

Comparison of Stray Load and Inverter-Induced Harmonic Losses in Induction Motors Using Calorimetric and Harmonic Injection Methods

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Abstract

This paper addresses two types of additional losses in induction motors. One is stray load loss resulting from loss segregation when induction motors operate from a sinusoidal supply voltage and the other is harmonic loss when induction motors operate from inverter-fed supply voltage. Both losses are of concern in machine design and operation but they are difficult to predict accurately without the use of empirical factors. This is due to their complex loss mechanisms and small magnitudes in most cases. Investigation into the correlation of the two loss components could enable effective quality control of the manufacturing of machines for use on inverter supplies. With the availability of advanced calorimetric and harmonic injection techniques, it becomes possible for these small loss components to be measured with precision. In this paper, seven induction motors ranging in power through 1.1, 7.5, 15 to 30 kW are tested for experimental comparison. Among these are four 7.5 kW machines. Test results suggest there is a need for induction motors designed specifically for inverter-fed operation.

1 Introduction

When operated from a sinusoidal supply voltage, induction motors have a residual loss component termed "stray load loss" which is not accounted for by loss segregation of the total power loss. When operated from an inverter-fed supply voltage, induction motors have an extra loss termed "harmonic loss" resulting from the characteristic harmonics of high frequency switching. Both the losses have received much attention in the literature [2-5,7-13,15-19]. However, it would be of interest to know their connection, if there is any, in nominally identical machines. That is, if an induction motor has a high stray load loss would it also have a high harmonic loss. The significance of this question lies in quality control of production. If stray load and harmonic losses do not relate with each other at all or they do but not in proportion, it may be necessary to have a wider range of quality control measures to ensure efficiency levels when manufacturing machines for application on inverter supplies than is required for those intended solely for normal mains

operation. Work on this subject has never been reported previously.

At first glance, the intuitive answer may be that stray load and harmonic losses change with certain correlation or even pro rata since they stem from similar harmonic components by their nature. Yet, proving with precision if this is correct requires advanced experimental techniques to be developed simply because both the additional losses are complicated mixtures of loss components and they are extremely difficult to quantify precisely. Therefore much effort of this paper is put into the development and application of those techniques to a small group of test machines.

Developments in the high precision calorimeter [3,14] enable power losses to be measured to a high level of accuracy whatever the nature and harmonic content of the voltage supply to the machine under test. A purpose-built calorimeter used in this study is capable of measuring the power loss in machines rated up to 30 kW. Determination of the traditional loss and separation of the stray load loss are in accordance with IEEE 112-B [22].

The harmonic injection facility [4] includes a specially modified inverter with complete freedom over the generation of the pulse width modulation (PWM) signals supplied to the IGBT power stage. This allows for the combination of the fundamental PWM modulating wave with one or more harmonics of smaller amplitude, independent frequency and phase sequence. The harmonic loss is measured via high frequency sampling of line voltage and current.

In order to ensure a stable testing environment, harmonic injection experiments are conducted within the 30 kW calorimeter. When the test machine reaches its thermal balance, harmonic injection procedures can then be carried out. By analyzing the frequency spectrum of a PWM scheme, the order and amplitude of each individual harmonic can be derived and the individual harmonic power loss is summed to find the total harmonic loss. The results are also validated by the direct measurement in the calorimeter.

2 Additional losses

Stray load loss and inverter-induced harmonic loss are two types of additional losses in induction motors when they are

supplied by sinusoidal and inverter supply voltages, respectively.

2.1 Stray load loss

The subject of stray load loss has been extensively examined previously. By its nature, stray load loss simply reflects the non ideal realization of a practical machine. It consists of many loss components within the stator and rotor, involving variations of the winding distribution, number of slots, slot opening shape, rotor construction, skewing and saturation, irregularities and mechanical imperfection in the airgap. The sources of the stray load loss are described in detail in [17]. A key source of stray load loss is high frequency flux pulsation in the airgap of the machine due to stator and rotor slotting and the interaction between them.

Significantly, as its name implies, stray load loss varies in magnitude with the load applied to the machine. In fact, stray load loss may be assumed to vary very closely in proportion to the square of the applied load torque [21,22].

Generally stray load loss represents only a small fraction of the total power loss so that precisely quantifying this loss experimentally is extremely difficult in the input-output method. Although certain success in numerical simulation has been achieved in the earlier studies using the FEM approach [16,19], little attention has been paid to effective experimental measurements. Alternatively, some standards suggest various empirical factors. IEC 34-2 [20] provokes a long lasting debate by allocating a fixed 0.5% of the rated input power to the stray load loss. NEMA MG1 [23] recommends 1.2% for induction motors rated less than 2500 hp, and 0.9% for 2500 hp and above. As an improvement, IEEE 112-E1/F1 [22] provides a variable portion of output power to stray load loss, dependent on the machine ratings. This is listed in Table 1. Similarly, the new revision of the IEC standard 61972-2 [21] provides a range of figures which is also a function of motor ratings, as is plotted in Fig. 1.

In the authors' previous study [6] on 23 induction motors rated between 5.5 and 225 kW, the ratio of the stray load loss to the input power are found to be within the range of 0.1-1.8%. As shown in Fig. 2, the stray load loss varies significantly from one machine to another even though some are similarly rated machines.

In terms of standard deviation, the spread of this portion can be expressed as

$$R_{\text{stray}/\text{input}} = 0.84 \pm 0.43 \quad (1)$$

Motor ratings (hp)	Stray loss in output power (%)
1-125	1.8
126-500	1.5
501-2499	1.2
≥ 2500	0.9

Table 1: Assigned allowance for stray load loss in IEEE 112-E1/F1

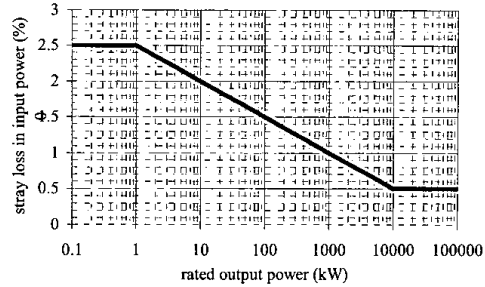


Fig. 1: Assigned allowance for stray load loss in IEC 61972-2

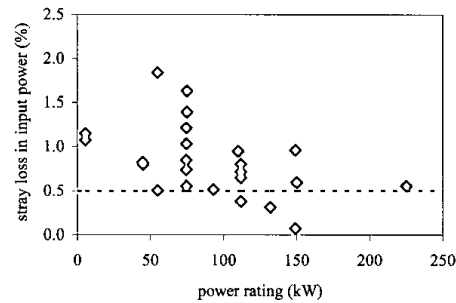


Fig. 2: The spread of stray load loss portion in the input power

Obviously, for this group of 23 new products, the IEC 34-2 Standard underestimates the magnitudes of the stray load loss but IEEE 112-E1/F1 and NEMA MG1 overestimates these. Nonetheless, the stray load loss is indeed machine specific and any arbitrary allocation for this loss is unjustifiable when measurements can be made [3].

2.2 Harmonic loss

The development of high performance power electronic devices has led to an increasing application of adjustable speed drives (ASDs) in industry. It has been well established that the use of inverters improves energy efficiency of the drive system, such as in many pump and fan applications with time dependent changing fluid flow demands. However, ASDs induce additional time harmonics in the airgap flux of the machine under control. These harmonics are produced by high levels of distortion in the stator voltages caused by PWM switching. The time harmonics of flux are primarily of fundamental spacial distribution in the airgap. The consequent adverse effects are many. Of concern here are the additional losses and high-temperature hot spots in the machine stator windings or core laminations [7,24].

Commonly, a PWM output voltage is presented as being obtained by comparison of a sinusoidal wave reference with a triangular waveform (carrier). In practice, in modern digitally controlled drives there are a number of ways of

approximating or improving on this basic analogue technique [12]. By changing the ratio of the modulating signal magnitude to that of the carrier signal (modulation depth), a varying fundamental output voltage can be achieved. The frequency-modulation ratio, the ratio of the carrier frequency to the modulation frequency, determines the general pattern of the predominant harmonics in the PWM voltage waveform. In theory, harmonic frequencies can be given by

$$f_k = (nM_f \pm m)f_o \quad (2)$$

Where M_f is the frequency-modulation ratio and f_o is the modulating frequency. The harmonic order k corresponds to the m th side band of the n th carrier harmonic.

If $n=1$, harmonics are of order $M_f \pm 2, M_f \pm 4, M_f \pm 6 \dots$,

If $n=2$, harmonics are of order $2M_f \pm 1, 2M_f \pm 3, 2M_f \pm 5 \dots$

It should be noted that: (1) n and m can not be both even or odd; (2) harmonics of triple multiples are not applied to the three phase load. To these harmonics must be added a series of low order harmonics introduced by dead time during switching commutations.

In a modern ASD, the PWM carrier frequency is usually high enough to make harmonic loss small enough relative to the input power. This makes harmonic loss difficult to measure with precision. For experimentally quantifying harmonic loss, two methods have been reported previously. One is to determine the difference between the measured input powers of the machine when successively fed by a pure sinusoidal and a PWM converter supplied voltage for equal fundamental conditions (voltage and torque) [4,13]. The other is to determine the difference between the total input power and the simultaneously measured fundamental input power of the machine when fed by a PWM inverter [15].

Clearly, for simple v/f control schemes, the magnitude of the harmonics produced by the inverter change very little with load at a particular motor speed and thus fixed fundamental voltage. They do change however with differing motor speeds and thus differing fundamental output voltage and modulation depth. This implies that for any particular operating speed, harmonic loss is virtually independent of load unlike stray load loss which is load dependent. In practice there is some variation of harmonic loss with load at lower harmonic frequencies due to the changing impedance of the machine with increasing load as rotor slot bridges saturate [1].

Nevertheless, it is also clear that both harmonic loss and stray load loss are associated with high frequency flux pulsations in the airgap of the machine and as such one might expect some degree of correlation between them.

3 Advanced measurement techniques

Experimental evaluation of the additional loss in induction motors fundamentally relies on accurate measurement techniques. As a result, improved calorimetric and harmonic injection methods have been applied in this study.

3.1 Calorimetric method

In the calorimetric method, the machine is installed in an insulated enclosure (calorimeter) with a coolant fluid flowing in and out. When thermal equilibrium is attained after a period of time, the energy extracted by the fluid is balanced by that dissipated by the machine under test. This gives the total power loss but the stray load loss is still obtained by loss segregation as done in the input-output method [22].

From the previous development of an air-cooled calorimeter [14], some difficulties identified are in: (1) determination of air mass flow rate and specific heat; (2) measurement of the mean air temperature of the coolant; (3) changing mass flow distribution across inlet and outlet ducts between tests, and (4) heat flux leakage by conduction.

Based on the previous design, the authors have developed an improved 30 kW calorimeter. Major improvements made are below.

- (1) Automatically and dynamically controlling the coolant flow to provide a fixed thermal capacity equivalent to a set mass of dry air. This is achieved by using an accurate full flow turbine to measure coolant flow. Coolant temperature is controlled to be constant at the measurement point. Atmospheric parameters are measured with precision and are input to the LabView program.
- (2) Careful design of inlet and outlet ducts, of temperature averaging sensors in those ducts and of an internal air to air heat exchanger which forms part of the outlet duct. These minimize errors in the mean temperature of the mass of coolant.
- (3) Active neutralization of heat flow in leakage paths. This is realized by controlling heaters attached outside the calorimeter walls, machine support bed and drive shaft. For other conducting exits, special insulation arrangements are also made to reduce the heat leakage.

The calorimeter is calibrated by a dc heater on the basis of a zero point and a range of high power point measurements. Overall accuracy including the influence of the test machine replacing the heater is measured to be better than 5.6 W on the 2 kW range of the calorimeter which has a maximum power capability of 4.5 kW.

3.2 Harmonic injection

Over a wide range of harmonic frequency, when an induction machine is fed from a PWM inverter, the harmonic loss at a harmonic of order k is commonly assumed as

$$P_{loss}(k) = V_k^2 \times \left(\frac{A}{f_k^\alpha} + \frac{B}{f_k^\beta} \right) \quad (3)$$

Where V_k, f_k are the harmonic voltage and frequency at order k , respectively. A, B, α, β are the corresponding factors to the particular machine under test.

In equation 3, the harmonic loss has two components. They represent low frequency and high frequency components, primarily associated with conductor loss and core loss, respectively. The harmonic injection method is to identify

these four factors through injecting a wide range of harmonic frequencies (up to half the carrier frequency) into the fundamental component of the PWM when the machine is under test. The injected harmonic also appears as sidebands of the carrier frequency harmonics so that the effect of a wide range of injected frequencies can be examined which is much greater than the single harmonic injected. The technique has been described in [4,11].

The advantage of this method is that large amplitudes of individual harmonics can be injected which makes the subsequent experimental measurement of the harmonic voltages, currents and power much more accurate than when measuring the total power loss due to harmonics under normal operating conditions. In order for the technique to work best, sufficient headroom must be available from the dc link to ensure that the injected harmonic when added to the fundamental does not over-modulate the inverter. Accordingly results are taken for operation at two thirds of base frequency but at the flux and current levels in the machine corresponding to full load operation at base frequency.

The harmonic loss is measured via high frequency sampling of line voltage and current. For a specified order of harmonic, its coefficient factors can be attained by curve fitting. By analyzing the frequency spectrum of any subsequent PWM scheme, the order and amplitude of each harmonic may be derived and the total harmonic loss may be obtained by summing the individual power loss due to each harmonic obtained using equation 3. However, this requires that the stator current and fundamental flux are of similar values to those used in the harmonic injection tests. Thus, the harmonic injection test yields data which can be applied throughout the v/f operating range of the drive when account is taken of the particular harmonic spectrum of that operating point.

Above all, this approach only works well when the order of the significant PWM harmonics exceed 10 as low order time harmonics might produce non-negligible torque ripples. The harmonic injection facility used here provides an overall accuracy of better than 10 W in 300 W of harmonic loss.

4 Results and discussions

In this study, seven induction motors (labeled A to G), rated at 1.1, 7.5, 15, 30 kW were carefully tested in two groups, using calorimetric and harmonic injection methods. The first group comprises machines A to D with different ratings while the second group of machines B, E, F and G are similar 7.5 kW machines but made by different manufactures. In addition to comparison of the effect of sinusoidal and PWM inverter voltage sources on losses, the latter group is also used to check loss spread of machines of similar power rating and pole number. The machine details are tabulated in the appendix.

All the machines were operated at 50 Hz fundamental frequency from a sinusoidal supply. PWM inverter supplies used a carrier frequency of 8 kHz. Harmonic injection tests were conducted at their full load flux and full load current

level but below base speed. A single turn search coil installed mimicking the stator winding distribution for one phase of the stator winding was used to ensure replication of the fundamental magnetizing conditions for the sinusoidal and inverter tests. Under both sinusoidal and PWM tests the fundamental stator current was also maintained similar. The dc bus voltage of the inverter was controlled to be the same under all inverter fed test conditions so as to ensure that similar modulation depths and PWM harmonics were applied.

Four of the machines, A to D, were tested using the calorimeter to measure total power loss at full load when they were operating at 50 Hz fundamental frequency from inverter supplies. These tests provided a means to measure the harmonic power loss directly by comparison with the similar sinusoidal tests. They thus could provide validation of the harmonic injection method. These tests were limited to four machines due to the extreme difficulty in controlling the supply and loading conditions to the motors so that sinusoidal and inverter fundamental operating conditions were closely identical.

In order to sustain a constant ambient temperature for a meaningful comparison, the tests were all conducted inside the calorimeter with a constant air mass flow rate and an inlet temperature control of the calorimeter. When operating from the sinusoidal supply and after the machine reached its thermal balance, the total power loss was measured and segregated to find the stray load loss. At the full load point, a voltage reading was taken from the search coil to be used as a reference for all subsequent tests.

In the experiments, all the machines were loaded to the rated full load condition except machine D which was loaded to 2/3 load for inverter tests owing to the limited inverter power capacity. The sinusoidal value of stray load loss for machine D is that applying to full load since the inverter fed time harmonic loss for the machine is not significantly affected by load. There is however room for a further small error in this assumption.

4.1 Calorimetric validation of the harmonic injection method

The harmonic injection method is validated by direct measurement of harmonic loss for the first group of machines. Test results are given in Fig. 3.

From this figure, a very good agreement can be seen between the harmonic loss measured directly for a particular operating condition and the harmonic loss computed for that operating condition using the harmonic spectrum and the loss factors of equation 3 derived from the harmonic injection test. Clearly the harmonic injection technique is proved to be effective.

Among the four machines, the variations of the two loss figures are well within the worst case measurement accuracy for harmonic injection with the exception of machine C. The measured harmonic loss in this motor is 15 W higher than the calculated one. Nonetheless, this may be due to the error in getting the two operating conditions to be identical, between

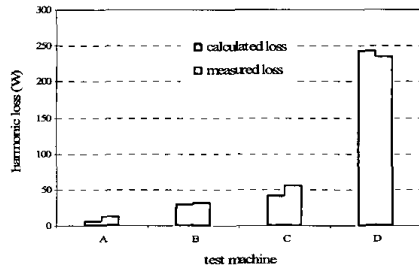


Fig. 3: Comparison of directly measured harmonic loss and that computed from harmonic injection

PWM and sinusoidal in terms of the fundamental, and between the two load conditions. Not only is this theoretically impossible when harmonics induce drag or motoring torques, this is also exceptionally difficult experimentally.

4.2 Comparison of stray load and harmonic losses

Test results of the additional losses for two groups of motors are illustrated in Fig. 4. It is shown how the ratio of stray load loss to harmonic loss varies with machine power rating at full load. It can be seen that irrespective of machine power rating, the harmonic loss for the particular PWM scheme employed at a PWM frequency of 8 kHz is always less than the stray load loss. Furthermore, the harmonic loss is typically between about 25 and 59% of the stray load loss for these seven machines.

For the second group of four similar 7.5 kW machines, the variation in the percentage of harmonic to stray load loss is lower and converged, being between 25–45%.

Overall, it may be said that a machine with a higher stray load loss is likely to have a higher harmonic loss. A close relationship is evident in these machines between stray load and harmonic losses, indicating that measurement of one may be used as a guide to the other.

In general, using standard techniques and instruments of normal precision, the stray load loss value carries with it the errors in measuring all of the other losses and the input and output powers. A high degree of correlation between stray load and harmonic losses would not therefore necessarily mean a greater accuracy in estimating harmonic loss from stray load loss.

Yet there is no strict proportional correlation found between the two losses. This is due to their complex loss mechanisms. The stray load loss consists of loss components not accounted for by the traditional loss where the harmonic loss is the summation of loss components on a wide frequency spectrum. Although both losses are related to high frequency flux pulsations in the airgap of the machine, the former loss is closely associated with high frequency, high pole number fluxes and the latter mainly involves high frequency, low pole number fluxes. Inter-bar losses in skewed machines are also a source of difference due to the differing harmonic pole

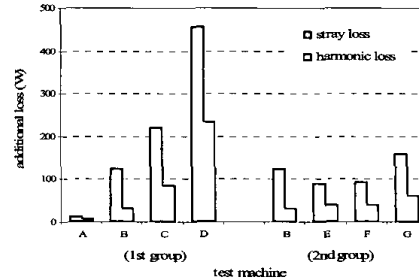


Fig. 4: Experimental comparison of the two additional losses

numbers. All of the test machines are skewed in common with the majority of low power induction machines. Moreover, both of these additional losses, in particular stray load loss, are machine specific.

5 Conclusion

This paper has described advanced measurement techniques for quantifying stray load and inverter-induced harmonic losses. Developments of the calorimeter and the harmonic injection facility make it possible to investigate the correlation between the two additional losses with precision. Stray load loss is measured by a purpose-built 30 kW calorimeter capable of measuring the power loss to an accuracy of better than 5.6 W in 2 kW. Harmonic loss is assessed by the harmonic injection method to an accuracy of better than 10 W in 300 W. Experimental results clearly show both calorimetric and harmonic injection methods employed is suitable of detecting small additional losses although there is still room for the harmonic injection facility to improve.

Comparisons are made on two groups of induction motors rated at 1.1, 7.5, 15 and 30 kW. Overall, the harmonic loss is shown to be less at full load than the corresponding stray load loss for a PWM frequency of 8 kHz. Machines in the first group, with different power ratings, show that the ratio of harmonic to stray load loss changes more with power rating than it does for the machines of the same power rating but of different manufacturers of the second group. However, a loose correlation is clearly indicated between stray load and harmonic losses.

Despite having similar loss mechanisms, stray load and harmonic losses are two different collections of many loss components, the former involving high frequency, high pole number fluxes while the latter associated with high frequency, low pole number fluxes. As a consequence, There should be no general-purpose machine used for both inverter-fed and normal mains operations, nor should a single quality control measure mitigate both additional losses altogether. Indeed they require different consideration in the design and manufacturing processes.

Appendix

List of test machines

Machine	A	B	C	D	E	F	G
kW	1.1	7.5	15	30	7.5	7.5	7.5
Pole number	4	4	4	4	4	4	4
Hz	50	50	50	50	50	50	50
V	415	400	415	415	415	400	400
A	2.63	14.5	27	54	14.6	14.9	16.3
RPM	1410	1450	1470	1470	1415	1445	1450

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