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Rapid Efficiency Evaluation of Three-Phase Induction Motors Using Synthetic Loading

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This paper describes a novel method for rapid full load efficiency evaluation of three-phase induction motors using the synthetic loading technique, without the need to connect a load to the machine's drive shaft. The new method utilizes a Digital Signal Processor (DSP) and a controlled high switching frequency power electronic inverter to synthetically load the induction machine, while using a new real time data acquisition system to accurately determine and record the machine performance. The method proposed considerably reduces the testing time compared with the conventional methods of efficiency measurement while the accuracy of the result is maintained. Moreover, the use of the power electronic inverter creates a comprehensive control over all the quantities which determine the rate at which the power is dissipated inside the induction machine. This method can also directly quantify rotational losses of the induction motor under examination.

INTRODUCTION

Determining the energy dissipated as heat and the resulting temperature rise of the induction machines is of importance to both users and manufacturers. High temperatures cause deterioration of the insulation materials and high rates of power dissipation imply low efficiency values [1]. The power losses of induction motors are categorized as electrical and mechanical losses. Some of the electrical losses can be predicted reliably from the machine design data but some components such as stray load and mechanical losses are less predictable. Similarly, there is still a substantial amount of uncertainty attached to the prediction of cooling properties of the machine [2].

In developed economies, 53 to 58 percent of the electrical energy generated is consumed by electric-motor driven systems [3]. The three-phase induction motor is by far the most common of the electrical motors used. This type of motor has been described as the "workhorse of industry" and is produced in a very wide range of output from fractional to large multi-megawatt units.

The cost of electricity used by this type of motor during its working life is typically a hundred times greater than the motor purchase price [4]. Efficient use of induction motors has always been important with respect to energy cost saving, however, recently it has become even more important due to concern over greenhouse gas emissions, a very large proportion of which is produced by electricity generation. In the new federal American legislation, rebate programs and increased industry standards have been implemented placing enormous emphasis on the advantages of energy conservation and the use of energy efficient motors. Motor manufacturers now have a separate category referred to as "energy efficient motors" [5]. Despite the attractiveness of such energy efficient motors, they are still only used in relatively small numbers. It has been recently reported [6] that one of the reasons for the low acceptance of energy efficient motors is poor information available regarding these machines.

Unfortunately, there is no single definition of an energy efficient motor. Similarly, there is no single efficiency standard test method for polyphase induction motors, which are used throughout industry. A motor labeled as "high efficiency" from one supplier might be less efficient than the standard motor from another supplier. There could be a 10 percent range of efficiency across different brands but to find out about performance, the user generally has to rely on information provided by the suppliers. This leads to uncertainty about the relative efficiency performance of different motors, encouraging users to ignore energy

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efficiency and concentrate on other criteria such as price.

In Australia, it has been reported [6] that the main focus of a Bureau of Industry Economics study is to investigate what the Australian Government can do to decrease the uncertainty about motor performance and, in particular, efficiency.

Currently the most common method used for carrying out full-load performance testing of a three-phase induction motor is applying full-load torque to the machine's output shaft [7]. To load a large machine, equally large test equipment or a duplicate machine is required. The cost of setting up such a test facility, maintaining the equipment and time along with setting up procedures for mechanically coupling the load machine, may result in prohibitively expensive full load tests. Large vertically mounted machines are extremely troublesome to test through applying a load to the shaft, due to the difficulty in finding a suitable vertical load [8,9].

Obviously, a method in which the rated efficiency of the machine is established without requiring mechanical coupling of a load is highly desirable.

Several authors have recognized the need for such a synthetic loading method and a number of schemes have been developed. The method of Fong [10] whilst claiming to provide excellent agreement with conventional loading, requires the use of two equally rated machines as well as 12 leads to be brought out of the machine. According to Kron [11], as long ago as 1921, Ytterberg proposed connecting two voltage supplies of different frequencies in series with an induction motor to achieve synthetic loading; this technique is now generally known as the two-frequency or dual-frequency method.

Schwenk [12] reported that his company, Westinghouse Electric Corporation, has used the two-frequency method of equivalent loading for several years. The two-frequency method has also been incorporated into the Japanese Test Code for induction motors [13].

The method used by Schwenk has the disadvantage of requiring two Motor-Generator (MG) sets to provide the dual frequency supply and the auxiliary (i.e., lower frequency) power source which demands all leads to be brought out. A modified version of this procedure requires only three leads to be brought out of the secondary source, however, the additional use of an isolating transformer is necessary.

The authors have already shown that induction motors can be fully loaded for carrying out the temperature rise tests [8,9,14,15]. This paper briefly describes methods of loading three-phase induction motors using DSP, controlled power electronics techniques, without the need for connecting a mechanical load to the drive shaft; furthermore, it defines an extension of this research whereby the synthetic load test is used to rapidly and easily evaluate the machine efficiency.

Two methods of synthetic loading utilizing DSP (Control Power Electronics) are explained here. In the first method, two distinct frequencies are generated, thus replacing the electrical machines of the existing dual-frequency. The second method uses DSP to rapidly change the machine supply frequency.

The tests are carried out for an industrial 7.5 kW squirrel cage induction machine using three different synthetic loading techniques and also a conventional dynamometer for comparing the results.

SYNTHETIC LOADING

Dual and Sweep Frequency Methods

The importance of the Dual Frequency (DF) method described above is in providing a supply containing two distinct frequencies; this leads to production of two magnetic fields rotating in the air-gap at different speeds.

If all quantities are represented as per unit of value, for sinusoidal voltages, the flux can be set equal to the supply voltage divided by the frequency. With two voltages in series, the total flux is the sum of two flux waves of different magnitudes and frequencies. Figure 1 illustrates these flux vectors rotating at different angular velocities.

Schwenk [12] analyzed these two rotating vectors and demonstrated that the variation of magnitude and angular velocity of the resultant flux wave as a function of time is given by:

$$\Phi_t = \frac{V_a[1 + a^2 + 2a\cos(\omega_a t - \omega_b t)]^{1/2}}{\omega_a}, \tag{1}$$

$$\omega_t = \frac{\omega_a + a\omega_b + a(\omega_a + \omega_b)\cos(\omega_a t - \omega_b t)}{(\Phi_t \omega_a / V_a)^2}, \tag{2}$$

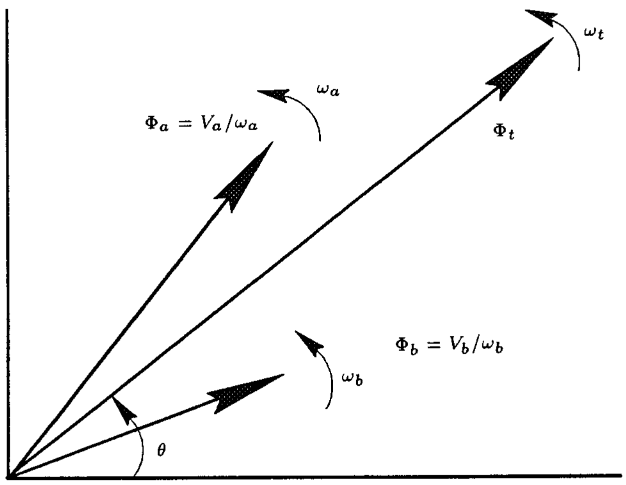


Figure 1. Space vector diagram of rotating flux waves.

where:

$a = \omega_a V_b / (\omega_b V_a)$,

ω_a = angular velocity of the main voltage sources,

ω_b = angular velocity of the auxiliary voltage sources,

Φ_t = total magnitude of flux due to Φ_a and Φ_b,

ω_t = angular velocity of the total flux wave,

V_a,V_b = main and auxiliary voltage sources RMS values.

These equations represent a flux wave which varies in magnitude and angular velocity as a function of time, supply voltage and frequency. From Equations 1 and 2, it can also be observed that the oscillation frequencies are the same for the flux wave angular velocity and magnitude and equal to the difference between the main and auxiliary supply frequencies, i.e., $f_a - f_b$. Because of the inertia of the rotor, the varying frequency causes alternating induction motor-generating action, thus increasing the effective RMS current flowing in the machine.

An alternative method for establishing the effect of the two individual supplies is to assume that the motor is running at a speed between that of the two supplies. The machine, therefore, draws motoring current with respect to the higher speed field and supplies generating current with respect to the lower speed field. The two currents beat together to form a modulated current whose RMS value, over a period greater than the beat period, can be set equal to the normal load current for the machine, through adjusting the amplitudes and frequencies of each of the supply components.

This method, which previously required a system of electrical machines for generating the two frequencies, can be conveniently implemented using DSP controlled power electronics to generate the necessary voltages and frequencies for the two supplies.

Another method of artificially increasing the motor current is to use a single supply frequency, while rapidly modulating this frequency over a small range centered on the rated frequency. This causes alternating induction motor-generator action.

Unlike the former, this method of synthetic loading cannot be implemented through using an electrical machine power source, because it is not possible to produce the required rapid modulation of frequency. However, with the DSP based software algorithm controlling a power electronic inverter, the necessary modulation can be achieved, the basis upon which the second method is implemented.

There are, therefore, two separate methods for producing synthetic loading of the induction motor using microprocessor or DSP controlled power electronics. These two methods, i.e., dual and sweep frequency, require the production of sine function voltage at power levels appropriate to the machine rating. A Pulse Width Modulated (PWM) inverter is ideal for this purpose.

The necessary frequency and/or amplitude modulation required by these methods (i.e., DF, SF) can be easily obtained, using the software based universal test facilities designed and developed for this purpose.

If dual-frequency output is required, then it is simply necessary to calculate $A\sin(\omega_a t) + B\sin(\omega_b t)$, where ω_a and ω_b are the required frequencies and A and B are the amplitudes of the modulating waveform. If sweep frequency is required, it is necessary to calculate:

$$A\cos\left\{\left[\omega_a + \frac{B}{\omega_b t}\sin(\omega_b t)\right] t\right\}.$$

These calculation must be conducted in real time, which is now possible with DSP technology.

The interface between the user and the DSP which controls the whole process is a Personal Computer (PC) with a video display terminal which facilitates the 'on-line' parameter entries, via a keyboard, as well as computerized real time monitoring of the motor performance under synthetic loading conditions. It is also possible to store the monitored performance in the computer memory for later evaluation, if required.

MOTOR EFFICIENCY TESTING STANDARDS

Accurately comparing the efficiency of two induction motors requires the motors to undergo similar tests [7]. The testing method depends upon the rating of the motor, the available equipment and the degree of accuracy required. A more exact efficiency will be obtained if a direct measurement of the losses is made and then the input minus losses divided by the input is calculated as the efficiency, instead of the ratio of input to output. The IEEE Rotating Machinery Committee have produced a standard IEEE 112-1991 by which efficiency is tested in the United States. In addition, the International Electrotechnical Commission (IEC) produced IEC-34-2 standard for use in Europe, which is similar to British Standard BS269 and the Japanese Electrotechnical Committee (JEC) produced standard JEC-37 [7].

Comparison of the above efficiency measurement standards illustrates that the methods are similar, differing only in the details of procedure followed in each test. The IEEE 112 test method B is the most rigorous and more detailed than those that measure all the motor losses using a dynamometer such as specified in the IEC or JEC standards.

MOTOR EFFICIENCY TESTING USING DYNAMOMETER

A dynamometer is an easy and flexible tool for evaluating motor performance at various conditions of operation. The National Electrical Manufactures Association (NEMA) considers dynamometers as its preferred means of measuring motor efficiency in ratings from 1-100 kW.

The dynamometer testing method provides actual operating conditions for the machine under examination. Consequently, this method was first used to identify the efficiency of the machine under examination, the results of which will be used to investigate the accuracy of the efficiency evaluations using the new synthetic loading techniques.

Note that available test equipment varies with each motor manufacturer and so does the accuracy, e.g., dynamometers with eddy current clutches, water brakes, or DC generator [16].

The conventional dynamometer was used to fully load a 7.5 kW, 13.9 A, 415 V, three-phase induction machine. The input power and the total loss of the induction machine at nominal operating conditions and a settled down working temperature of 85°C was recorded and the efficiency was calculated using the following results:

$P_1 = 861$ W	$P_i = 8178$ W	$\eta = 0.895$

EFFICIENCY TESTING USING SYNTHETIC LOADING

The essence of the novel synthetic loading technique developed in [8,9,14,15] is its capability in varying the stator frequency, about the rated frequency, using a digital signal processor (DSP) and a controlled high switching frequency modular IGBT type inverter, thereby, causing alternating induction motor/induction generator operation.

Three methods for synthetic loading technique can be used. The first technique utilizes DSP and its associated inverter to generate the two distinct frequencies of the Dual-Frequency (DF) method. The second method uses DSP to rapidly frequency modulate the machine's normal single supply frequency for the Sweep Frequency (SF) method. Finally, the third method uses DSP to produce a rotating magnetic field which rotates at constant speed but with sinusoidally varying amplitude and is known as the Constant Speed Of Rotating Magnetic Field (CSORMF) method.

It has been shown in [15] that all three synthetic loading methods yield similar results, but for brevity this study will be restricted to the SF method, although the final efficiency results of the other two methods will be included for comparison.

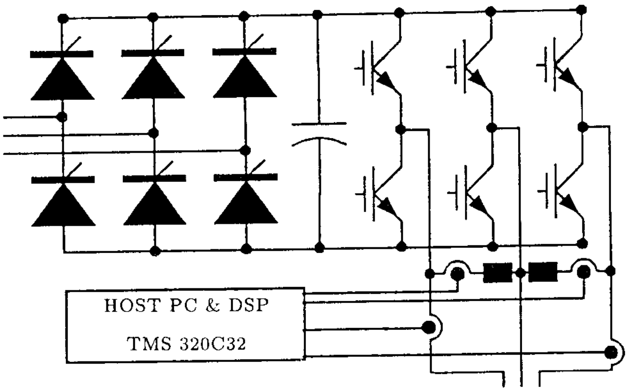


Figure 2. DSP based system configuration.

High Frequency Inverter and its Software Based Control Algorithm

A software-based algorithm was used to generate the necessary logic and control signals needed to drive, control and protect the high frequency IGBT module based inverter. DSP calculates the PWM pulse widths in real time, while at the same time monitoring the currents, voltages and speed [15,17]. This system is very flexible, because the software can be changed to produce output waveforms other than simple sine functions, as in the case of synthetic loading. Also using DSP digital inputs, it is possible to change the different parameters of the program in real time, e.g., modulation index, frequency, sweep frequency, etc. Figure 2 illustrates the system configuration.

EXPERIMENTAL RESULTS

Figure 3 shows the measured instantaneous values of line voltage and current, while the sweep frequency synthetic loading technique is used for loading the induction machine.

It is important to notice that in this technique the frequency of the supply voltage is variable while its amplitude is fixed; this will cause the machine current to vary in amplitude and frequency as shown in Figure 3b. Figure 4 illustrates the spectrum of the above voltage and current waveforms.

Input power is drawn by the machine during acceleration as a motor and returned to the supply when the machine decelerates as an induction generator. The average power over a cycle is equal to the total losses in the machine, from which the efficiency can be readily evaluated.

Figure 5 shows the measured instantaneous value of three-phase power for the induction machine under test, measured using the author's DSP based monitoring system [17].

Using the measured average power (i.e., total losses) and the machine nominal power for calculating

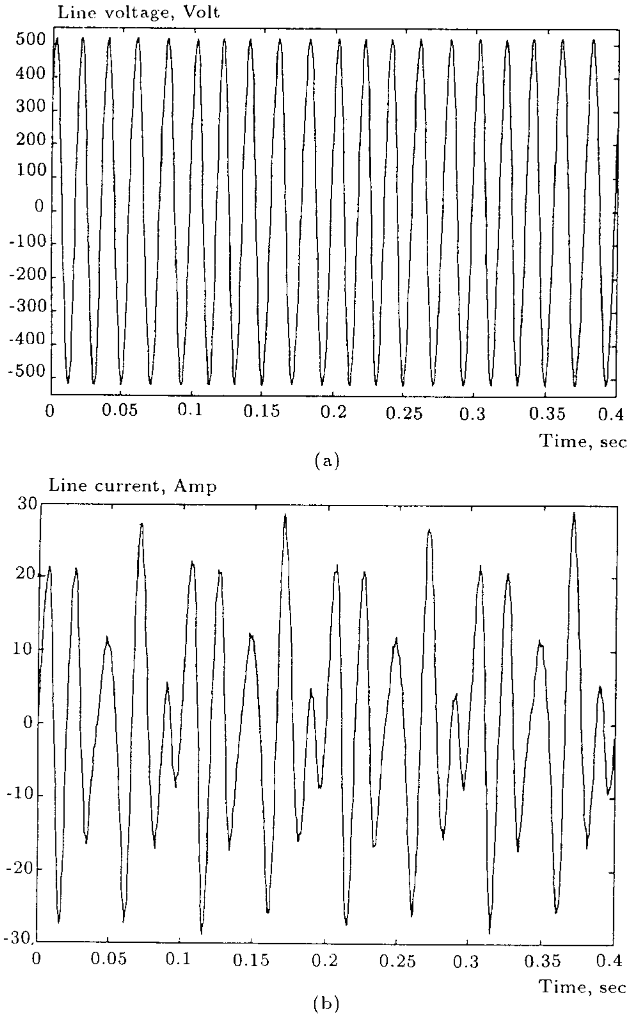


Figure 3. Variation of line voltage and current during synthetic loading.

the efficiency results in:

$P_l = 897$ W	$P_i = 8397$ W	$\eta = 0.893$

.

The efficiency evaluation using the new synthetic loading technique is in very close agreement with that achieved when measured with a dynamometer. In order to compare the results with the DF and CSORMF methods and also to establish the sensitivity of the new technique to supply voltage, the SF method was repeated at nominal current but at a reduced line voltage of 250 V (shown in Table 1).

In the Australian Standard (AS 1359.69-74), "General Requirements for Electrical Machines", the efficiency tolerance for machines up to 50 kW is 0.15 of (1-η) where η is the efficiency. It is observed that although different techniques were used to load test the same machine, the final efficiency results shown in Table 1 are all very close and well within the efficiency tolerance limit set by the Australian Standard 'AS1359.69-74'.

Note that all methods give final efficiency results which are close to the conventional method; however,

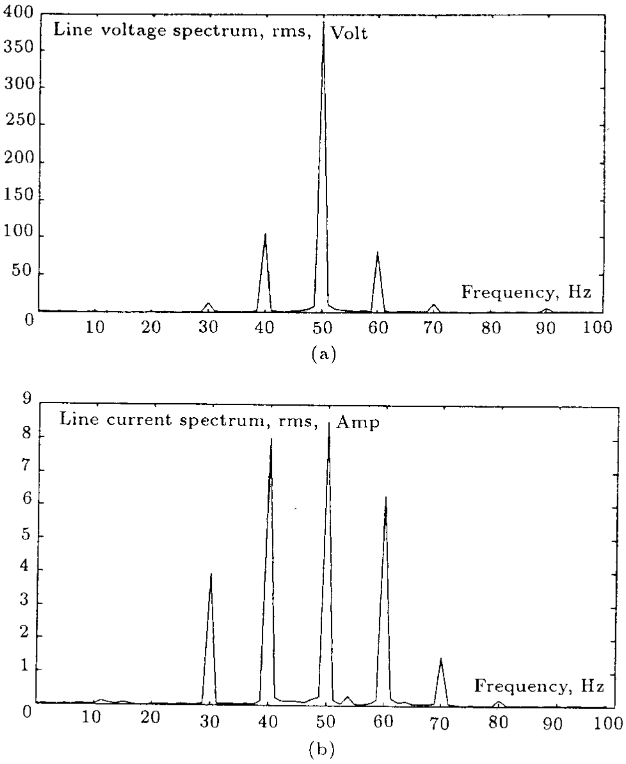


Figure 4. Spectrum of line voltage and current during synthetic loading.

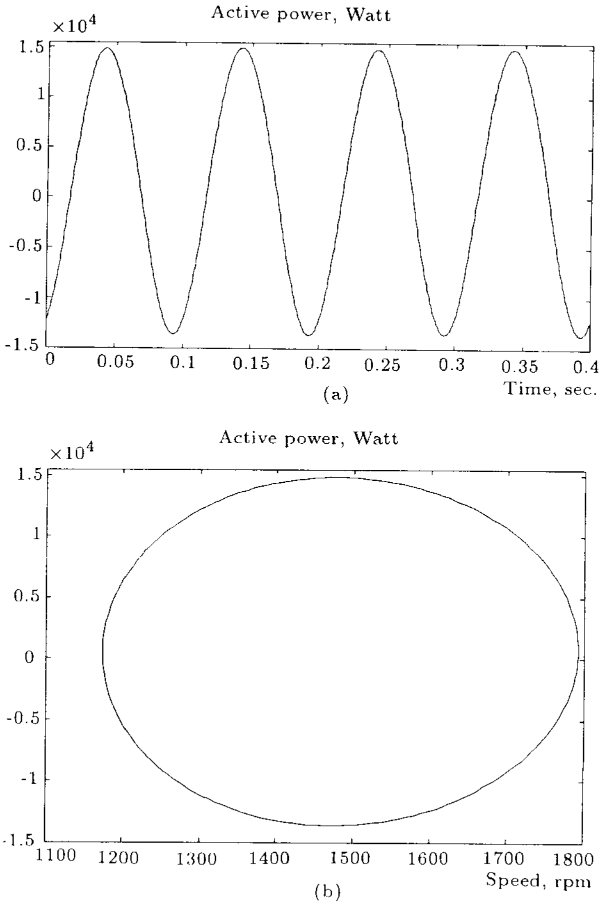


Figure 5. Measured input power with time and speed during synthetic loading.

Table 1. Summary of efficiency evaluation tests.

Type of Loading	P_l W	P_i W	η
Conventional	861	8178	0.895
SF reduced voltage	873	8373	0.896
SF	897	8397	0.893
DF	919	8419	0.891
CSORMF	724	8224	0.912

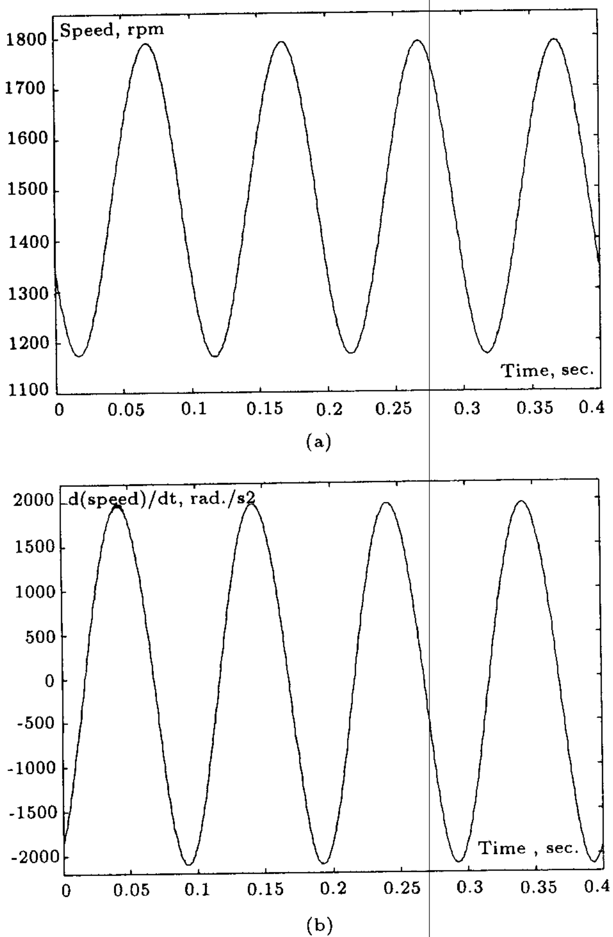
that of the reduced voltage (SF) test give a slightly higher efficiency due to the reduced iron loss at the lower supply voltage. In this later test, the copper losses would be essentially unchanged because in the synthetic loading technique, the current load on the machines is adjusted to be equal to the rated value. Furthermore, repeated tests have consistently shown that the same results can be reproduced for each method.

Figure 6a shows the measured variation of speed and differential of speed with respect to time versus time. Note that although the machine speed is actually varying with time, the average of 1462 rpm is very close to the rated nominal speed of the machine.

The speed variation of Figure 6a clearly demonstrates that during synthetic loading the machine accelerates as a motor and decelerates as an induction generator and, thus, the machine can be fully loaded via repeated acceleration and deceleration and without the need to connect a mechanical load to the machine drive shaft.

To investigate the actual mechanical loading effects of the sweep frequency synthetic technique on the machine drive shaft, the measured differential of rotor speed, which is shown in Figure 6b, can be simply multiplied by the rotor inertia to calculate the variation of effective torque.

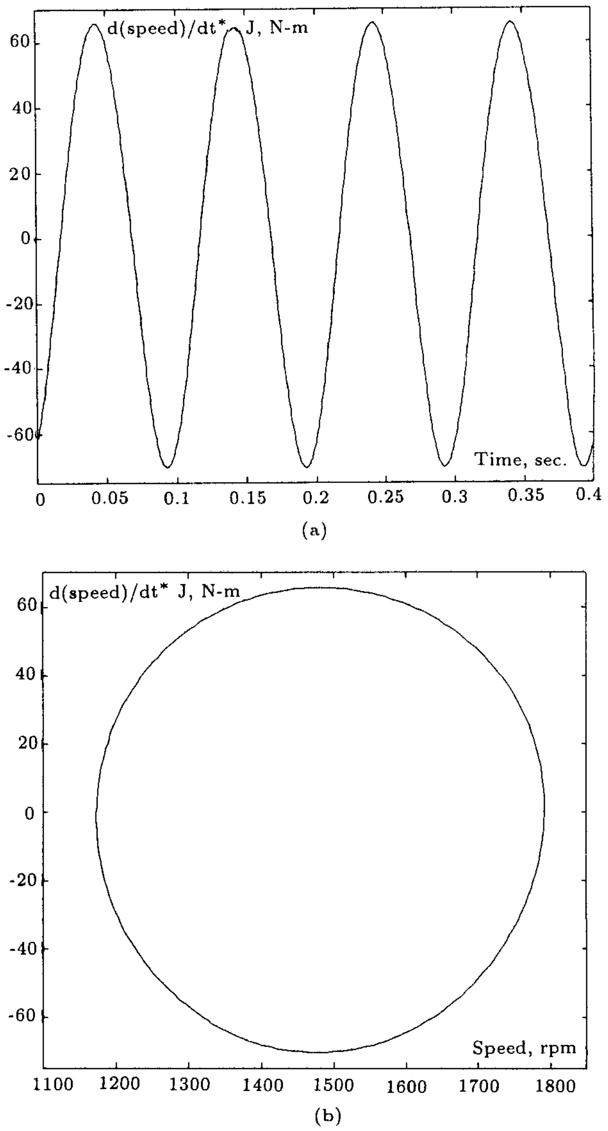
Figure 7 illustrates the variation of differential speed with respect to time, multiplied by the machine



(a)

(b)

Figure 6. Measured variation of speed and differential of speed with time.



(a)

(b)

Figure 7. Variation of torque with time and speed for SF synthetic loading technique.

rotor moment of inertia $J = 0.0334$ kg m^2, which was measured using a retardation test [18].

These figures clearly indicate that the machine is heavily loaded by this synthetic technique, in which the machine is acting as a motor for half a cycle of torque variation and as a generator for the other half cycle.

The average value of torque over a cycle will be a negative value proportional to the rotational losses and any other fixed mechanical torque effective on the rotor.

This torque cycle will be exactly repeated in the settled down operating condition and can be used to separate the mechanical losses from the total losses, if required.

CONCLUSIONS

The new efficiency evaluation technique gives results which are in excellent agreement with the conventional dynamometer method. The new method will enable motors to be tested at virtually any location including on site. Efficiency can be established easily and quickly for both sinusoidal quality and inverter supplies with control over harmonic content of the inverter output. By using the new technique, the so-called "energy efficient" motors in industry can be tested in order to determine whether the manufacturers' claimed efficiency is in fact accurate. (Note that external appearance does not indicate whether motors are truly of the energy efficient type, rather than just claimed to be so; testing will certainly be necessary to substantiate the manufacturers' claims.)

The equipment proposed will be easy to set up, requiring the connection of a three-phase inverter output to the machine terminals. The control facilities will be user friendly allowing simple keyboard input to define and change the necessary control parameters. The equipment will require no external load to be connected to the test machine's drive shaft, setting up time will, therefore, be considerably reduced, particularly for large machines. It is just as simple to test vertically operated induction motors as horizontal ones; hitherto, it was extremely difficult to test large vertical motors because of the difficulty in finding suitable vertical loads.

The equipment will draw only sufficient power from the mains to supply its own losses and those of the test machine; this total power being minor compared with the full load power of the machine under test. One piece of test equipment can replace a number of large, heavy and expensive electrical machines, for testing a complete range of machine frame sizes. The equipment will offer an integrated test apparatus for the first time; conventional test methods involve the use of a system of electrical machines.

The equipment will be very light compared to the alternatives. Because of the reduced setting up time, ease of operation and low overall power absorption, test costs will be considerably reduced.

NOMENCLATURE

P_l	total power loss, W
P_i	input power, W
η	efficiency
V	RMS voltage, V
I	RMS current, A
P_a	average power, W
N_a	average speed, rpm
J	moment of inertia, kgm^2

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