Energy savings on induction motors

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This is an abridged version of a paper that investigates the possibility of obtaining power savings by reducing voltage supply of squirrel cage induction motors (SCIM) that are running at low load factors.

It is known that the load factors of some squirrel cage motors used in some industries have values in a region of 0.1 to 0.4. This value suggested that for relatively long periods the motors could run close to no-load. This suggests that such motors are either grossly oversized or are cycling with significant time spent near no-load or idling duty. A typical variable load profile is shown in Fig. 1.

The objectives

There are two fundamental assumptions considered in motor design and operation. First, at full load operation the SCIM is fully loaded, magnetically and electrically. The second one is that the electrical load is reduced at low loading while the motor remains fully magnetically loaded.

Therefore, one could ask a logical question: “Can the magnetic loading be reduced with the motor running under nominal load to improve part-load efficiency?”

The research objectives were to conduct an evaluation of the effects of supply voltage variation on various components of motor power losses and the motor efficiency as a function of supply voltage variation.

The experiments

The simulation study was done on a 15 kW, 1760 rpm, 460 V 23 A, 91.2%, EPACT, TEFC, NEMA design SCIM. This motor type and size are common in sawmills, usually found operating at low loads for long periods.

Research methodology

Phase 1: Setting of the motor model. A squirrel cage induction motor design program was used to generate a mathematical model “MM1” that simulated the performance characteristics of the motor.

Phase 2: Simulating the loads. The MM1 model was used to simulate various working regimes of the motor running at 60 Hz (no-load, idling at 20% load, actual load, rated load).

Phase 3: Site measurements and setting the baseline. The load profile was obtained by measuring input power and time intervals related to a planer saw divider (sawmill).

The loading profile:

\[ P_1 = 9.24 \text{ kW (≈ 60% load factor); operating time } T_1 = 1110 \text{ h/year.} \]

Unloading profile:

\[ P_2 = 3.15 \text{ kW (≈ 20% load factor); operating time } T_2 = 3530 \text{ h/year.} \]

Short description of the experiment

Simulations were conducted on the mathematical model (motor system) to obtain the performance profile under various loads and voltages:

- Load factor as function of output power at 10%, 20%, and 35%
- Supply voltages as function of rated voltage at 100%, 60%, 50%, 40%, and 35%

The power losses data obtained at each load point as a result of simulating the motor at 100% of rated voltage is considered the reference case \( P_{\text{loss, ref}} \).

The power saved \( \Delta P \) is equal to the reference value \( P_{\text{loss, ref}} \) minus the \( P_{\text{loss}} \):

\[ \Delta P = P_{\text{loss, ref}} - P_{\text{loss}} \]  

The minimum of total power loss \( P_{\text{loss, min}} \) will coincide with maximum value of \( \Delta P \).

This process is repeated for all desired load points. The congruence of test results indicates the consistency of the method.

General observations

For a given loading, the total power losses of the motor \( P_{\text{loss, ref}} \) have the following components:

- Iron losses \( P_{\text{Fe}} \) are a function of the magnetic loading and the supply voltage.
- Stator and rotor copper losses \( P_{\text{Co.St + Ro}} \) are a function of the electrical loading and the rotor speed.
- Friction and windage losses \( P_{\text{F&W}} \) are constant.
- At reduced part-load stray losses \( P_{\text{LL}} \) are relatively small and thus considered constant.

The results indicate that the total power losses \( P_{\text{loss, min}} \) decrease with load \( P_{\text{load}} \) and reach a minimum value at various supply voltages. Friction and windage and stray losses (not being shown) are considered constant.
required and iron losses \((P_{Fe})\) become higher values of magnetic loadings are at load factors greater than 0.5 because magnetic loading become insignificant. Power savings obtained by reducing the characteristic is shown in Fig. 2. Below its rated speed value. This parabolic rotational speed of the rotor decreases losses becomes very significant when the copper losses \((P_{Co.St} + R_{o})\) are dominant. The proportion of the rotor copper to the effect of increasing copper losses further, the total losses increase again due function of the applied voltage. This could be explained by the weight of the iron losses reduction \([\% of P_{loss}, 100]\) 61\% 45.3\% 25.9\% Reduced voltage \(E_{i} [100\%] \) 703 W 731 W 796 W Saved power \([W] \) 429 W 331 W 206 W Loss reduction \([% of P_{max,i}] \) 61\% 45.3\% 25.9\% Saved power \([% of P_{e,full}] \) 19.5\% 8.9\% 3.4\% Table 1: Minimum losses of a 15 kW motor at 20\% load factor.

<table>
<thead>
<tr>
<th>Item</th>
<th>Load factors of the motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output shaft power ([% of P_{in}] )</td>
<td>10% Pout 20% Pout 35% Pout</td>
</tr>
<tr>
<td>(P_{loss,i}@ ) full voltage (E_{i} [100%] )</td>
<td>703 W 731 W 796 W</td>
</tr>
<tr>
<td>Reduced voltage (E_{i} [% of E_{i}] )</td>
<td>30% 50% 60%</td>
</tr>
<tr>
<td>(P_{loss,i}@ ) reduced voltage ([W] )</td>
<td>274 W 400 W 590 W</td>
</tr>
<tr>
<td>Saved power ([W] )</td>
<td>429 W 331 W 206 W</td>
</tr>
<tr>
<td>Loss reduction ([% of P_{max,i}] )</td>
<td>61% 45.3% 25.9%</td>
</tr>
<tr>
<td>Saved power ([% of P_{e,full}] )</td>
<td>19.5% 8.9% 3.4%</td>
</tr>
</tbody>
</table>

Table 2: Power savings as function of load factor and reduced voltage.

| Load factor \([% of P_{in}] \) | 10\% 20\% 35\% |
| Speed \(N @ E_{i,nom} [rpm] \) | 1796.1 1792.4 1786.8 |
| \(E_{i} [\% of E_{i}] \) | 30\% 50\% 60\% |
| Speed \(N @ [rpm] \) | 1753 1762 1762 |
| \(\Delta N / N \) [\%] | 2.4\% 1.3\% 1.4\% |
| \(\Delta E \) [\%] | 70\% 50\% 40\% |
| \(\Delta N / N \) [\%] per \(\% \) of \(\Delta E \) | 0.034 0.026 0.035 |

Table 3: Speed variation as function of voltage variation.

| Output power \([% of P_{e,full}] \) | 10\% 20\% 35\% 50\% |
| \(n_{nom} @ E_{in} \) | 68.2 80.4 88.8 89.8 |
| \(E_{i} [\% of E_{i,nom}] \) | 30\% 50\% 60\% 80\% |
| \(\Delta E / E_{i,nom} \) [\%] | 70\% 50\% 40\% 20\% |
| \(\Delta N / N \) [\%] per \(\% \) of \(\Delta E \) | 0.232 0.156 0.075 0.055 |
| Saved power \([W] \) | 429 W 331 W 206 W 110 W |

Table 4: Efficiency and power savings as a result of voltage reduction.

This could be explained by the weight of the iron losses that are a quasi-parabolic function of the applied voltage. When reducing the supply voltage even further, the total losses increase again due to the effect of increasing copper losses \((P_{Co.St} + R_{o})\). The proportion of the rotor copper losses becomes very significant when the rotational speed of the rotor decreases below its rated speed value. This parabolic characteristic is shown in Fig. 2.

Power savings obtained by reducing the magnetic loading become insignificant at load factors greater than 0.5 because higher values of magnetic loadings are required and iron losses \((P_{Fe})\) become constant, and the required electrical loading becomes more significant and therefore the copper losses \((P_{Co.St} + R_{o})\) are dominant.

At higher load factors, the electrical and magnetic loading of the motor are closer to their rated design values and additional power savings with voltage variation diminish. Therefore, when various motor losses are more significant and the copper losses are dominant, such as at higher load factors, the proportion of the iron losses reduction becomes insignificant when the supply voltage is going to be reduced (keeping the rotor speed at rated values).

Estimating power savings by using mathematical model The total power losses \((P_{loss,i})\), efficiency and power factor with the motor mechanically loaded at a load factor of 20\% and supplied at variable voltages \(E_{i}\), are shown in Table 1. As shown in Table 2, there is a significant opportunity for motor losses reduction at reduced voltages when motors operating at low loads of near or less than 0.35 output shaft power.

Evaluation of power savings and efficiency The paper evaluated the increase in simulated motor efficiency by varying the power supply voltage for various motor load factors. The results of the expected efficiency gain \(\Delta \eta \) [\%] are shown in Table 4 in absolute power savings for the 15 kW motor.

Energy savings obtained for a 15 kW motor installed on this particular application (planer/saw/divider in a sawmill) are: \(ES = 0.331 \ kW \times 3530 \ h/y = 1.16 \ MWh/y\)

This value of energy saving would be used by a customer and a utility to calculate the payback period (if an enabler is installed) and when customer sends an incentive application for this specific energy conservation measure.

Mention must be made of the high value of power losses on transmission – this could be addressed during maintenance activity.

If transmission efficiency could be improved, the load factor on “unloading profile” could drop from 20\% to 10\% and the energy savings could become: \(ES' = 0.429 \ kW \times 3530 \ h/y = 1.514 \ MWh/y\)

This new value of energy savings can shorten the payback period by about 30\% !

Conclusions Power savings can be obtained by varying the voltage supply to squirrel cage induction motors running at low load factors (typically 0.4 to 0.5) For motors operating at low mechanical loads, minimum power losses can be achieved by manipulating the motor’s magnetic loading, which traditionally is considered constant.

Motor performance simulations conducted on a 15 kW motor at various motor shaft loads and under various power supply voltages using specialised motor design software, indicated power savings of up to 2\% and up to 20\% of the total input power at motor loadings of 0.5 and 0.1 respectively can be achieved by varying the supply voltage.

The findings of this study suggest a method of evaluating possible power savings for any SCIM prior to installing such a control device.

Acknowledgment The authors gratefully acknowledge the valuable support of using SCDES2 that brought value to the paper.

The software was used with permission and courtesy of Dr. Charles F Landy, cflandy@esi-mo.com. Contact Dr. Constantin D Pitis, BC Hydro, constantin.pitis@bchydro.com.

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