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Predicting Inverter-Induced Harmonic Loss by Improved Harmonic Injection

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Abstract—This letter presents an improved harmonic injection method for determination of inverter-induced harmonic power loss across a range of induction motors rated at 1.1, 7.5, 15, and 30 kW. Techniques to obtain the necessary experimental precision and repeatability are investigated in detail. The harmonic injection method allows the machine to be tested under normal operating conditions while a range of selected harmonics are superimposed on the fundamental frequency of the pulse width modulation (PWM) waveform. This technique is validated by direct loss measurement using a specially built calorimeter capable of detecting power loss as low as a few watts in induction motors of up to 30 kW. Comparisons of segregated losses by IEEE 112 method B for the machines operating on sinusoidal and inverter-fed supplies show a good correlation between high frequency PWM harmonic loss and core loss. Core loss is not a constant proportion of total loss for any machine and neither is harmonic loss independent of machine design.

Index Terms—Harmonic analysis, induction motors, loss measurement, power conversion harmonics, pulse width modulation inverters, variable speed drives.

I. INTRODUCTION

The additional power loss, relative to operation from sinusoidal supplies, incurred by operating induction motors from inverter supplies has been a research topic virtually since power electronic inverters were introduced [1]–[4]. The use of inverters for adjustable speed drives (ASDs) induces new time harmonics into the airgap flux of the machine under control which are not present in a pure sinusoidal voltage supply and which do not normally contribute to the power output developed by the machine. These harmonics, in turn, produce high levels of distortion in the stator voltage and current waveforms caused by pulse width modulation (PWM) switching. In terms of load components, voltage harmonics tend to give rise to core loss—current harmonics to conductor loss. At times, the total harmonic loss is significant and even dominant, for example, for operation from early six-step inverters or from PWM inverters with low frequency ratios between the carrier and base frequency. Under these conditions, some degree of success in predicting the additional loss has been achieved [5], [6]. At other times, it is observed as being insignificant when describing the operation of low-power drives with high PWM frequencies. Modern low-power (up to 30 kW) PWM inverters normally have a higher carrier frequency of up to 20 kHz; the consequent harmonic loss only accounts for a small fraction of the total machine loss. As a result, experimental measurement or analytical prediction of the additional loss becomes a challenge [3]. For those drives greater than 30 kW, limited carrier frequencies give rise to harmonic power loss. This feature is of particular importance, with a growing concern about motor drive system efficiency [7].

Previously, the harmonic injection method has been attempted [8], [9] to assess the harmonic loss in induction motors, but earlier work suffered from low accuracy in measurement and a limited harmonic frequency range. In this study the technique is fully implemented experimentally and validated by direct power-loss measurement using a specially built high-precision calorimeter which ensures a stable testing environment and accurate power-loss measurement. In addition, the technique is extended to include harmonic frequencies up to 25 kHz.

II. HARMONIC INJECTION METHOD

The principle of harmonic injection methods is to add a certain amount of a specific harmonic to the supply waveform (such as a PWM waveform) and to evaluate the effect precisely. Realistically, the order of this harmonic should exceed 10 times the fundamental so as to reduce the torque ripple and speed variation. Also, this injected harmonic should be of relatively significant amplitude so that its effect can be measured with some accuracy. For a particular frequency of injected harmonic, the harmonic loss is proportional to the square of the harmonic voltage and is therefore here normalized to 1 volt of harmonic aid to subsequent calculations and analyses. This ratio is termed harmonic loss factor $K_h(n)$ with units of mW/\(V^2\).

$$K_h(n) = \frac{P_{\text{loss}}(n)}{V_n^2} \tag{1}$$

where \(P_{\text{loss}}(n)\) and \(V_n\) are the harmonic power loss in mW, voltage in V at order \(n\), respectively.

By injecting a range of harmonics, one by one, from several times the fundamental up to half the effective sampling frequency of the PWM generator, a harmonic-loss-to-frequency characteristic curve (for this particular machine) may be obtained. This is later used to predict the harmonic loss at other frequencies. Extending the frequency range further requires use of the sidebands of the carrier together with their harmonics that are consequent on the added signal. By curve-fitting to expand the prediction of harmonic loss to still higher frequencies from the plot, a formula can be derived with reasonable precision. Yet, increasing extrapolation would give rise to measurement uncertainty. This formula, together with the harmonic spectrum for a particular inverter operating at a defined modulation index, frequency ratio and fundamental frequency, can be employed to predict the total inverter-induced harmonic loss. It is worth
emphasizing that the loss prediction must be for an operating condition where the stator current and the fundamental flux are equivalent to those applicable when $K_h$ is measured.

Defining a function describing the variation of the harmonic power loss with harmonic frequency is a common approach [9], [10]. In the literature, there is general agreement that two principle terms are required. One term describes the behavior of increased core loss in the machine with increasing frequency, while the other describes that of conductor loss. By a least-squares method, the harmonic loss factor can be decomposed into two parts [11]

$$K_h(n) = \frac{A}{f_n^\alpha} + \frac{B}{f_n^\beta}$$

(2)

where $A$, $B$, $\alpha$, and $\beta$ are the corresponding correlation factors to the particular machine under test and $f_n$ is the harmonic frequency.

In (2), two harmonic loss components representing low-frequency and high-frequency components, are primarily associated with conductor and core losses, respectively. They can be derived from the harmonic power characteristic curve. A typical plot of normalized harmonic losses versus harmonic frequency from experimental tests is shown in Fig. 1. A general observation is that the conductor loss plays a dominant role at the low-frequency end of the harmonic spectrum but gradually diminishes to insignificant levels with increasing harmonic frequency, even though skin effect is taken into consideration. In contrast, the core-loss component extends to high frequencies and includes loss in both main and leakage flux paths. This partially explains why it is difficult to be predicted analytically. It is suggested that skin effect in the machine lamination may eventually lead to core loss with increased frequency [10]. Certainly, the gradient of the experimentally obtained curve at high frequencies can be very shallow, making extrapolation a critical factor.

The dependence of harmonic loss on load current arises from the fact that saturation conditions in the leakage flux paths and main flux paths through cross saturation change with load current [12]. This is particularly the case for skewed rotors with closed slots, which is a common form of induction machine construction.

III. EXPERIMENTAL SETUP AND IMPROVEMENTS

Preliminary investigation by the authors suggests that there is room for improvement in the accuracy and repeatability of harmonic injection tests and in the frequency range of measurement.

A. Test Rig and Instrumentation

A schematic of the experimental test rig is illustrated in Fig. 2. The test rig uses Ward–Leonard type speed control of the dc machine to produce variable loads. The dc generator supplying the dc load machine is coupled to the ac generator that supplies the test motor. Both generators are driven by a vector-controlled induction motor using a 15 kW Eurotherm inverter to provide precise frequency control of the ac voltage. In essence, this vector drive only needs to make up the system losses. A Norma D6000 power analyzer is used to measure electrical parameters including voltage, current, frequency, slip and power factor, and is calibrated against a Datron-Wavetek 4705 calibrator to an accuracy of better than 0.1%. Voltage dividers, LEM current transducers and a 12 bit LeCroy digitizer operating at 500 k samples per second per channel are employed to record two line-to-line currents. As for fundamental voltage, the power analyzer is employed to extract its amplitude during the tests for Fourier analysis and for correcting any drift in fundamental level.

In addition to the fundamental component, it is also vital to measure the injected harmonic voltage and current with precision and to compensate the phase-angle errors. At high harmonic frequencies the phase angle difference between voltage and current approaches 90° and, consequently, a small error in phase angle measurement can lead to a relatively large error in the indicated power. These errors are evaluated by comparing the digitized signal from voltage and current sources measured, respectively, by a wideband coaxial current and by a wide band potential divider with those from the measuring transducers. Phase-angle errors stored in the computer are then used to correct the digitized signals and to evaluate the injected harmonic powers. The sampling of the voltage and current signals is synchronized to the clock controlling the production of the synchronous PWM generator. Therefore, inter-harmonic components are eliminated and repeatable results can be obtained from the harmonic analysis algorithm.

B. Extending the Frequency Range

Previously, the authors employed Transtech transputers for computation of the PWM switch periods and thus the results suffered from a limited frequency range; the maximum carrier frequency was only 5.1 kHz. In this study, the frequency range has been effectively extended to 25 kHz by using an 8 kHz, regular asymmetric, PWM generator and an SAB 167 microcontroller with some additional digital logic to enhance the controller’s built-in PWM generator. The injection system is based around a 22 kW IGBT inverter with enhanced cooling to allow for the additional switching losses in the devices. The expanded frequency range also improves prediction accuracy of harmonic loss with high carrier frequencies.
C. Controlling the Test Conditions

The direct determination of the harmonic loss at a frequency implies a comparison of two test results, one being the loss measurement made on a machine operating from a pure sinusoidal supply and the other from an inverter. The importance is self-explanatory—to obtain the same fundamental supply and load conditions between the two tests. Even tiny changes in the fundamental voltage, current, or load would produce significant variations in the fundamental loss that might invalidate the harmonic loss. As illustrated in Fig. 2, the test motor is directly fed from the generated sinusoidal supply and the stable loads are guaranteed by the Ward–Leonard configuration. The variation between the two testing conditions is within a couple of watts of the total fundamental power loss. Ideally, the ambient and machine temperatures are also repeated between the two tests. The significance lies in the fact that stator-winding conductor loss generally appears to be the primary loss component for low-power machines. This problem is overcome by conducting the tests inside a specially built 30 kW calorimeter [13] where the ambient temperature is controlled to be less than 0.1 °C of the setpoint.

D. Harmonic Loss Magnitude

Similar to the segregation of stray-load loss using the input-output method [13], harmonic loss is also given by subtracting two large quantities to yield a much smaller value of power loss. The difficulty is obvious and long standing. The use of the high-precision calorimeter in power-loss measurement can ease this problem, since this calorimeter is capable of measuring power loss to an accuracy of better than 0.2%.

IV. Results and Discussion

In this study, four 50 Hz four-pole induction motors of 1.1, 7.5, 15, and 30 kW (labeled A to D) were carefully tested inside the calorimeter. These were all standard production motors provided by different manufacturers so that the relative impact of core and conductor losses could also be observed. A single-turn search coil was installed in each machine along with one phase of the stator winding. This was used to check the similarity of the fundamental magnetizing conditions of the sinusoidal and inverter tests. All the inverter-fed injection tests were carried out with an 8 kHz PWM carrier frequency and a fundamental of 25 Hz, making available additional harmonics of substantial magnitude before reaching over-modulation. After the harmonic-loss-to-frequency characteristic was obtained, loss prediction could be extended further to include harmonics of up to 25 kHz. These were not injected in the experiments but were present in the harmonic spectrum for the specific inverter in use.

A. Test Under Sinusoidal Supply

The four motors were first tested when operating from sinusoidal supply voltages to determine their component losses and efficiency in accordance with IEEE 112 Method B [14]. Both no-load and full-load tests were conducted in the calorimeter so that accurate readings of total power loss and a stable testing environment could be achieved. The full-load tests also provided the stator conductor loss using the phase-current and equivalent star-connected resistance. This resistance was determined by plotting back to switch-off time values of stator-winding resistance. These were measured at less than 30-s intervals over a 3-min period, following a switch-off on completion of the approximately 6-h constant-load calorimetric test. This differs
from the IEEE standard method of stator resistance measurement. Using the Norma D6000, the rotor conductor loss was determined directly from the output power, windage and friction losses, and the accurately measured slip. Core loss was obtained from a series of no-load tests performed at different supply voltages. The power loss from windage and friction, and that due to stator resistance and stator current, was subtracted from the no-load input power. The supply voltage was corrected for the voltage drop in the stator resistance and a quadratic function fitted to the relationship between core loss and the square of the corrected supply voltage. This is the second difference from the IEEE standard method—and an improvement. The quadratic function was used to determine the core loss at full load where the supply voltage was again corrected for the voltage drop in the stator resistance.

The segregated losses for the four test motors are given in Table I for comparison. Of the four motors, A, B, and C were operated at full load and motor D was only for 2/3 load owing to the inverter power capacity. Nonetheless, this reduced load should not be seen as having influence on the measurement of harmonic loss. Previous study has indicated that the load conditions may be ignored when harmonic frequency is in excess of approximately 7 kHz [11].

### B. Repeatability Test

At the outset of the harmonic loss measurement, it is necessary to check the repeatability of the methodology and facility used for harmonic injection. This was carried out on machine B by performing two injection tests on two different days. The test results were superposed in Fig. 3. From this figure, two features of the harmonic-loss factor curve can be clearly observed. First, the repeatability of the harmonic power-loss tests is very good. Second, the curves are not totally smooth. This latter effect results from interactions between the injected harmonics and the rotating saturation vector in the machine due to the fundamental flux. The interaction is a modulation process which leads to sidebands of the injected harmonic being developed. These are separated from that harmonic by the fundamental frequency. When sidebands occur at a frequency where there are other harmonic sources of current, there will be an interaction and false power readings. The true smoothed curve lies through the centre of this noise.

### C. Segregation of Harmonic Loss

Fig. 4 shows the variation of $K_h$ changing with frequency for machines A to D. From this figure, the similarity of the curve shape is self evident. When plotted on the logarithmic scale, considerable relative difference is presented, especially at high frequencies. For machine A in Fig. 4, $K_h$ falls off very quickly with increasing frequency. The results for machine B show at full load: $K_h$ becomes almost constant above 15 kHz. For machines C and D, the curves display a further increase in $K_h$.

<table>
<thead>
<tr>
<th>Motor</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power loss (W)</td>
<td>194.9</td>
<td>490.4</td>
<td>937.8</td>
<td>859</td>
</tr>
<tr>
<td>Power loss (%)</td>
<td>59.9</td>
<td>40.3</td>
<td>47.9</td>
<td>28.5</td>
</tr>
<tr>
<td>Stator conductor loss</td>
<td>76.8</td>
<td>367.6</td>
<td>475</td>
<td>604</td>
</tr>
<tr>
<td>Stator conductor loss (%)</td>
<td>23.6</td>
<td>30.2</td>
<td>24.3</td>
<td>20.1</td>
</tr>
<tr>
<td>Core loss (W)</td>
<td>33.3</td>
<td>189</td>
<td>239</td>
<td>1013</td>
</tr>
<tr>
<td>Core loss (%)</td>
<td>10.2</td>
<td>15.5</td>
<td>12.2</td>
<td>33.7</td>
</tr>
<tr>
<td>Windage &amp; friction losses (W)</td>
<td>7</td>
<td>44</td>
<td>84.8</td>
<td>331</td>
</tr>
<tr>
<td>Windage &amp; friction losses (%)</td>
<td>2.2</td>
<td>3.6</td>
<td>4.3</td>
<td>11</td>
</tr>
<tr>
<td>Stray load loss (W)</td>
<td>13.5</td>
<td>125.3</td>
<td>221.4</td>
<td>203</td>
</tr>
<tr>
<td>Stray load loss (%)</td>
<td>4.1</td>
<td>10.3</td>
<td>11.3</td>
<td>6.7</td>
</tr>
<tr>
<td>Total fundamental loss (W)</td>
<td>325.5</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Total fundamental loss (%)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Predicted harmonic loss (injection)</td>
<td>6</td>
<td>30</td>
<td>42</td>
<td>244</td>
</tr>
<tr>
<td>Predicted harmonic loss (%)</td>
<td>1.8</td>
<td>2.5</td>
<td>2.1</td>
<td>8.1</td>
</tr>
<tr>
<td>Measured harmonic loss (calorimeter)</td>
<td>8</td>
<td>31</td>
<td>57</td>
<td>235</td>
</tr>
<tr>
<td>Measurement error</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>
as would be expected for larger machines. Moreover, $K_h$ almost doubles at low harmonic frequencies for fully loaded machines. As the power rating is doubled while at high frequencies, machine D is much lossier than twice machine C. Fig. 5 is used for a further comparison between no-load and full-load conditions on machine B. It can be seen that the curves for both loads are approaching a constant value as harmonic frequency increases. This confirms the independence of high-frequency harmonic loss on load condition.

### D. Determination of Total Harmonic Loss

The total harmonic loss across a wide range of frequencies was predicted by the harmonic loss factor technique with reference to the spectrum analysis of that inverter used in the test. Experimentally, it was also directly measured by the calorimeter for validation. These results are also given in Table I, together with an estimate of the error in measurement between tests. From the comparison, the agreement between the direct and indirect methods of harmonic loss determination is extremely good. Although there are still errors involved in the $K_h$ evaluation, the calorimetric results clearly justify the use of the harmonic injection technique. Table I also provides a comparison between the additional harmonic loss at the 8 kHz PWM carrier frequency and the total fundamental loss. It is obvious that the harmonic loss accounts for a small fraction of the total loss for machines A to C. Machine D seems to have a great proportion (8.1%), but this is misleading because the fundamental loss is for 2/3 load only. Clearly, the higher carrier frequency would be expected to make the harmonic loss insignificant.

With regard to the core loss, machine D has the greatest percentage core loss among the four machines, followed by machines B and C. The percentage of predicted harmonic power loss faithfully reproduces these changes. This would be expected because high-frequency harmonic loss associated with high-carrier PWM frequencies is acknowledged to be due to core loss, even though skin effect gives rise to conductor loss. Yet, such a correlation between harmonic and core losses can only be said to be positive but not linear.

### V. Conclusion

The additional harmonic content of PWM inverter supplies relative to pure sinusoidal supplies would unavoidably result in an increase in machine conductor and core losses owing to the increased RMS current and the peak flux density respectively. High-frequency PWM inverters for small motors may produce negligible additional harmonic loss in machines, which appears as core loss and accounts for a small proportion of their total fundamental loss. For larger drive systems, the additional harmonic loss can be significant and therefore impacts on the overall system efficiency. In the literature, prediction of the harmonic loss generally involves theoretical analysis and numerical simulation but lacks experimental verification.

This letter has presented an improved harmonic injection technique which adds a range of harmonics in the fundamental frequency to indirectly predict inverter induced harmonic loss while the machine is operated under normal operating conditions. The results are validated by direct measurement using a high-precision 30 kW calorimeter. Experimental results of four test motors show a good agreement between high-frequency PWM harmonic loss and fundamental core loss. Machine D, with the relatively high proportion of harmonic loss, suggests that larger machines, where the core loss is a greater proportion of the total loss, may benefit from PWM frequencies in excess of those normally employed in high-power IGBT inverters in terms of loss reduction.

### APPENDIX

Details of the test motors are provided in Table II.

### ACKNOWLEDGMENT

The authors wish to acknowledge the contribution of Dr. R. Magill in preparing some of the results.

### REFERENCES


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