INDUCTION MOTOR PERFORMANCE TESTING WITH AN INVERTER POWER SUPPLY, PART 1

By:

H.E. Jordan
R.C. Zowarka
T.J. Hotz
J.R. Uglum

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Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

Induction Motor Performance Testing With an Inverter Power Supply: Part 1

Howard E. Jordan, Raymond C. Zowarka, Thomas J. Hotz, and John R. Uglum
The University of Texas at Austin – Center for Electromechanics

The development of high power density electrical machines continues to accelerate, driven by military, transportation, and industrial needs to achieve more power in a smaller package. Higher speed electrical machines are a recognized path toward achieving higher power densities.

Existing industry testing standards describe well-defined procedures for characterizing both synchronous and induction machines. However, these procedures are applicable primarily to fixed frequency (usually 60 or 50 Hz) power supplies. As machine speeds increase well beyond the 3,600 rpm limitation of 60 Hz machines, a need for performance testing at higher frequencies is emerging.

An inverter power supply was used to conduct a complete series of tests on two induction motors (0.5 MW and 1.0 MW) with speeds up to ~ 5,000 rpm. The use of a non-sinusoidal power supply with limited power output capability required the development of measurement techniques and testing strategies quite different than those typically used for 60/50 Hz testing.

Instrumentation and techniques for measuring voltage, current and power on harmonic rich waveforms with accuracies approaching 1% are described. Locked-rotor and breakdown torque tests typically require large kVA input to the motor, much higher than the rated load requirement. An inverter sized for the rated load requirements of the motor was adapted to perform locked-rotor and breakdown torque tests. Inverter drive protection features such as anti-hunting and current limit that were built into the inverter had to be factored into the test planning and implementation.

Test results are presented in two companion papers. This paper (Part 1) correlates test results with the results of an algorithmic induction motor analysis program. Part 2 presents the test results compared with a Matlab™ simulation program and also provides a comprehensive discussion of the instrumentation that was essential to achieve testing accuracy.

Correlating test results with calculated values confirmed that the testing techniques developed during this testing program are useful for evaluating high speed, high power density electrical machinery.

I. INTRODUCTION

Testing practices for synchronous and induction machines have been developed over the years and documented in detail in IEEE Standards [1,2]. Since the vast majority of electrical machines are applied at electrical power frequencies, it is to be expected that the testing procedures are based on a fixed frequency power supply, usually 50 or 60 Hz. An increasing number of induction motors are now being designed to operate from inverters and, therefore, are not constrained to 50 or 60 Hz. power. Testing at 50 or 60 Hz does not provide the performance information needed for the inverter-powered motors operating at higher frequencies.

An inverter rated to power the induction motors being tested was used as the power supply for a complete series of tests which included:

- No-load saturation
- Locked-rotor saturation
- Breakdown torque
- Load performance
- Temperature test

A partial list of the issues which distinguish motor testing using an inverter power supply from using a fixed-frequency supply is:

- A non-sinusoidal voltage supply causes the currents and losses to be different from the comparable values normally calculated by design programs. The harmonic effects must be accounted for in correlating test results with the calculated values.
- Voltage, current and power instrumentation must be responsive to the frequency components of the quantities being measured.
- Locked-rotor and breakdown tests normally require currents and power which are several times the rated load current and power. Inverters typically have current limit protection restricting the output current to 1.5 to 2 times the rated value. The onset of the current limit control can severely distort the voltage, current and power measurements obtained during these tests.
- There are several options to select from in picking the data acquisition system to be used. Unfortunately, different types of systems give different results in the presence of harmonics. Two different measurement systems were employed in the testing reported here. The features of these systems are discussed in the “Test Equipment and Instrumentation” section.

II. TEST EQUIPMENT AND INSTRUMENTATION

Fig. 1 displays the overall system schematic.

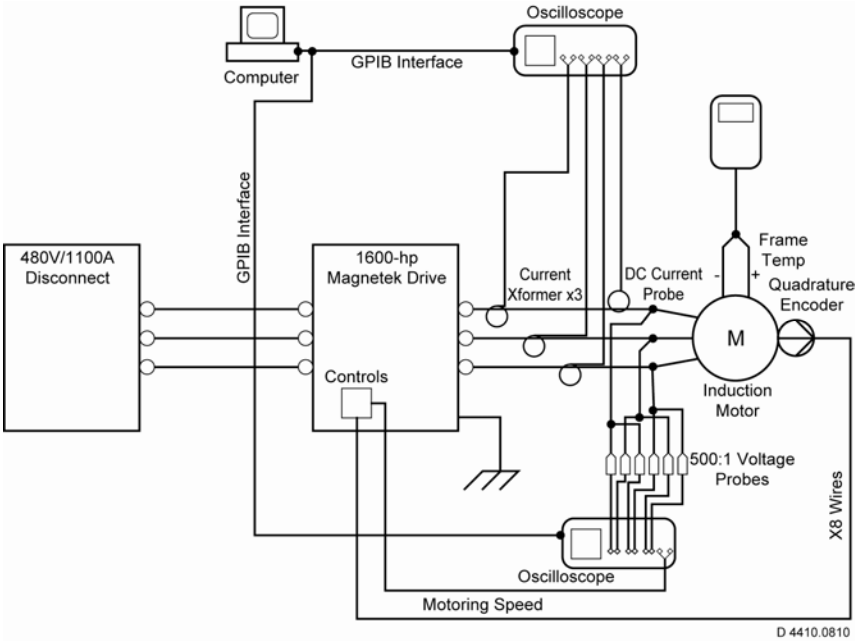

Fig. 1. Induction motor test system schematic diagram

The inverter was connected to a 600 V, 60 Hz power line and supplied variable frequency and variable voltage power to the motor over a range of 0 to 200 Hz and 0 to 600 V. Currents were measured by Hall Effect current sensors in each line. Both of the motors that were tested were 12-lead motors so that current probes could be placed in each phase, even though the load was delta connected. Therefore, both phase and line currents could be measured. Voltage probes, as shown in Fig. 1, measured the line-to-line voltage at the motor terminals.

The motor was coupled to a water dynamometer for load testing. The dynamometer included a force transducer used to measure torque and a digital tachometer for speed measurement. At various times a Yokagawa power meter was used as one means of measuring power. Power was also determined by forming instantaneous values of $v * i$ and summing these to obtain total power.

$$\begin{aligned} &\text{Total power} = (va * ia) + (vb * ib) + (vc * ic) \\ &\text{where:} \quad va, vb, vc = \text{voltage across phases } a, b, \text{ and } c \\ &\qquad\qquad ia, ib, ic = \text{current in } a, b, \text{ and } c \end{aligned} \tag{1}$$

Power measurement, which is perhaps the most difficult measurement in the system, is discussed below.

All of the transducer signals were transmitted via a webDAQ unit and a PXI-8186 system into a computer. All of the data was collected, stored, and analyzed by the computer. Many times during the testing program there were occasions to call up and review data taken on a previous test. Each test was assigned a number and the data retrieval system worked very well.

As stated above, the power measurement was the most difficult one to achieve the accuracies needed for induction motor testing. The system was calibrated by operating the inverter into a delta connected resistance load bank. Power was measured using the instantaneous $v * i$ method and this was compared to the I^2R calculation made from the measured currents in the delta and the measured resistance.

Using the fundamental components of current and voltage, the power calculated by summing the instantaneous voltage-current products was 149,016 W and the sum of the I^2R power in each of the three delta legs was 147,296 W. This is a 1.16% difference, which was considered to be excellent agreement.

The measured fundamental currents agreed within 0.58% of the calculated value across one leg of the delta load. It should be noted, however, that it was necessary to measure and include the inductance of the resistors in these calculations to obtain this accuracy. At 60 Hz, the resistance of these resistor loads was 2.921 Ω and the inductance was 0.3748 μHenries.

A Yokagawa power meter was used at various times during the testing but was, however, unable to achieve the accuracy cited above on a consistent basis. Therefore, the $v * i$ summation method was used as the standard method for measuring power.

A picture of the test facility is displayed in Fig. 2.

Left to right (proceeding from the concrete blocks guarding the operator's station) are the water storage tank, the dynamometer, and the motor coupled to the dynamometer. The red coupling guard for the dynamometer/motor coupling is partially visible just to the right of the dynamometer. The two-bay cabinet behind the dynamometer is the inverter.

Fig. 2. Motor test area

III. MOTOR CHARACTERIZATION TESTS

The induction motor equivalent circuit constants can be evaluated from test by conducting no-load saturation and locked-rotor tests [3]. Both of these tests were conducted and the equivalent circuit constants were derived from the test results as described in reference [3].

IV. NO-LOAD SATURATION TEST

The motor is operated unloaded. The line-to-line voltage, line current and power are measured at various voltages starting at ~20% of rated voltage and proceeding in ~20% intervals, up to a top voltage of 110, to 125% of the motor's rated voltage.

A V/Hz inverter control mode was selected for this series of tests, but it did not allow the operator to adjust the voltage output for a given frequency, as could be done if the field of a 60 Hz alternator were adjusted in a sine wave test. The inverter frequency was set to the rated frequency and, for each data point a different V/Hz curve was keyed into the inverter's computer. The motor was accelerated to its rated speed, the data taken, and the process repeated until all of the no-load saturation points had been acquired. The resulting data for power and current are plotted in Figs. 3 and 4.

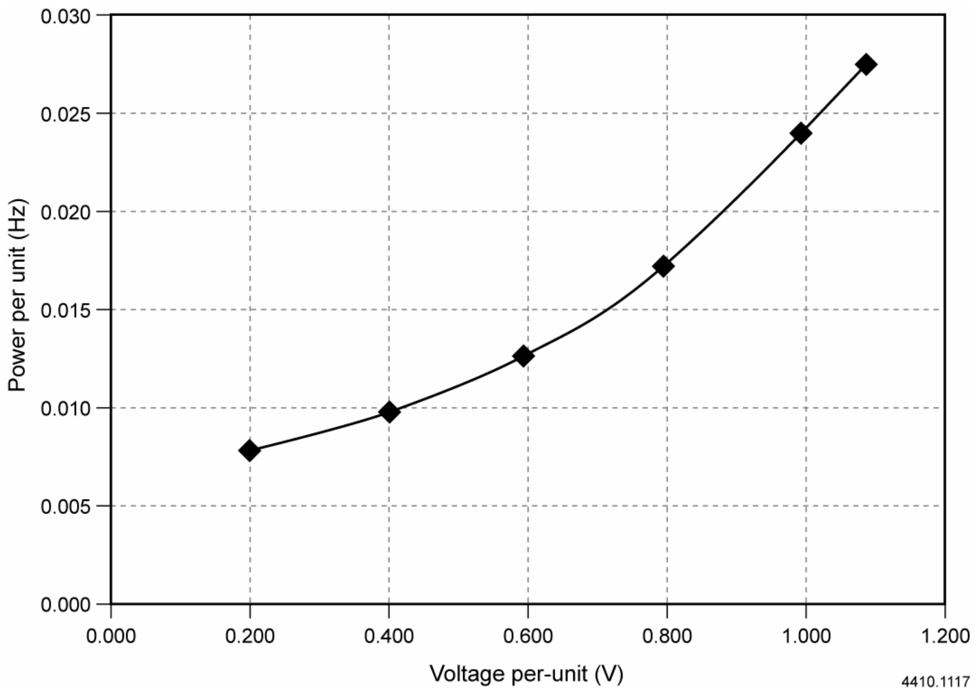

Fig. 3. Power vs. voltage curve from no-load saturation test

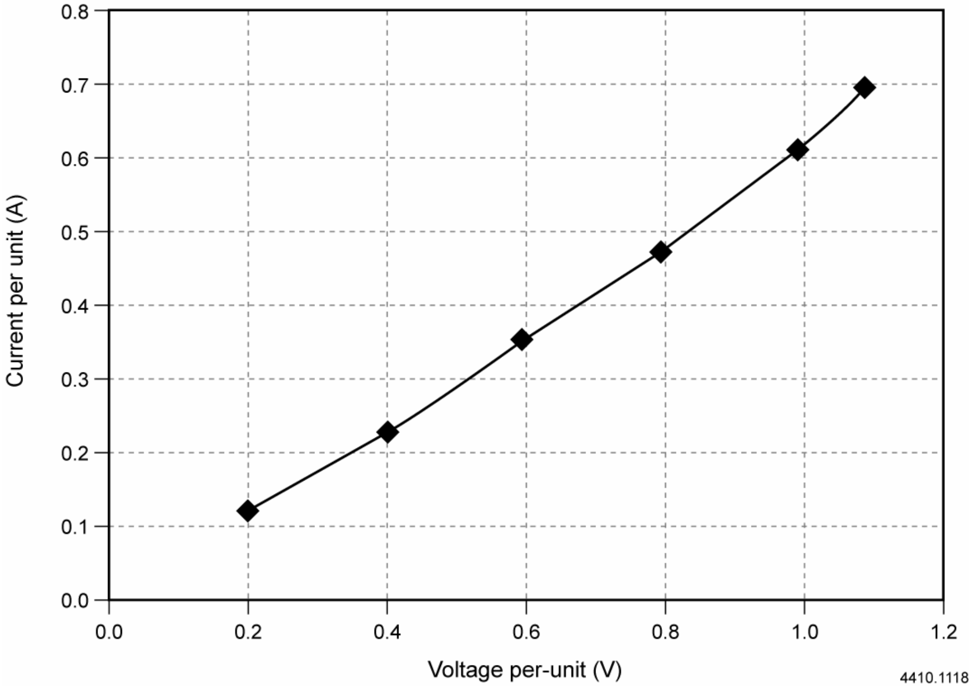

Fig. 4. Current vs. voltage curve from no-load saturation test

The data from Fig. 3 is used to calculate the friction and windage loss, and the motor's core loss. The procedure for doing this is explained in reference [1] and will not be repeated here. The only difference between the data analysis for fixed frequency tests and the inverter tests is that the fundamental values (not the total inverter rms) of voltage, current, and power were used for the calculations. This allows direct comparison of the test results with calculated values, which are normally calculated based on a sinusoidal waveform assumption.

V. LOCKED-ROTOR TEST

The rotor shaft was locked with a torque arm which applied force to a force transducer so that the motor torque could be measured. Locked-rotor torque measurements are normally taken with the voltage reduced below the rated value because of the rapid rotor heating due to large inrush currents that occur during this test. For fixed frequency tests, the usual practice is to set the voltage to some value less than rated value and close a contactor to suddenly apply voltage to the motor. Alternatively, if a dedicated alternator is available, the contactor between the test motor and the alternator is closed and the voltage is adjusted via adjusting the alternator field. In either event, power is left on the motor for only a few seconds to avoid overheating the motor.

The inverter used for these tests was designed as a motor drive, as are most inverters suitable for motor applications. The testing technique described in the preceding paragraph is likely to destroy many industrial inverters or cause the over-current protection circuits to trip off. For this test, the inverter control was set to the appropriate V/Hz value, for example, one half rated voltage/rated Hz. The acceleration time was set to a short value (typically 3 to 5 seconds) and the inverter turned on. After the inverter output reached its set value, time was allowed for the transients to die away and then the data input triggers were switched on. The total time from the instant that the inverter was turned on to the instant that it was switched off was less than 10 seconds. The time interval during which the motor was exposed to the large currents expected during a locked-rotor test was so short that the stator temperatures only increased a few degrees Centigrade.

Tests were conducted at both rated frequency and at a very low frequency (i.e., 5 to 10 Hz) so that data could be obtained which approximated motor-load conditions where the slip in the rotor is only a few Hz, and locked-rotor conditions where the rotor slip frequency is the applied frequency.

The rotors being tested displayed significant deep-bar effects. At rated frequency, the per-unit value of R2 was 0.0153 and at 10 Hz, it was 0.0033.

The data analysis of the locked-rotor tests provides test values for the equivalent circuit parameters R2 and X1+X2. The technique for doing this is described in reference [3].

Since the locked-rotor tests are taken at lower than rated voltage, and the information such as torque and current is desired at rated voltage, the procedure for doing this is to plot the desired value (i.e., current vs. voltage) and extrapolate the curve to rated voltage. One such curve is displayed in Fig. 5.

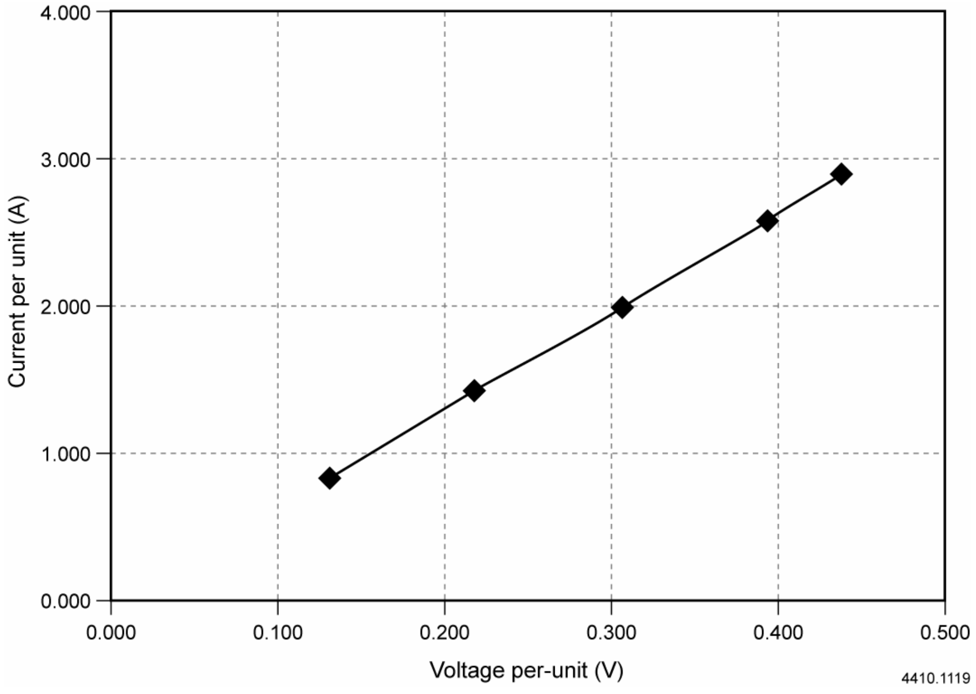

Fig. 5. Locked-rotor current vs. voltage

A curve fit of current to voltage using a linear curve fit was developed from Fig. 5.

$$i(v) = (6.667 * v) - 0.037 \quad (2)$$

Using equation (2), the value of the per-unit locked-rotor current at rated voltage is 6.630. In a similar manner, the torque can be extrapolated to full voltage, except that a second order polynomial curve fit is more appropriate for torque.

VI. BREAKDOWN TORQUE TEST

The procedure for conducting a breakdown torque test with an inverter is, as in the case for locked-rotor tests, quite different from the traditional technique used for fixed frequency testing. The motor was coupled to a water dynamometer and the dynamometer load was set to its minimum value for starting the motor. The inverter powered the motor up to the speed at which the torque measurement was to be made.

The dynamometer used in this test program was computer-controlled. After the motor reached its test speed, the dynamometer control was initiated. The torque load on the motor was ramped from its minimum value up to a value that exceeded the expected breakdown torque. Once the torque load exceeded the motor's breakdown torque, the motor speed began to decline rapidly. At this point the data acquisition process was initiated and the operator pressed the "STOP" button. The peak torque recorded by the data acquisition system is the breakdown torque.

Reduced voltage was used for this test to avoid damage due to higher current.

VII. LOAD PERFORMANCE AND TEMPERATURE TESTS

Load performance and temperature tests more closely follow the fixed-frequency test procedures than the other test procedures described above. The major concern involved in these tests is acquiring accurate test data. For those not familiar with this problem in induction motor testing, an example [4] will illustrate the accuracy issue.

Table 1 illustrates how a small error in one of the many measurements involved in motor efficiency measurement can result in a relatively large error in the reported value of efficiency [4].

A 0.5% of full-scale error in the power input measurement causes the true value of efficiency (92.5%) to be reported as 93.1%. The 0.5% measurement error, which is not unusual for power measurements, caused an error in the observed motor

TABLE 1. WATTMETER ERROR EFFECT ON MOTOR EFFICIENCY

	Reading	Wattmeter error *	True value
Input power, kW; polyphase wattmeter	80.129	0.500	80.629
Output power, kW	74.6		74.6
Losses Input –Output, kW	5.529		6.029
Efficiency %	93.1		92.5

* Calibration error is 1/2% of the full-scale reading, and the full-scale reading for the wattmeter and instrument transformer combination is 100kW.

losses of 8.3%. This arises from the fact that efficiency, calculated by dividing output by input, requires the measurement of two quantities, both of which are large with respect to the motor losses.

This intrinsic measurement problem was managed in two ways.

IEEE 112 [1] specifies a loss segregation technique for improving efficiency measurements. The technique features evaluating the individual losses and combining these losses to evaluate the motor efficiency. The IEEE 112 technique was applied to the efficiency measurements used in this series of tests.

The power measurements were the most difficult of all of the measurements to accomplish with the required accuracy. As explained in a previous section of this paper, the $v*i$ summation technique proved to be the most accurate and was the one used. Table 2 summarizes a comparison of the measured and calculated losses, efficiency and power factor.

TABLE 2. COMPARISON OF TEST AND CALCULATED LOSSES, EFFICIENCY, AND POWER FACTOR

Item	Test values Per-unit * 100	Calculated values Per-unit * 100
Pri. I^2 R	1.348	1.445
Sec. I^2 R	0.490	0.488
Core	1.463	1.420
Stray	1.908	1.908
F&W	0.763	0.756
Total	5.972	6.017
Efficiency	94.4	94.3
Power Factor	79.8	78.6

The correlation between the calculated and tested results confirmed that the testing procedures utilized in this series of tests were providing accurate values.

A companion paper describes simulation studies which were conducted on one of the two motors which were the subjects of this paper. The companion paper, “Induction Motor Performance Testing With an Inverter Power Supply, Part 2,” presents a comparison of a Matlab™ simulation against test results obtained by the testing techniques described in this paper. Also presented in the companion paper is an expanded, detailed description of the instrumentation used in this test program.

VIII. SUMMARY AND CONCLUSIONS

- Characterization and performance testing of an induction motor utilizing an inverter power supply presents a unique set of technical problems quite different from the conventional fixed frequency testing.
- High speed motor designs require testing with a high-frequency power source, such as an inverter, if they are to be characterized at their rated frequency and voltage.
- Techniques for conducting a complete set of no-load, load performance, locked-rotor and breakdown tests have been presented.
- Agreement between the test and calculated results confirms that the test procedures used provided accurate results.

IX. REFERENCES

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