimeter:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Load</th>
<th>High Load</th>
<th>Low Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap. Temp (°C)</td>
<td>-23.3</td>
<td>-6.7</td>
<td>-29.8</td>
</tr>
<tr>
<td>Suction/Discharge (Psig)</td>
<td>4.5 / 183</td>
<td>21 / 249.5</td>
<td>0 / 140.5</td>
</tr>
<tr>
<td>Equalized pressure for startability (Psig)</td>
<td>60</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>Ambient temp (°C)</td>
<td>32</td>
<td>46</td>
<td>32</td>
</tr>
</tbody>
</table>

**Startability Model:**

The design has to ensure that the minimum torque (ST) is higher than the maximum torque (BDT) that the pump needs for starting plus a safety factor. That breakdown torque is given by the worst starting case expected, taking into account system characteristics, friction variation at the bearing surfaces, lower and higher temperatures expected. Note that this torque is a mechanical requirement and does not have any connection with the motor voltage or other motor characteristics.
Induction and applied voltage in a given motor are linked by the no of turns used in the motor windings. By choosing the no. of turns, any magnetic induction (torques) can be obtained before magnetic saturation occurs. The following startability model [5] was considered for torque calculations.

Torque balance equation \[ T_M - T_c = I \cdot \omega \]

Linear drive equation \[ T_M = SLT + \left[ T_{3000} - \frac{SLT}{3000} \right] \cdot \omega \]

Ramp up Torque \[ t = \frac{1}{C_1} \cdot \ln \left( \frac{\omega - C_3}{C_3} \right) \cdot C_3 / C_2 \]

We determined the margins from the specifications and test data available. Then, with the help of computer program, simulations were made to optimize motor design definition. The optimization studies considered material cost and manufacturing possibilities.

**Design Simulations:**

That compressor had a starting voltage about 168V at given condition. That voltage was considered high, mainly because the compressor was designed for the south Indian Market, where voltages under 160V are expected. The compressor and motor data:

- Capacity : 456 Btu/h
- EER : 3.7
- Load torque : 2.85 Kg.cm
- Motor efficiency @ 230V : 68.7 %

The parameters that the old motor started at 168V were

- Starting Torque : 4.55 Kg. cm
- Breakdown torque : 10.76 Kg.cm

It was found during preliminary test that ST/BDT ratio in the motor was higher and design simulations done to lower the ratio. A minimum starting voltage lower than 160 V was asked and expected that the EER was preserved.

The motor design simulations were done keeping winding temperatures as 120°C at 160, 230 and 260V supply conditions. A 10% increase in main winding wire diameter resulted, 2.5 % and 0.6% improvement in Breakdown torque and locked rotor torque respectively. A 5% decrease in main winding turns resulted, 5% and 3% improvement in breakdown torque and starting torque respectively. Starting winding turns simulation not shown improvement. Also 5% increase in rotor resistance through skew angle change, shown 4% increase in locked rotor torque but no improvement in breakdown torque.
Consolidating the above simulations at an extrapolated winding temperatures, a final cost effective motor design was approved. Prototype samples were made and the results noted were:

- Efficiency @ 230V : 68.3%
- Starting torque : 4.94 Kg. cm
- Breakdown torque : 13.70 Kg. cm
- Starting voltage noted : 154 V

The modified motor performance curves shown in fig. 3.0. The motor started and ran without problems at the designed voltage range. The compressor efficiency was maintained because efficiency reduction was not noticeable and also mechanical improvements compensated the differences.

**CONCLUSIONS**

The compressor startability and voltage range has strong impact on the motor efficiency, and if a given efficiency is necessary, the motor cost will be very dependent on this range.

Better understanding of the product engineering standards and correlation of the standards with motor design simulations along with the process capabilities improvement resulted cost effective solutions.

This effort has optimized the process and designs of PTCR motors in all aspects.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

FIGURE 1. A
UNEVEN AIR GAP MOTOR

FIGURE 1. B
MOTOR WITH ROTOR DISPLAYED

FIGURE 2.A
STACK OUT OF SQUARENESS

FIGURE 2.B
MODIFIED FEELER CAN

CAN WALL THICKNESS: \((D2-D3)/2\)
FIGURE 3.0
MODIFIED PTCR MOTOR PERFORMANCE CURVES