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Assessment of Methods for Estimating Motor Efficiency and Load Under Field Conditions

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1. INTRODUCTION

1.1 Background

Industrial electric motor systems include electric motors and controlling devices along with the connected electrical, mechanical, and chemical devices, such as pumps, fans, blowers and compressors. These systems constitute the backbone of industrial operations, accounting for nearly 70% of all electricity used in industry.

The efficiency of these systems derives from the efficiency of individual components and the integration of these components into an operating system. The greater energy efficiency opportunities are found in the system integration rather than the selection of individual components -- these opportunities could save 240 billion kilowatt hours annually by the year 2010 [**Scheihing, et al, 1995**]. An estimated 41% of the energy savings associated with industrial electric motor systems is attributed to better matching of the motor and mechanical system components. Electrical distribution correction and process optimization are estimated to contribute 8% and 33% respectively. While also important, only 18% of the potential energy savings is associated with improvements in the efficiencies of motors themselves. Substantial improvement opportunities can be uncovered, therefore, when the design, control, and operations and maintenance of the driven equipment (i.e., fans, blowers, pumps, and compressors) are examined along with motors and drives.

To address these efficiency opportunities, the DOE established the Motor Challenge Program. The defining objective of Motor Challenge is to increase the market penetration of energy efficient industrial electric motor systems by working with a variety of stakeholders in the distribution chain for electric motors. The basic thrust of DOE's action will be to improve the quality and dissemination of relevant motor system information and to assist in the demonstration and recognition of efficient electric motor systems in various representative end-user settings. DOE activities will also support public and private sector efforts to organize and coordinate demand for products and services that can improve system-level performance.

Motor Challenge is comprised of the following elements: (1) partnership activities involving stakeholder planning, coordination, and education and training; (2) showcase demonstrations; (3) an information clearinghouse; (4) an electric motor systems database, and; (5) market transformation strategies focusing on the pumps, fans, blowers, and compressors that, along with electric motors and drives, constitute electric motor-driven systems. The primary and prevailing program strategy is to provide national leadership to augment the resources and help focus the capabilities of trade associations, research institutions, utilities, states, and public interest groups to assist U.S. industrial motor system end-users in realizing greater cost-effective energy efficiency, productivity, and environmental performance more quickly than they otherwise would. Other strategic elements of the program include: providing comprehensive, timely, and reliable information and technical know-how to end-users; discovering and recognizing engineering excellence in the design and operation of efficient electric motor systems for the goal of encouraging other companies to emulate these examples; educating and training practioners and trainers about the latest "best practices" associated with efficient electric motor systems; and assessing the electric motor system markets to improve the currency and reliability of information on the population of motor systems in the economy and for the purpose of focusing public and private marketing efforts on the most promising segments.

As a first step in developing "best practices", an assessment of techniques for estimating motor efficiency and load in the field has been conducted. Starting with the motor was a logical choice since the motor will be a component in all systems considered. The intent is to then extend the development of best practices to other system components and then combine them into motor system tools.

1.2 Objective

The objective of this manual is to determine, for the Motor Challenge Program, recommended practices for estimating motor efficiency and load in the field and documenting these methods, so that they can be used by industry to estimate accurately the efficiency of motors while they are in operation.

1.3 Discussion of Motor Efficiency Measurement

1.3.1 Bench Testing

In general, bench testing provides the highest accuracy of the various motor efficiency test methods. A load absorption device (dynamometer, pump or generator) is used to absorb the power generated by the motor and a torque measuring device is used to measure the torque on the motor shaft as it provides power to the load absorber. In addition, a speed measuring device is used to measure the revolutions per minute of the motor shaft as it supplies power to the load absorber. The motor output power is simply calculated by multiplying the measured torque times the measured rpm times the appropriate constant for the units desired. See Fig. 1.1 for a typical example of power flow and losses in a small motor.

Errors can be introduced through a number of avenues. The accuracy of the output power calculation is dependent only on the accuracy of two measured variables, speed and torque. Speed is relatively simple to measure accurately with hand-held strobe light devices. The measurement of torque is prone to error if one strain gauge is installed on the bench and is used to measure a wide range of shaft torque, for example from 15 to 900 foot pounds corresponding to range of motors from 5 to 300 horsepower. A strain gauge designed to read over this range will sacrifice accuracy at low levels.

Errors can also be introduced in the calculation of input power. This primarily occurs in the phase shift associated with the current transformer and the apparent phase shift that can be created by the difference in sample time between the samples of current and voltage in typical 6 channel data acquisition systems. These phase shifts can cause a shift in the relative displacements of the voltage and current waveforms which can lead to a significant error in the calculation of power and power factor (see Appendix A for a detailed description).

The power supply at the test bench may also introduce error into the efficiency determination. A three percent voltage imbalance can result in a negative sequence current flow and subsequent heating which requires nearly a 10% derating of the motor **[NEMA MG1]**. Similarly a 5% harmonic distortion can result in a motor heating and a required de-rating of 5% **[Sadanandan and Elton]**. An over voltage or under voltage condition can also have an effect on efficiency. The National Electric Manufacturers Association (NEMA) allows a voltage variation of plus or minus 10 percent of rated voltage on typical industrial motor applications, but these variations, if permitted on the test bench, can result in efficiency changes of ± 5 percent.

Thus even with a test bench and dynamometer there are possible sources of error due to the data acquisition method, torque transducer and the power supply. Therefore, measurement accuracies claimed to be correct within ±1% should be viewed with some skepticism unless each of these potential sources of error has been considered and controlled. For example, NEMA now performs a "round robin" of testing where a sample motor is shipped from test bench to test bench around the country to be tested for efficiency. Independent laboratories, manufacturers and universities are included in the testing. A range of more than 4% in the measured efficiencies for a sample motor in this "round robin" is not unusual.

The strength of bench testing, in a laboratory so equipped, is that all these potential sources of error can be carefully monitored and controlled so that a determination of efficiency can be made with a known value of accuracy. In addition, the dynamometer load can be varied so that several points on the motor performance curve (e.g. 100%, 75, 50, 25 and no load) can be measured. The associated weakness is that the field service conditions that may be present in a specific application such as phase imbalance, over or under voltage, or harmonic distortion, which can have a significant impact on efficiency, are not measured and their effect on motor efficiency and reliability is not determined.

A significant drawback to bench testing is the time required to remove the motor from service, transport it to the test facility, perform the testing, transport the motor back to its service location, and reinstall it, including alignment as necessary. There is a significant expense in downtime and manpower, that would only be acceptable when a high accuracy and high confidence level motor efficiency determination is necessary. Another drawback to bench testing is that the laboratory which performs the testing must be equipped not only with a load absorption device such as a dynamometer or water brake, but it also must maintain calibration on the torque sensing device, voltage and current instrumentation and normally must have power quality correction equipment installed such as a three phase variac and an isolation transformer.

1.3.2 Field Testing Methods

The most significant advantage of the in-service test methods is that the motor does not have to be removed from service and the manufacturing process is not interrupted. Measurements can be taken quickly with clamp-on current transformers (CTs) and voltage probes. Typically, these measurements are taken at the motor control center or switchgear, but they may be taken at the motor terminal box if the need for higher accuracy exists. Often field testing is the only practical method for efficiency testing because neither removal of the motor nor operational downtime is permitted by the end user.

A second significant advantage of performing in service testing is that the motor's service condition can be measured and recorded for evaluation. As previously discussed, voltage imbalance and harmonic distortion can have a severe negative effect on performance and motor lifetime. The level of harmonic distortion and voltage imbalance can be measured easily with an inexpensive hand held meter when the voltage, current and power measurements are being taken. These measurements can then be used to evaluate whether motor derating is necessary.

The fundamental disadvantage with field testing is that motor torque output is not measured. Thus motor power output is not measured. Rather measured currents, voltages, power factors, and speed are used in conjunction with nameplate data to estimate power output and efficiency. The approximation methods used for determining efficiency are generally divided into two groups: (1) those that approximate efficiency based only on motor speed, and (2) those that perform the calculation based on a mathematical model, or equivalent circuit, of the motor.

The methods of approximating efficiency in the field without measuring motor torque output and without using an equivalent circuit typically rely on a measurement of motor speed or power. An example of this methodology is the "Stanford Method" **[Wilke and Ikuenobe]** where the motor current, voltage and power factor are measured. The motor efficiency is calculated using empirical relationships that were developed based on data accumulated from a test group of over 50 motors. Another method is the slip method, which assumes that the motor speed torque curve and efficiency curves are approximately linear when the motor is near its rated operating speed. The slip method finds the percentage of motor load by finding the percentage of the rated slip at which the motor is operating, and then using this "percentage of load" to find an output horsepower. A compensated slip method exists where the motor running speed is corrected for terminal voltage

before the percentage of slip is found. These methods are in reality approximations and yield efficiencies that are often more than 15% from the true operating efficiency.

More sophisticated methods use techniques for calculating motor torque without actually measuring it and depend on the use of a motor equivalent circuit or some other mathematical model of the motor's electro-mechanical power transfer mechanism. The motor equivalent circuit is a mathematical model of the motor where the motor is represented as a simple single phase circuit. Typically, the stator resistance and inductance, the rotor resistance and inductance and the magnetizing resistance and inductance are assigned values and used in the motor equivalent circuit. The degree of accuracy of these methods is directly related to the degree of accuracy of the parameters in the equivalent circuit model.

If the equivalent circuit accurately represents the performance of the motor, accurate determinations of torque, power output and efficiency can be made with voltage, current and power factor measurements. If the speed is also measured, it can be used as a verification of the calculation by comparing the calculated speed with the measured speed. Development of a high accuracy equivalent circuit is normally done with information obtained from no load testing and resistance testing of the disconnected motor. If facilities permit, reduced frequency testing may also be performed. Equivalent circuit development is described at length in IEEE Standard 112, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators **[IEEE]**. In typical industrial applications, however, the user generally will not permit the motor to be disconnected to measure stator resistance, or uncoupled operation of the motor to measure the no load power input. For this reason, an alternate, less accurate, method of developing the equivalent circuit is often used.

An equivalent circuit may be developed by using motor nameplate data and data from Motor Master or standards developed by IEEE. Motor Master is a data base of motor performance information for over 10,000 motors available on diskette. **[WSEO]**. It is possible to develop an equivalent circuit from this information because the nameplate usually provides performance information, such as the locked rotor kVA code and NEMA Design type, which can be used in a set of equations to solve for the equivalent circuit constants. If the nameplate data is incomplete, Motor Master can be consulted to fill in the remaining information. Sometimes more information is available from Motor Master than is available on the nameplate. The problem with this approach is that the nameplate and Motor Master data are generic design data and may not be accurate in reflecting such parameters as the actual speed and power factor when the motor is delivering rated horsepower.

In general, the more information that can be obtained on a specific motor, such as no load current and power factor, stator resistance, running speed at rated load, temperature rise at rated load, etc., the more accurate the equivalent circuit can be made, and the more accurate the determination of efficiency will be. The unique aspect of the equivalent circuit method is that the circuit can be solved for any running speed. When the circuit is solved, it will calculate a motor power factor. This power factor can then be compared with the actual measured power factor to assess the accuracy of the equivalent circuit. If the calculated power factor does not match the measured power factor, the equivalent circuit parameter of magnetizing reactance can be adjusted until a match is found. Magnetizing reactance, does, in fact, decrease as a motor ages. As the magnetizing reactance decreases, the efficiency also decreases. Thus the equivalent circuit can be adjusted to match the present condition of the motor if the power factor can be measured.

1.4 Purpose and Scope

The purpose of this manual is to assess motor efficiency estimation methods that can be used in field applications for motors running in their normal service condition and select and document a recommended method for each of three intrusion levels: high, medium, and low. The low intrusion level is used for initial estimates of potential energy savings and is the least accurate method. However, it is relatively simple to implement and results in the lowest level of intrusion in normal operation of the system. The high intrusion level method yields the highest accuracy in calculating motor efficiency. However, it requires the greatest amount of data and results in the highest level of intrusion in normal operation (i.e. a locked rotor test may be required). The medium intrusion level yields efficiency estimates that are somewhere between the other two in terms of accuracy.

The methods will provide the information needed by end users for performance optimization studies and for evaluating relative motor performance and assessing savings potential, and in cases where performance degradation is suspected due to off-normal service conditions. They will also be used by DOE in the Showcase Demonstrations to benchmark the savings obtained by the motor replacements. In addition, the methods will also "dovetail" with the Electric Motor Systems Database to ensure that consistent and meaningful data is provided to the database. The purpose of this manual is to define a motor efficiency estimates method that can be used in field applications for motors running in their normal service condition.

1.5 Assessment Methodology

The assessment of field efficiency measurement techniques involved two assessment steps. In the preliminary selection phase, techniques were identified through literature search. Evaluation criteria were developed and the techniques were assessed against the criteria. Based on this assessment, candidate techniques were selected for each intrusion level. Each of the candidate techniques was then tested in the ORNL Electric Machinery System Test Center (EMSTC) to determine its accuracy and define appropriate procedures for implementing the technique. Additional verification was obtained through field trials of the methods. Based on these tests a "recommended practice" was selected for each intrusion level.

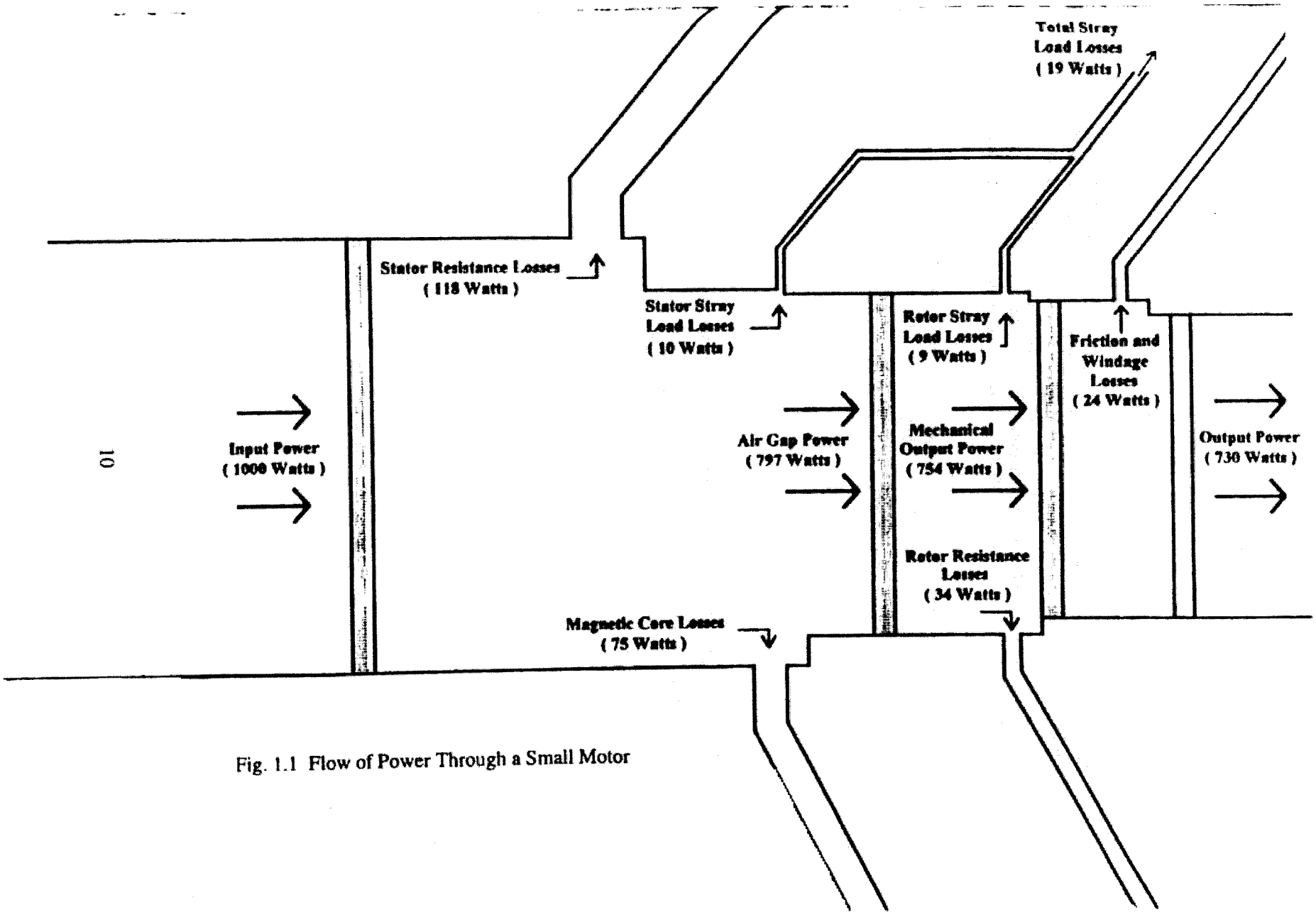

Fig. 1.1 Flow of Power Through a Small Motor

2. SELECTION OF CANDIDATE METHODS

There are a large number of methods for estimating motor efficiency in the field. A recent, comprehensive review **[Kueck, 1995]** documented nearly 25 methods that are in use or proposed for use. Selection of candidate methods for best practices began with this portfolio. These methods were screened using two qualitative criteria: intrusion level and accuracy.

Intrusion level refers to the level of disruption required in normal operation of the motor to obtain the data necessary to implement the efficiency estimation technique. A technique that requires only a motor speed measurement using an optical tachometer has a very low level of intrusion. A technique requiring current data using a clamp-on probe will have a slightly higher level of intrusion but will still be a relatively low intrusion level since this data can be acquired without impacting the operation of the motor. Power data, in general, will have a higher intrusion level because the data acquisition generally requires that the motor be shut down while the instrumentation is connected to the system. Any technique requiring this data was classed as a medium intrusion level. Methods requiring a custom built torque coupling were judged to have the greatest intrusion level. The methods were classified as high, medium, or low intrusion methods according to the intrusion level associated with the data acquisition required to implement the method.

Accuracy has several components. Each method has an inherent level of accuracy that is related to the assumptions and simplifications used in the method. For example, a method using the nameplate full load slip will, in general, have a relatively poor accuracy since NEMA allows a manufacturing tolerance of 20% on this value. Overall, accuracy is also affected by the measurements that are required (see Appendix A for a discussion of measurement techniques). Because measurement accuracy is external to the method, it was not considered when assessing the methods. Methods in each intrusion level were ordered with respect to expected accuracy. Those potentially providing the greatest accuracy were judged to be candidates for laboratory testing.

The methods selected and the qualitative assessment attributes that led to their selection is presented below. The methods are not discussed in detail since detailed discussion is presented in Kueck (1995). Those selected as recommended practices (one at each intrusion level) are described in Chapter 4.

2.1 Low Intrusion Level Methods

Current Method - The current method used here is a slight modification of the typical current method. This improved method provides a correction for the nonlinearity of the current-load relationship. Although it is anticipated that this will improve the accuracy of the method Nailen (1994) provides an example where such an improved method does not always provide an estimate better than the simple current method. A measurement of no load current is required because it is usually not found on the nameplate of older motors. The accuracy of this method is expected to be poor but it is included for the sake of completeness.

Slip Method - This method is a variation of the tachometer method and is in common use today. In this method, the nameplate data may be corrected by the square of the ratio of the actual terminal voltage and the rated terminal voltage. The power input to the motor may also be used. The power output may be estimated using the ratio of motor slip to rated slip times the nameplate power output. This is more intrusive than the standard slip method, but it is still relatively inaccurate because the motor full load speed is allowed a tolerance of 20% by NEMA.

Nameplate Equivalent Circuit Method - A modified version of IEEE standard 112 method F is used. An additional resistance is added to account for stray load losses. The information needed to construct the equivalent circuit is taken from the nameplate. Only a measurement of motor speed

is required to estimate the motor load and efficiency. The accuracy of the method depends upon the accuracy of the equivalent circuit model which in turn depends upon the accuracy of the nameplate data. It is anticipated that this method can yield reasonably accurate results (± 5 efficiency points) for efficiency estimation purposes.

Medium Intrusion Level Methods

Empirical Method - The Stanford Wilke Method was developed at Stanford University with K. Wilke as one of its developers. The method was developed to be applicable to motors between 10 and 50 horsepower. Some of the empirical assumptions were taken from IEEE 112 while others arose from the author's experience. It is anticipated that the method will yield ecy estimates are within ±4 efficiency points or better.

Ontario Hydro Modified (OHM) Method - This method is a modification of the Ontario Hydro version of IEEE 112 Method E Segregated Loss Method. In the original method an empirical value of 3.5% was used to find the no load losses (in lieu of performing a no load test). Thus the no load loss is estimated as 0.035 of the nameplate full load power. The modified version uses a value based on motor size, and the stray load loss approximation described in IEEE Standard 112. This results in an empirical factor for finding stray load loss based on motor size. The full load power is estimated using the nameplate current and voltage and a power factor of 0.8. The anticipated accuracy is on the order of that expected for the Stanford Wilke Method.

High Intrusion Level Method

Air Gap Torque Method - The air gap torque method calculates the power transferred across the motor's air gap. If a no load test is made to find the core loss and friction and windage loss, this method can be highly accurate (yielding efficiency estimates that could be within 1 efficiency point of actual values). The method requires acquisition of the voltage and current waveforms which are then used in the analysis. These waveforms are typically stored on a data acquisition tape recorder. Because the harmonic components can be obtained from the waveforms, the loss associated with the power supply pollution can also be assessed.

3. TESTING OF METHODS

The testing program was performed to assess the potential accuracy of the various efficiency test methods by comparing their results with laboratory dynamometer testing. In addition, field tests were made to evaluate the accuracies of the methods with actual field data. The field tested motors were then shipped to the laboratory for confirmatory testing.

3.1 Laboratory Testing

A sample of 12 motors ranging from five to 100 hp were tested at ORNL's Electric Machinery System Test Center (EMSTC). Seven of the motors were older standard efficiency designs, the remaining five motors were energy efficient designs. Two of the older motors had been rewound. One of the energy efficient motors used was considered to be near end-of-life condition.

The motors were tested with no load, and at 25, 50, 75 and 100 % load. In general, these tests were made at two voltage conditions: phases balanced within 0.5% and unbalanced to 3%. Voltage, current, and power RMS data were acquired for each test. In addition, waveform voltage and current data were recorded in each of the tests.

3.1.1. Laboratory Configuration of the EMSTC and Test Procedure

Power Quality - The EMSTC uses a three phase variac with a microprocessor control system to maintain voltage at the desired level and at the desired state of unbalance. The balanced testing was performed at a voltage within one percent of nominal voltage, and within a one percent unbalance. Unbalanced testing was performed with a three percent unbalance. The frequency was within 0.1 Hz of 60 Hz and the total harmonic distortion was under 3%. A harmonic distortion generator is under construction at the EMSTC but it was not available for this test. NEMA MG 1 provides derating guidelines for harmonic distortion where a Harmonic Voltage factor is defined. If the total harmonic distortion is less than 3% , the voltage distortion is far from the harmonic voltage factor where derating would be required.

Load Absorption - The EMSTC uses a 20 KVA , 3600 rpm generator with resistive load banks as a motor load absorber for motors up to ten horsepower, and a water cooled eddy current dynamometer for loads up to 100 horsepower. The load of the generator and dynamometer is varied by varying the field current. The field current was provided by a DC power supply.

Torque Measurement - For motors up to 10 horsepower, the EMSTC uses in line torque meters with a one piece stainless steel shaft and a bonded foil strain gauge. The signal from the strain gauge is coupled to the 4-20 mA transmitter circuit by a rotary transformer. For motors greater than 10 horsepower, the dynamometer moment arm is connected to a 250 pound load cell. The load cell may be calibrated for ranges smaller than 250 pounds when motors in the lower end of the 10 to 100 pound range are tested. Both the load cell and the in line torque meters are periodically calibrated with dead weights. A precision moment arm is used to calibrate the in line torque meter.

Power Measurement - The power input to the motor was measured using two methods. One method was with a commercially available three phase power analyzer. This analyzer uses internal current shunts for currents up to 100 amps, and external high accuracy Current Transformers for currents above 100 amps. The other method uses a virtual instrument (VI) on a LabView platform. The VI acquires voltage and current waveform data at 5,000 Hz and performs a multiplication and summation to find the power. The advantage of the VI is that the samples may be taken over a longer period of time, typically one second for the stable loads of the generator and dynamometer, and then averaged. The current input to the VI is provided by Hall Effect current transducers for currents up to 100 amps, and precision current transformers with a known phase shift for currents

over 100 amps. The phase shift of the current transformers is accounted for by the VI before the voltage and current multiplication is made.

Calibration - All measuring devices, the current transducers, load cell, torque meter, voltage dropping resistor, Analog to Digital circuit boards, power analyzer, etc. are calibrated periodically and traceable to NIST.

Test Procedure - The motor to be tested is mounted on the baseplate and aligned to the generator or dynamometer. A flexible coupling was used between the motor and the load. The motor was run for one half hour at full rated load before measurements are made to reach a stable temperature. Measurements were made at no load, 25, 50, 75 and 100 % power, and then back at no load.

Data - At each load condition, data was acquired by the virtual instrument. The RMS values of torque, speed, power in, voltage and current were written to a spreadsheet file. The waveform parameters of voltage and current were written to a binary data file. The spreadsheet values were used in all the efficiency calculations except the air gap torque method. The air gap torque method requires waveform data which was provided by the binary file. The power measurement provided by the power analyzer was acquired manually and noted in the test log.

Data Reduction for Efficiency Estimation - To ensure that the data reduction for each of the various methods was done in the same manner, the six efficiency estimation methods were programmed in Mathcad so that the same input data could be provided to each method and the results would be reported in the same way.

Accuracy - The overall accuracy of the laboratory efficiency measurement is calculated to be plus or minus 0.6 percent, based on the square of the sum of the squares of the individual measurement accuracies. The efficiency measurements are reported to three significant digits, although the last digit is not considered to be meaningful in terms of the ability to measure accurately to this level.

3.1.2 Results of Laboratory Testing

Figures 3.1 through 3.19 provide plots of estimated efficiency for four load points: 25, 50, 75, and 100% load. Each figure contains the efficiency estimates of each of the six methods in addition to the measured efficiency (using the torque gage and motor speed measurements). Each figure provides the results for one of the twelve sampled motors at one of the voltage conditions.

These results are also presented along with the no load results in Tables 3.1 through 3.12. The first column contains the measured efficiency. Successive columns contain the estimated efficiency using the indicated technique. The average difference (for all tests) between the measured and estimated efficiency for each method is shown in Table 3.13. The values in this table are expressed as a percentage difference (as opposed to efficiency points) between the actual and estimated efficiency. If the actual efficiency was 85% and the method estimated was 83.5% the percentage difference is 1.76% and this is the value that would be reported in Table 3.13.

3.1.2.1 Low Intrusion Methods

As indicated by the data in Fig. 3.1 through 3.19, the Improved Current method is most accurate very near full load. Its accuracy falls off dramatically as the motor load decreases. As indicated in Table 3.13 the method produces results that, on average, differ from the actual efficiency by almost 30%. This method exhibited the greatest average difference between actual and estimated efficiency. The data in Tables 3.1 through 3.12 also indicate that the method had the maximum difference beween estimated and actual efficiency obtained in any test (a 66.5% difference in the TECO test at 25% load). In fairness to the method , it must be pointed out that when no load

current is not available it was estimated by multiplying the rated current by 0.3. This led to gross inaccuracies at low loads.

Figure 3.1 through 3.19 suggest that the Compensated Slip Method is not as accurate as the Improved Current Method at full load. However, over the full range of operating loads it better tracks the actual efficiency. The average acuracy of the method, from Table 3.13, is in the 10 to 15% range.

Of the three low intrusion methods the Nameplate Equivalent Circuit (NEC) Method demonstrates the best ability to track the actual efficiency. Figures 3.1 through 3.19 show that the NEC method follows the shape of the actual efficiency plot quite well. Table 3.13 also indicates that, on average, it produces efficiency estimates that are within 3.4% of the actual values. This is an order of magnitude improvement over the Improved Current Method and a 66.7% improvement over the Compensated Slip Method. The results in Table 3.13 also suggest that the accuracy of the method is not affected by voltage imbalances up to the 3% limit used in the testing program. It is also clear that the accuracy of the method increases as the motor load increases. This is expected since the lack of no load data becomes less important to the model as motor loading increases.

3.1.2.2 Medium Intrusion Methods

The Stanford Wilke Method tracked the actual efficiency vs load trend fairly well (see Figs. 3.1 through 3.19). The average difference between actual and estimated efficiency for all tests, from Table 3.13, was 6.9% for the balanced voltage condition. With the unbalanced voltage conditions the average difference decreased slightly to 6.2%.

The Ontario Hydro Modified (OHM) method proved to be more accurate than the Stanford Wilke Method. The average difference between the estimated values and the actual efficiencies for the OHM method, from Table 3.13, was 2.6% for the balanced voltage tests. In the unbalanced voltage tests the average difference decreased to only 1.4%.

3.1.2.3 High Intrusion Method

It was felt that the average difference between actual and estimated efficiency obtained for the Air Gap Torque (AGT) method, 2% for balanced voltages and 1.7% for unbalanced voltages, was not representative of the accuracy potential for the method. In the method embodiment tested, only one cycle of wave form data was used to estimate efficiency. When only one cycle is analyzed, there is a strong possibility for error in the waveform analysis. An apparent dc offset could be created by not acquiring exactly one cycle. Additionally, an intermittent distortion of the waveform caused by a loose drive belt, misalignment, or any of a multitude of causes could corrupt the data. To overcome this deficiency in the model a second model was developed. This model refinement used more than one cycle of data for analysis. This modification was then tested during the field trial of the proposed recommeded practices as described in the next section.

3.2 Field Trial of Proposed Best Practice Efficiency Estimate Methods

Based on the laboratory assessment these methods were selected as preliminary recommended practice techniques:

Low Intrusion Level	Nameplate Equivalent Circuit
Medium Intrusion Level	Ontario Hydro Modified
High Intrusion Level	Air Gap Torque

A field trial of the methods was conducted to evaluate field results for these methods against laboratory efficiency tests. To accomplish this, a sample of four motors were first tested in the

field at the 3M Corporate Research and Development facility in Minneapolis. The tested motors were two 5 hp, one 7.5 hp, and one 10 hp. All were 1800 rpm, NEMA Design B motors. One of the 5 horsepower motors was installed on a pump while the other three were installed on fans. Plant operating conditions did not allow extensive modulation of the load on the motors, but the speed for each load condition was recorded. The acquired data was then used in each of the three efficiency estimation methods, Air Gap Torque (AGT), Ontario Hydro Modified (OHM), and Nameplate Equivalent Circuit (NEQ), to estimate efficiencies.

Later, these four motors were removed from service and shipped to ORNL's Electric Machinery Systems Test Center. At the center, the motors were tested again using a torque cell to measure their torque output. The motors were operated at the same speeds they were operating at during the field testing. The efficiencies estimated from the field tests were then compared with the actual efficiencies measured at ORNL.

3.2.1 Field Data Collection Method

To ensure that each of the efficiency estimation methods was treated equally, data was collected in the field using a TEAC Digital Data Acquisition tape recorder. This recorder was used to acquire the three phase voltage and current waveforms. The voltage signals were scaled using precision resistors wired in a connection. The current signals were scaled using clamp-on current transformers with a known phase shift. The phase shift was later factored into the data reduction as described in Appendix A. A hand held digital strobe was used to measure the motor speed.

Approximately one minute of data was acquired at each load condition. This allowed the power to be averaged over a period of several seconds so that oscillations in the load could be averaged. There were significant oscillations in the load because some of the loads were large belt driven fans. These oscillations and the calculation of average power are discussed in Appendix A.

When the voltage and current waveforms acquired on the tape recorder were played back in the laboratory, they were digitized and downloaded into software that measured the RMS values of current and voltage over a period of five seconds. These RMS values of current and voltage were used in the Ontario Hydro Modified method. The downloaded waveforms were also saved in binary files which were used in the Air Gap Torque method.

The stator resistance was also required for the Ontario Hydro Modified method, but this was measured later when the motors were shipped to ORNL to avoid having to shut down and disconnect the motors at 3M. The Air Gap Torque method also requires a measurement of the voltage and current waveforms at no load. This measurement was made later when the motors were shipped to ORNL to avoid having to uncouple the motors at 3M. All that is needed for the nameplate equivalent circuit method is the nameplate data and the measured speed. These measurements were made at 3M.

3.2.2 Testing at ORNL Electric Machinery Systems Test Center

The four motors were tested at ORNL using a generator as a load and an in line torque cell to measure the motor output torque. The load of the generator was modulated by varying the field of the generator. The input power was measured using both a conventional power analyzer and a LabView virtual instrument which calculated power based on the acquired three phase voltage and current waveforms. The output power was calculated using the measured speed and torque.

The motors were tested at no load, 25, 50, 75, and 100% load conditions. Results of these tests were included in the previous section on laboratory testing.

In the field it was not possible to perform torque measurements and calculate actual operating efficiency. Thus the approach used was to duplicate field operating conditions in the laboratory and use the measured efficiency in conjunction with the field data to assess the accuracy of the methods. The voltage unbalance at 3M was less than 1% and the voltage distortion was less than 1% THD. The terminal voltage was within 3% of the rated terminal voltage of the motors. These conditions were maintained in the EMSTC during testing.

3.2.3 Results of Testing

Table 3.14 shows the results of the testing. As indicated, two of the motors were tested at low load levels, approximately 40% and 31% load. These two motors are the 10 hp motor and the second 5 hp motor. In general, an efficiency estimation method which relies on an approximation of no load losses provides less accuracy at these low load conditions because the no load losses comprise a significant portion of the total loss at low load conditions. Both the OHM method and the NEQ method rely on approximations for no load losses. It should be noted, however, that at loads of less than 50%, it is less important to know the actual efficiency; the key information is that the motor is operating at less than 50% load and should be replaced with a properly sized motor.

A table of the motor efficiency test results is provided below:

Table 3.14 Motor Efficiency Results for 3M Motors Tested in EMSTC at Field Conditions

	7.5 hp 72% Load	10 hp 40% Load	5 hp 81% Load	5 hp 31% Load
Measured	84.5	85.2	86.2	74.3
NEQ	82.2	84.9	81.9	67
OHM	83.6	85.3	85.8	73.9
AGT	85	85.4	86.8	74.6

It can be seen that the maximum error of any method is 7.3 percentage points and that this occurs at 31% load with the Nameplate Equivalent Circuit method. The average accuracy in percentage points is 3.6 for the Nameplate Equivalent Circuit method, 0.5 for the Ontario Hydro Modified Method and 0.4 for the Air Gap Torque method.

3.2.4 Discussion

It must be noted that the accuracies obtained for the methods are for a relatively small population of motors. In addition, the best available method of acquiring field data - a digital data acquisition tape recorder acquiring several seconds of data for averaging - was used. Based on the possible sources of error discussed in Appendix A, the average accuracy obtained for the OHM method, 0.5%, is probably not representative of what a typical user could expect when using less sophisticated data acquisition equipment. However, an accuracy of 2 to 3 percent is obtainable and this is likely to be sufficient for many applications.

The average accuracy of 3.6% for NEQ method is expected to be typical. However, there is not enough experience with the method to make a definitive statement concerning actual accuracy that would be attained by users in the field. It should be noted that the motors used in this assessment tended to be older motors with less accurate nameplate data. In particular, the power factor was

not available for most of the motors and was assumed to be 0.8. With a more accurate power factor the method becomes more accurate.

The AGT method proved to be very accurate after the modification to include more than one cycle of data was made. It is believed that the accuracy attained in the laboratory tests is typical of what can be achieved in field application.

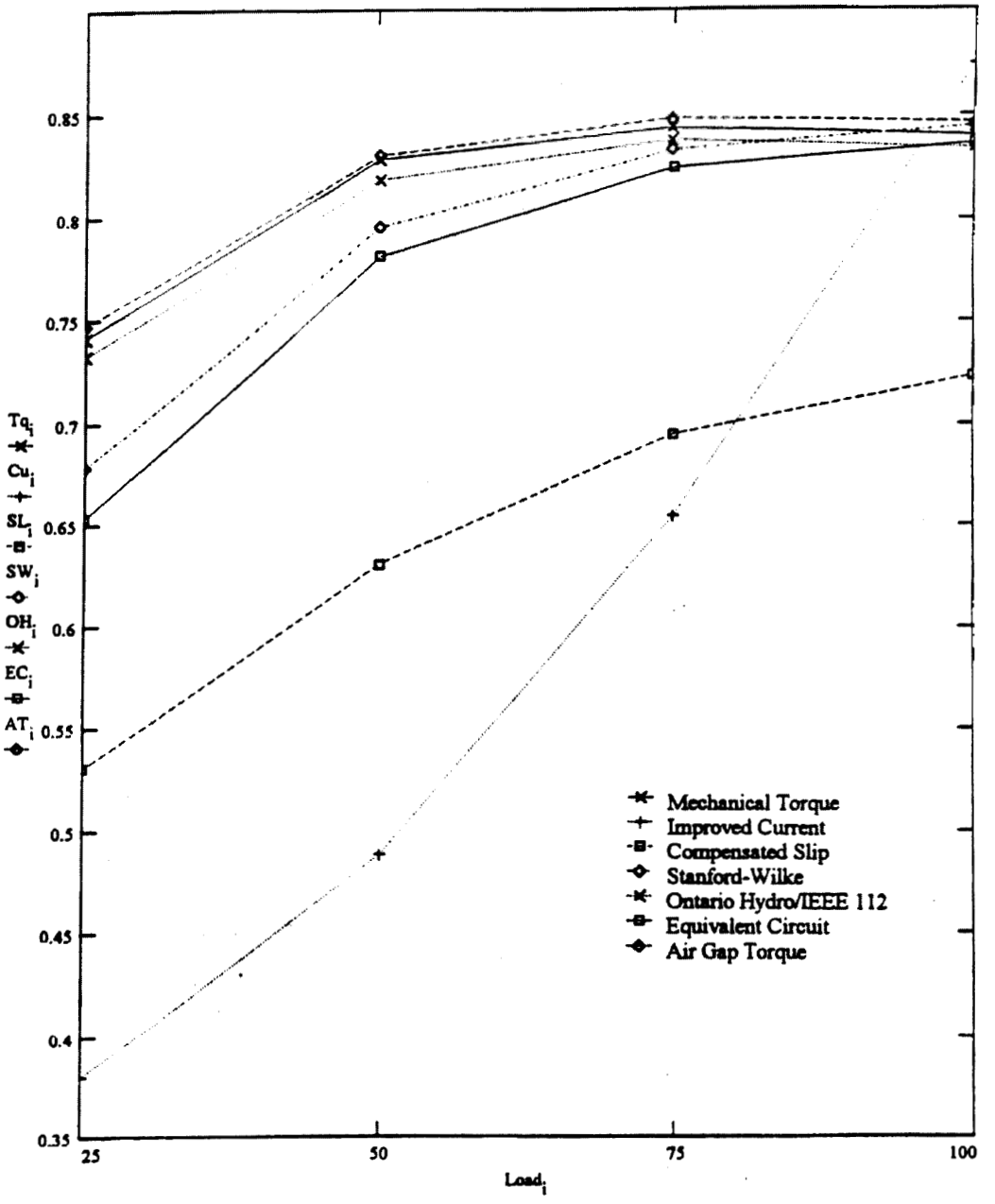

Fig. 3.1 Efficiency vs. Load for U.S. Electric Conventional 7.5 HP Motor (Balanced Voltages)

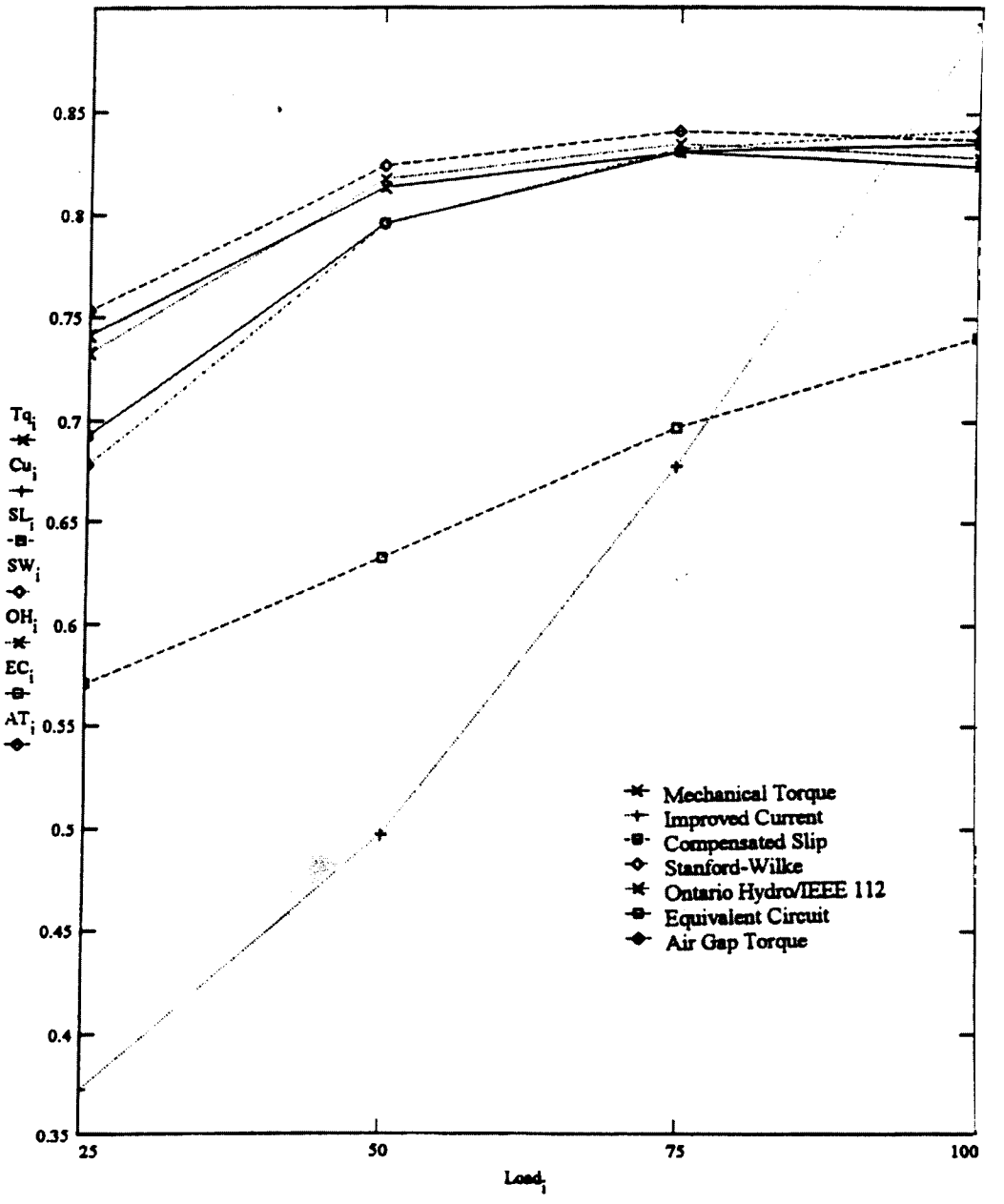

Fig. 3.2 Efficiency vs. Load for U.S. Electric Conventional 7.5 HP Motor (Unbalanced Voltages)

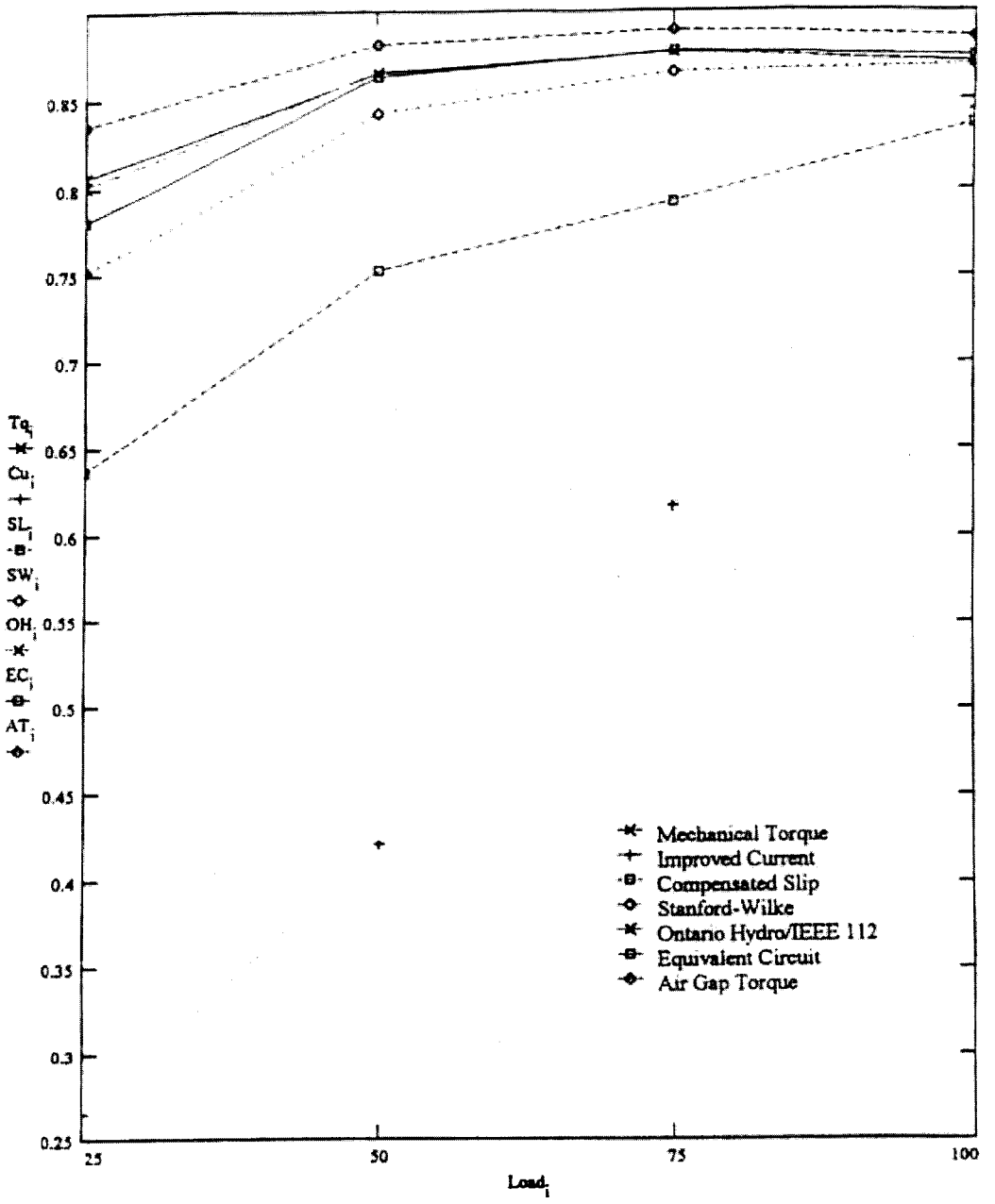

Fig. 3.3 Efficiency vs. Load for General Electric 10 HP Motor (Balanced Voltages)

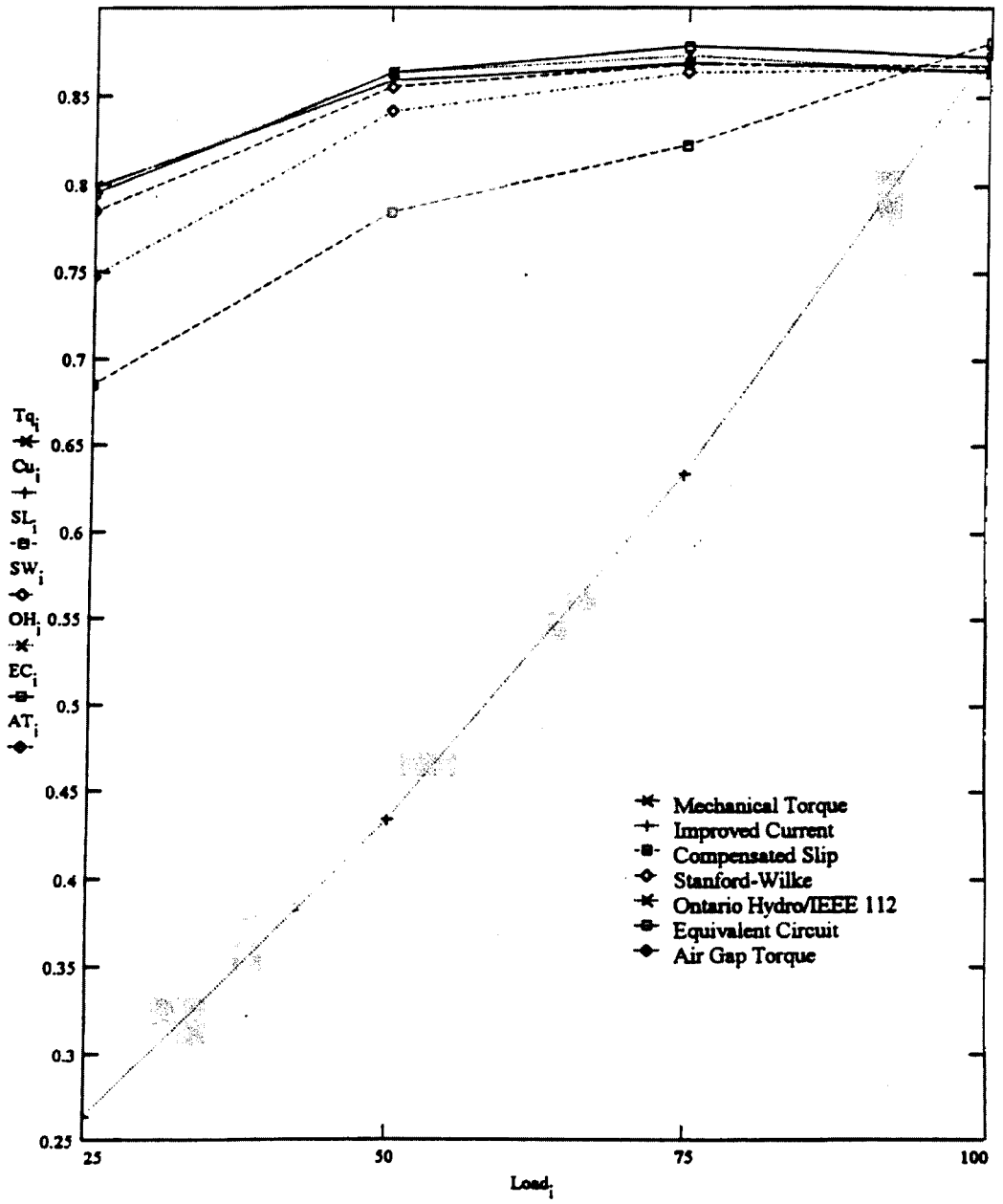

Fig. 3.4 Efficiency vs. Load for General Electric 10 HP (Unbalanced Voltages)

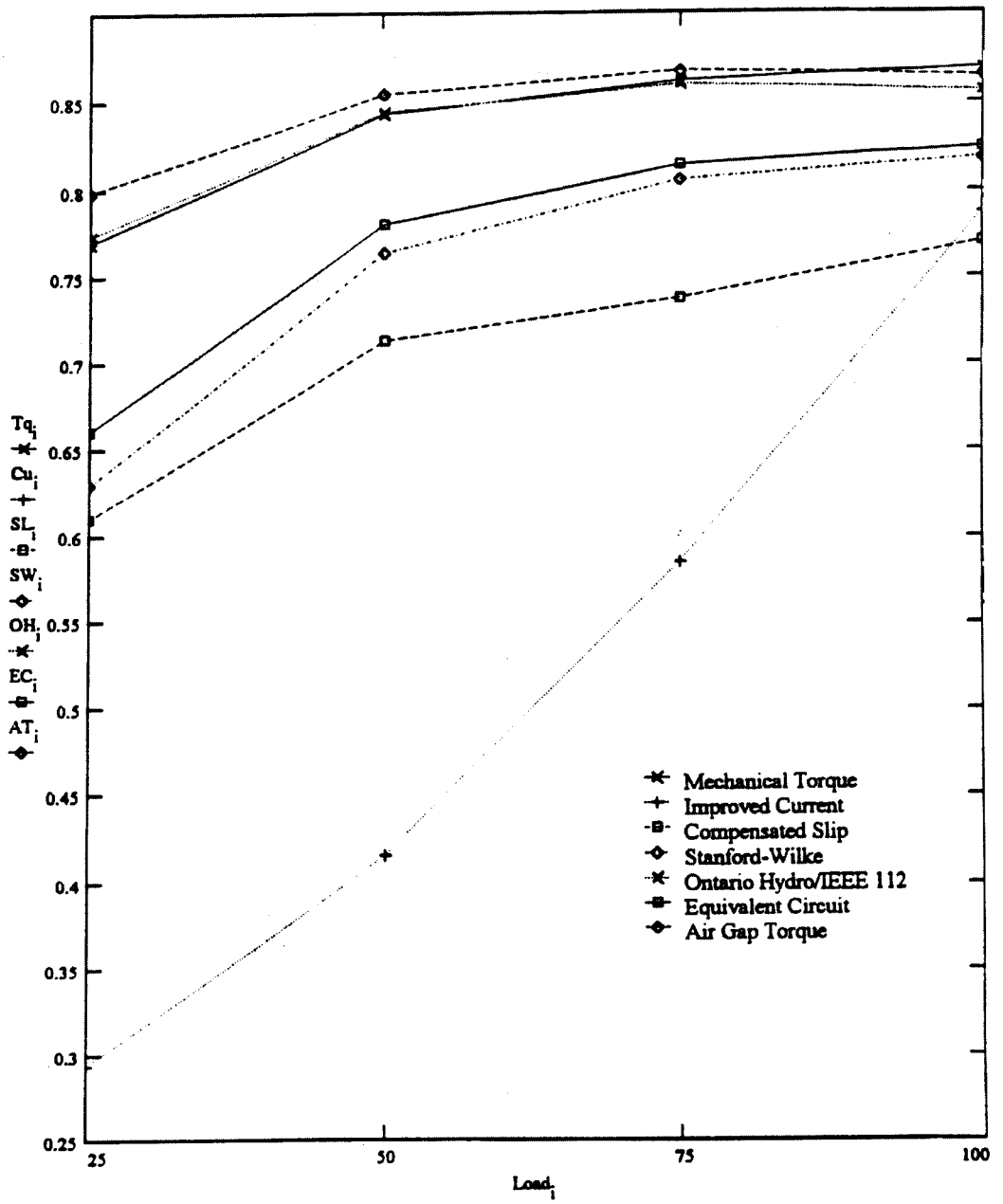

Fig. 3.5 Efficiency vs. Load for General Electric 5 HP (Motor 222) (Balanced Voltages)

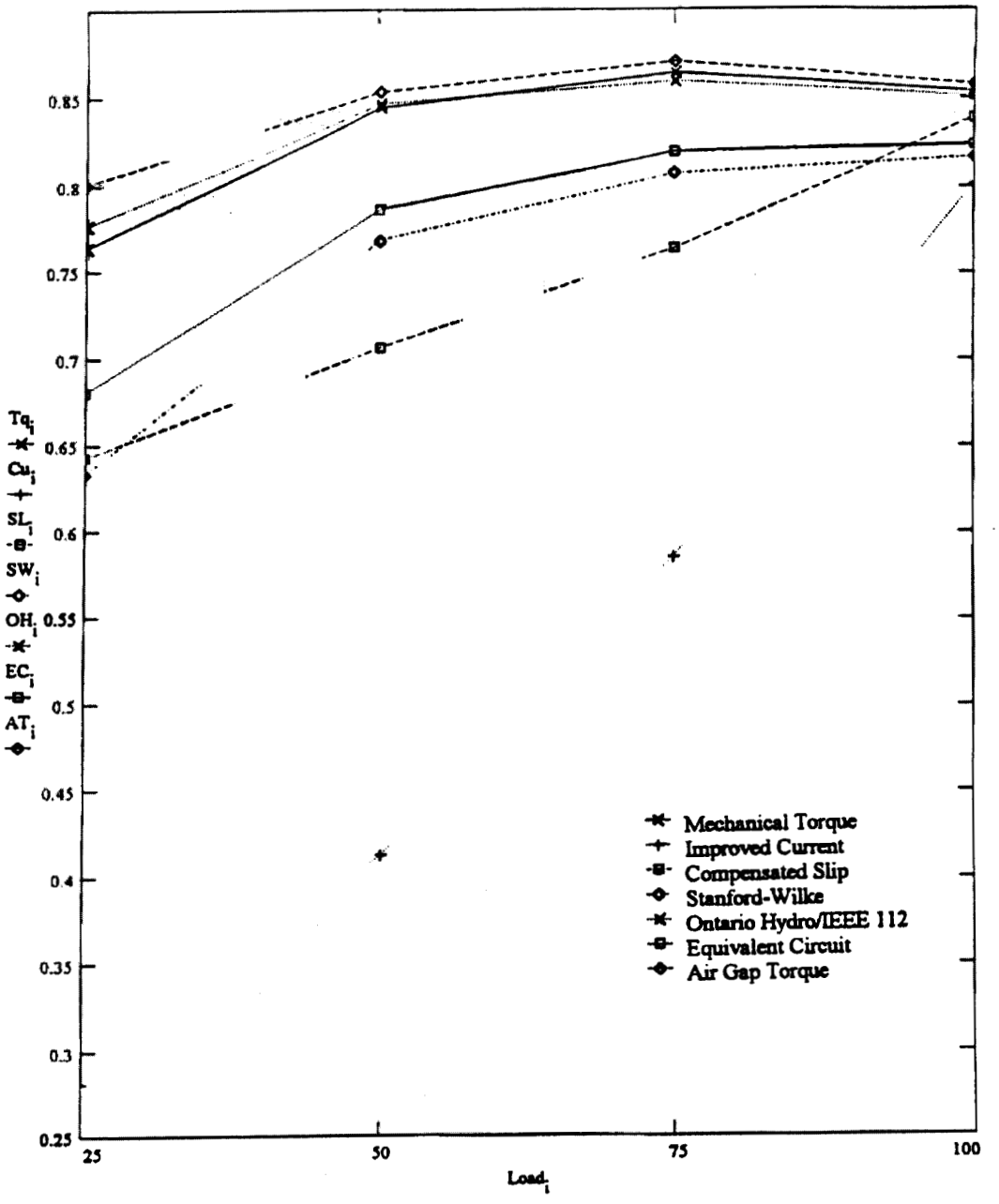

Fig. 3.6 Efficiency vs. Load for General Electric 5HP (Motor 222) (Unbalanced Voltages)

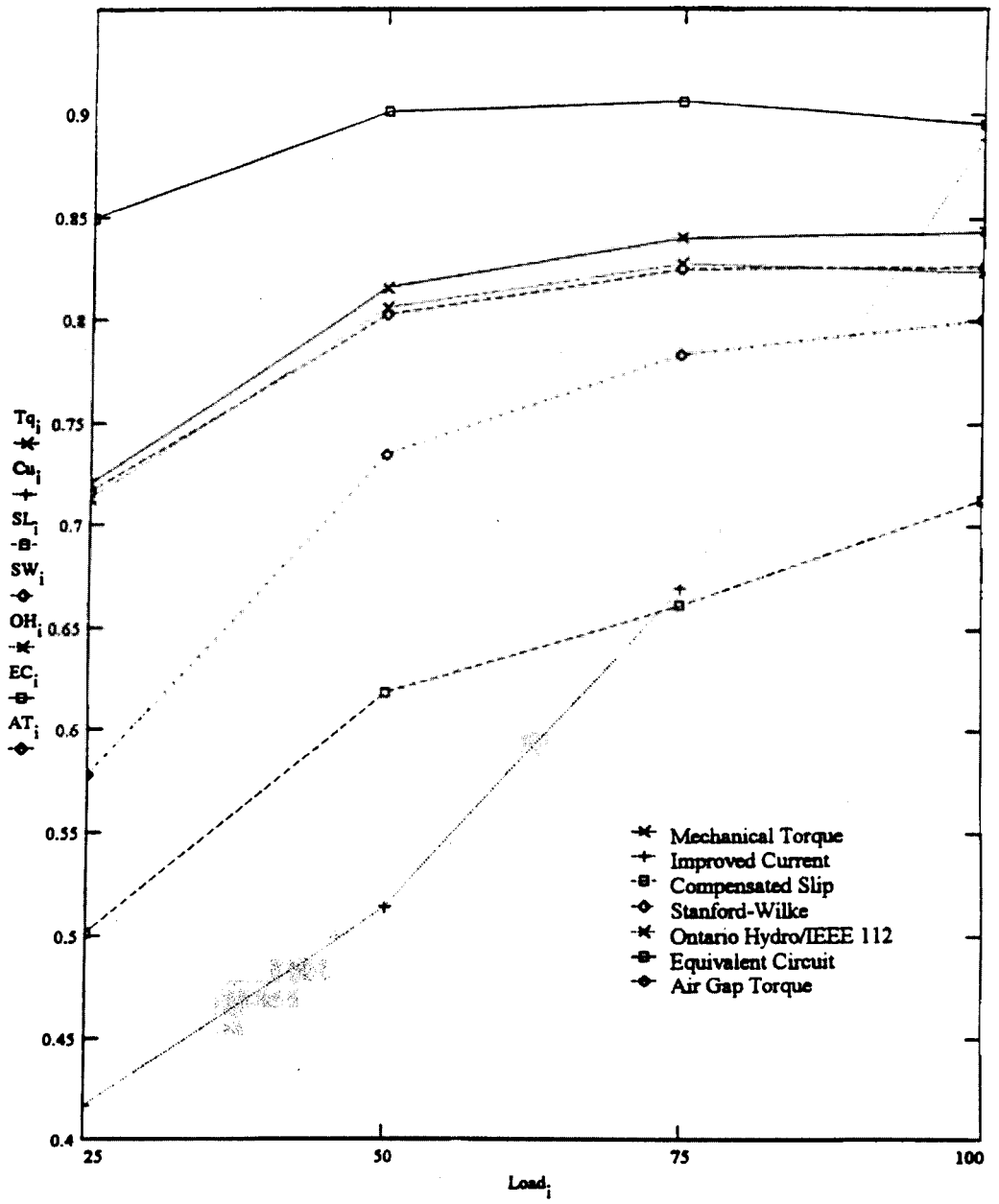

Fig. 3.7 Efficiency vs. Load for General Electric 5 HP (Motor 223) (Unbalanced Voltages)

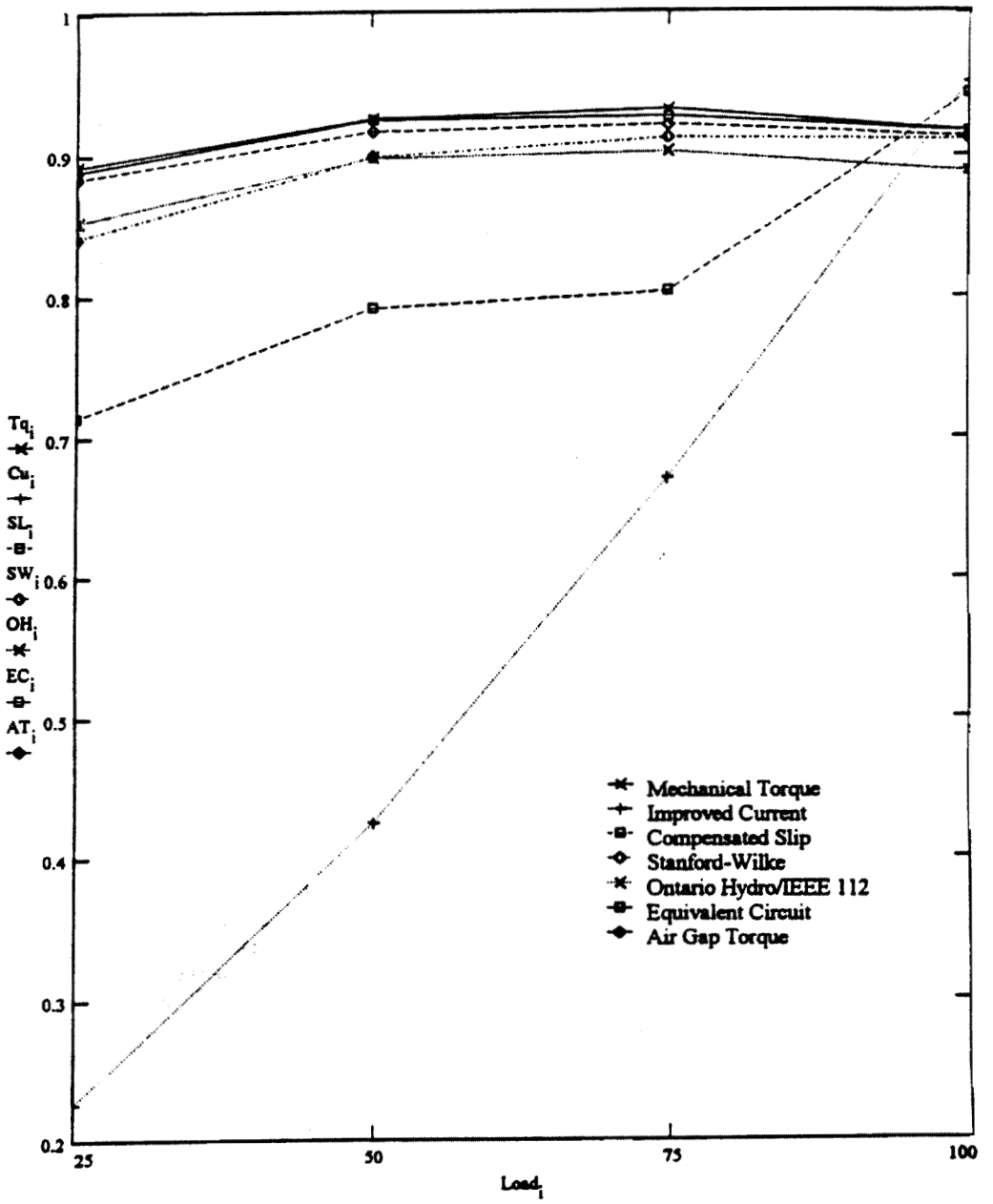

Fig. 3.8 Efficiency vs. Load for TECO 50 HP Rewound Conventional (Balanced Voltages)

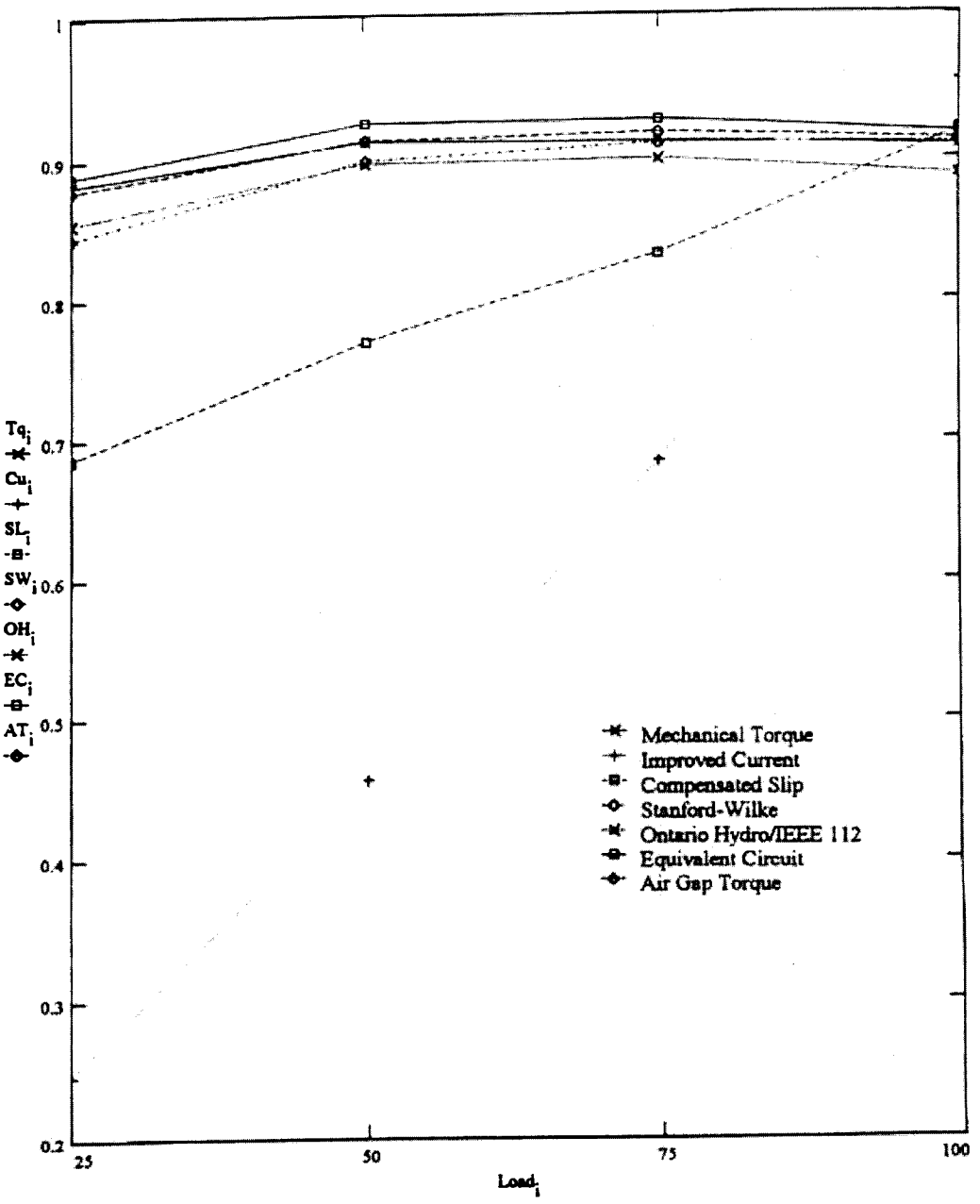

Fig. 3.9 Efficiency vs. Load for TECO 50 HP Rewound Conventional (Unbalanced Voltages)

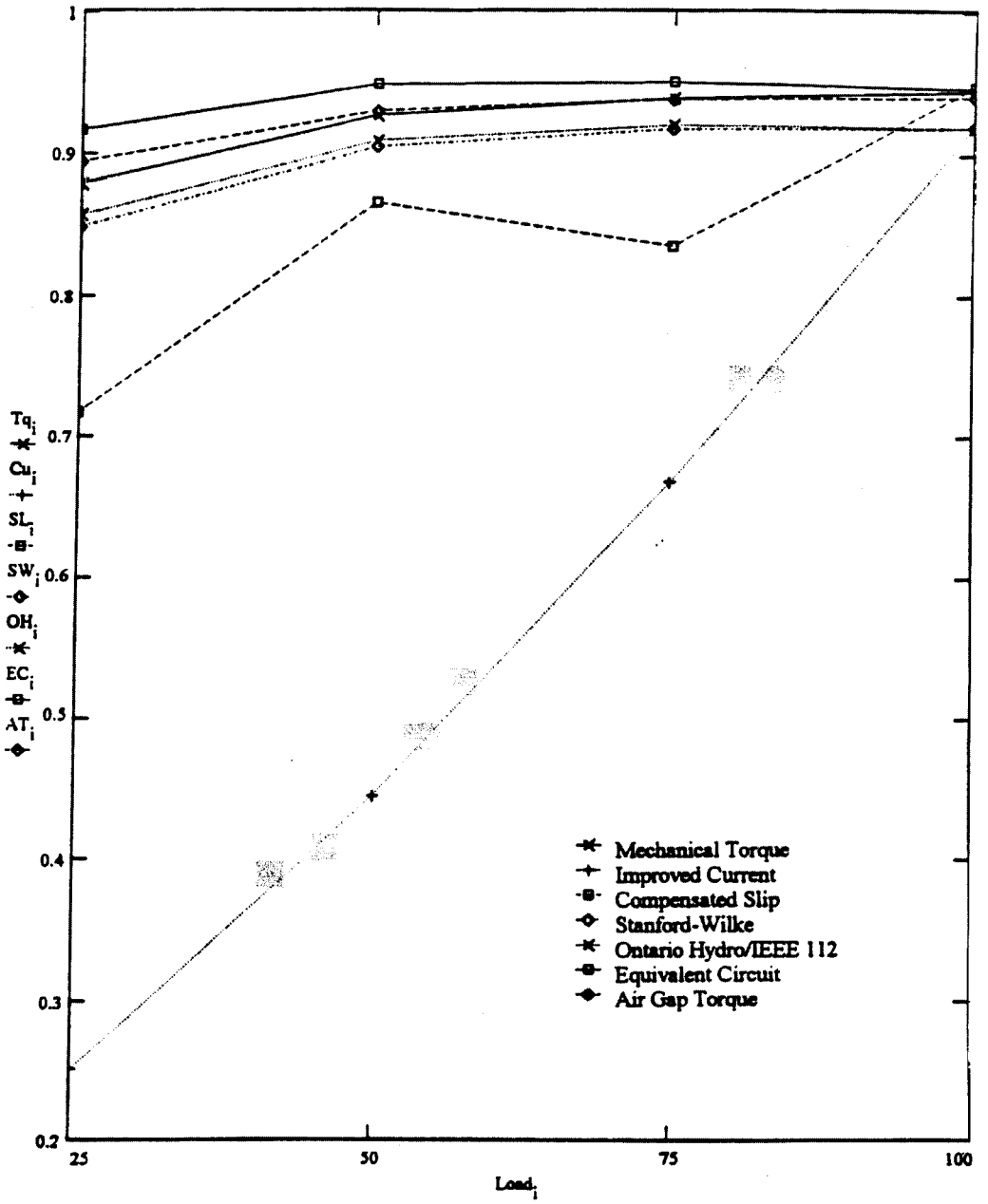

Fig. 3.10 Efficiency vs. Load for Reliance High Efficiency 100 HP (Balanced Voltages)

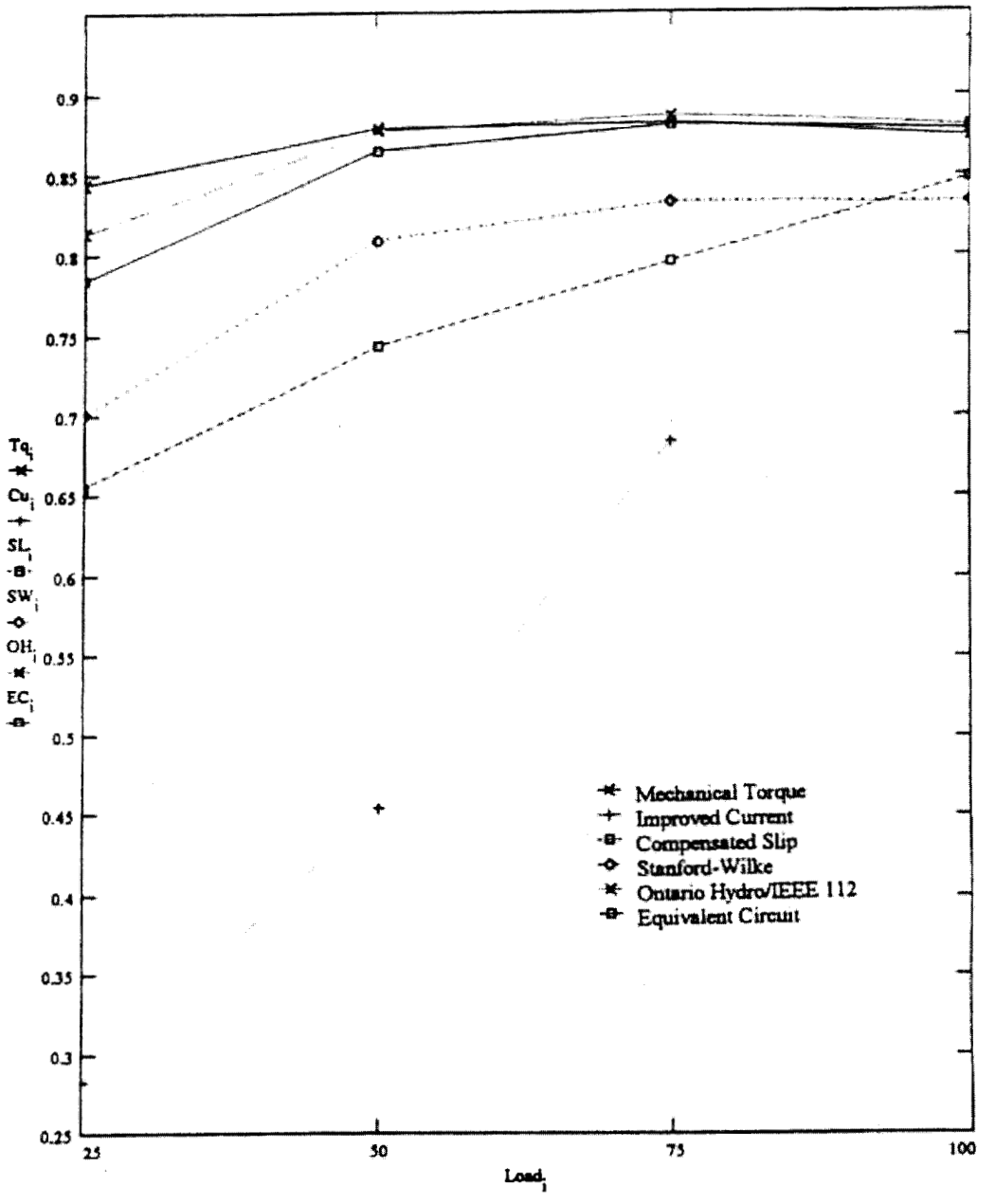

Fig. 3.11 Efficiency vs. Load for General Electric High Efficiency 7.5 HP (Balanced Voltages)

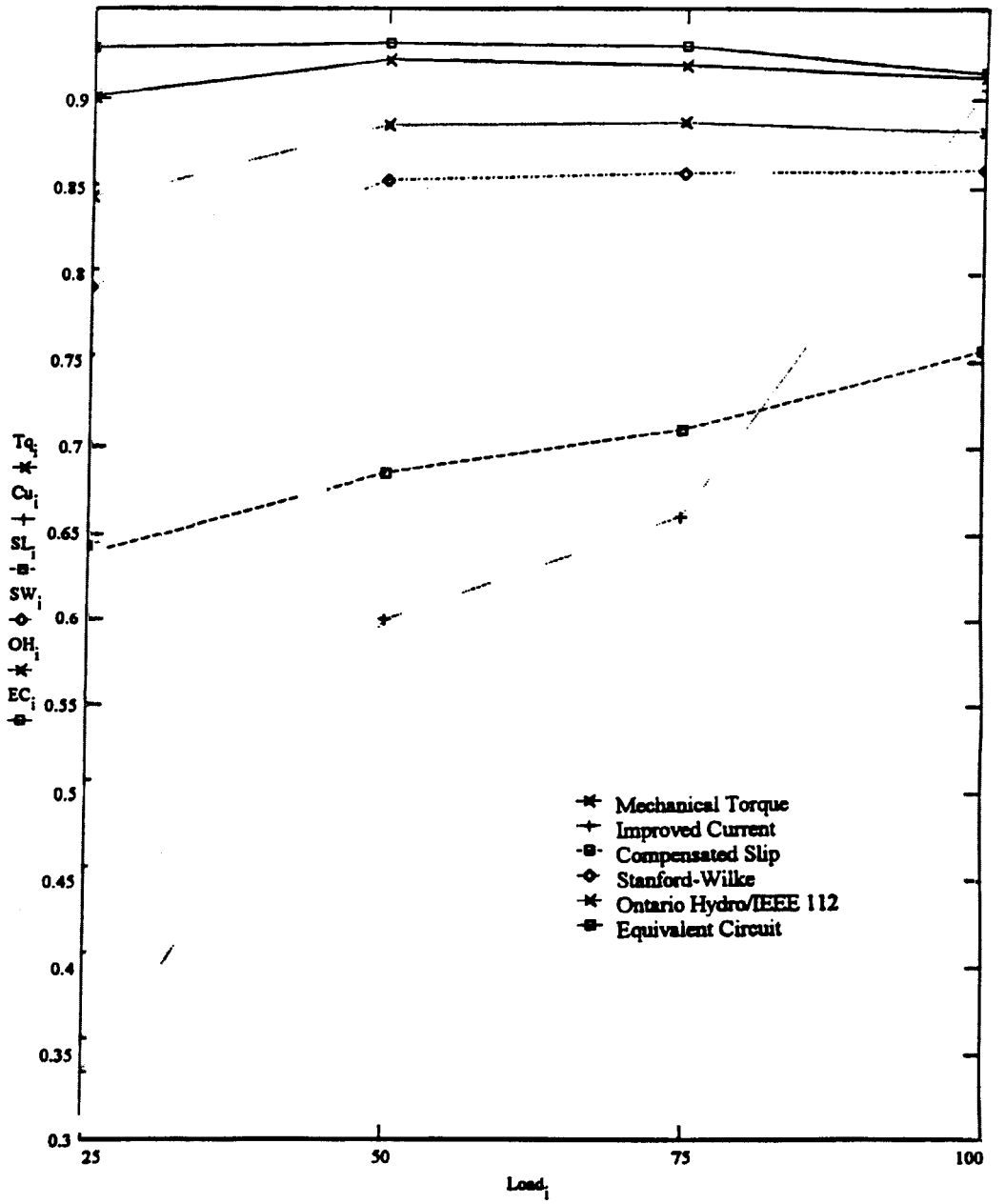

Fig. 3.12 Efficiency vs. Load for General Electric High Efficiency 10 HP (Balanced Voltages)

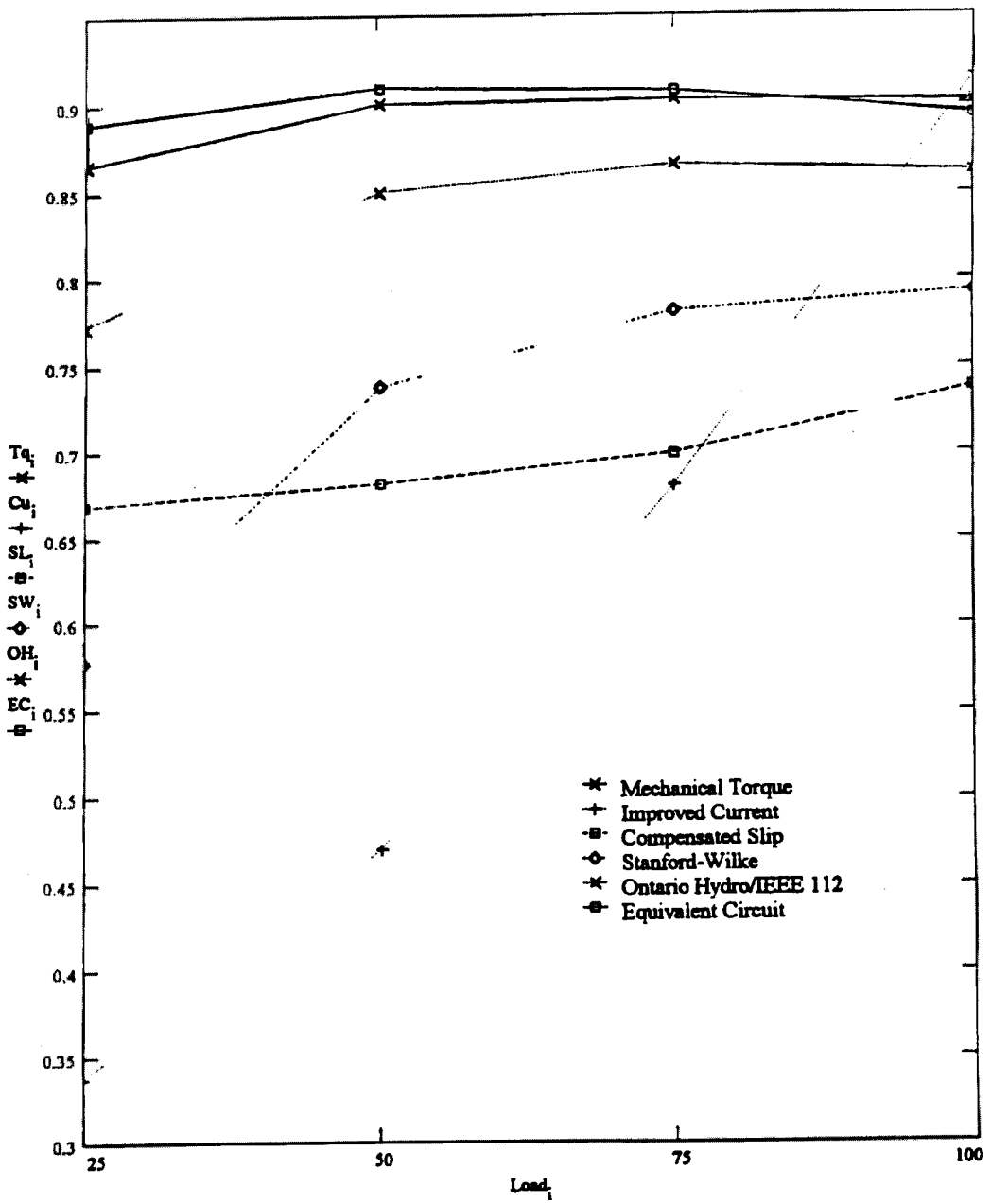

Fig. 3.13 Efficiency vs. Load for General Electric High Efficiency 5 HP (Balanced Voltages)

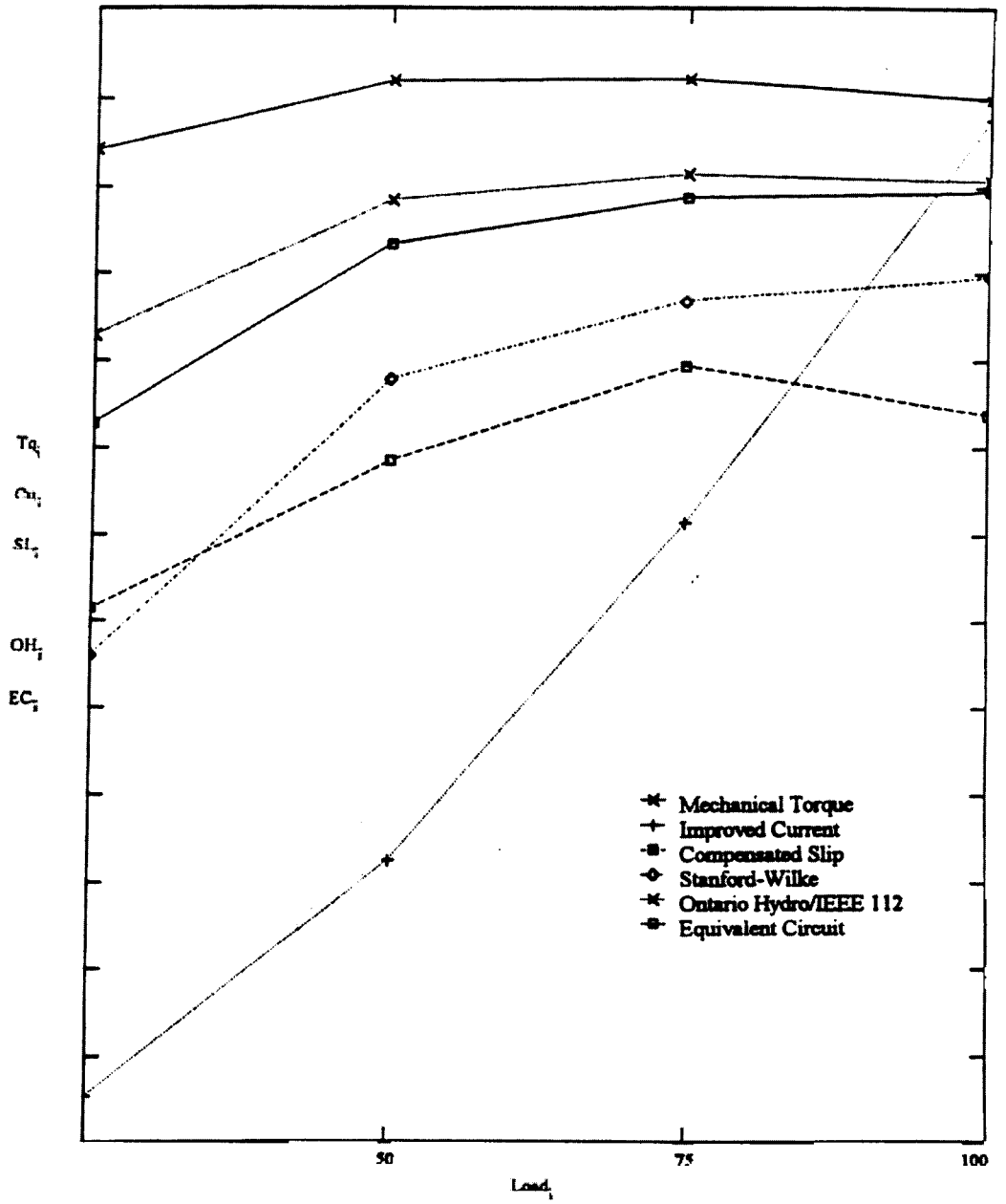

Fig. 3. Efficiency vs. Load forGeneral Electric High Efficiency HP (Balanced Voltages)

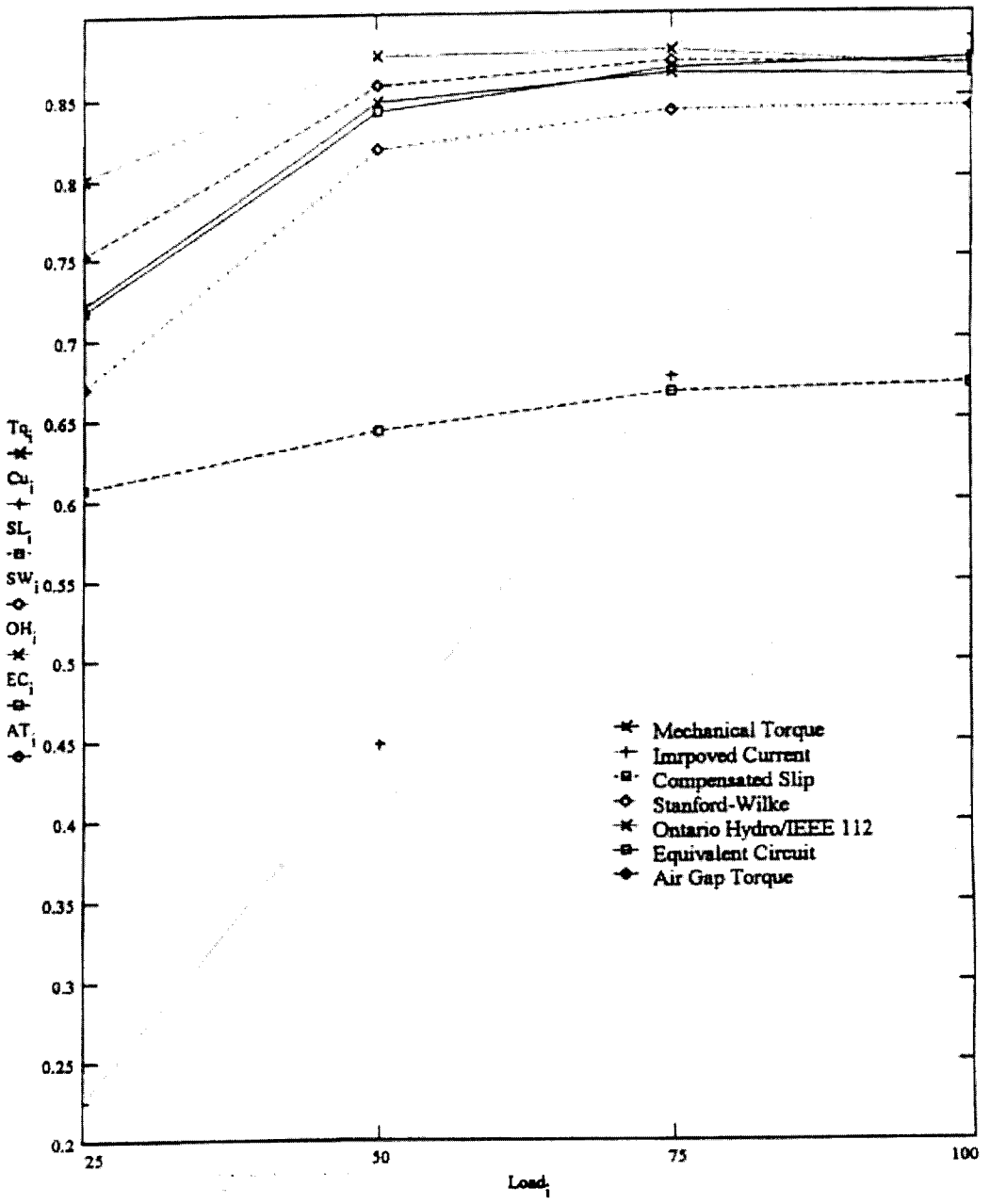

Fig. 3.15 Efficiency vs. Load for New Baldor High Efficiency 7.5 HP (Balanced Voltages)

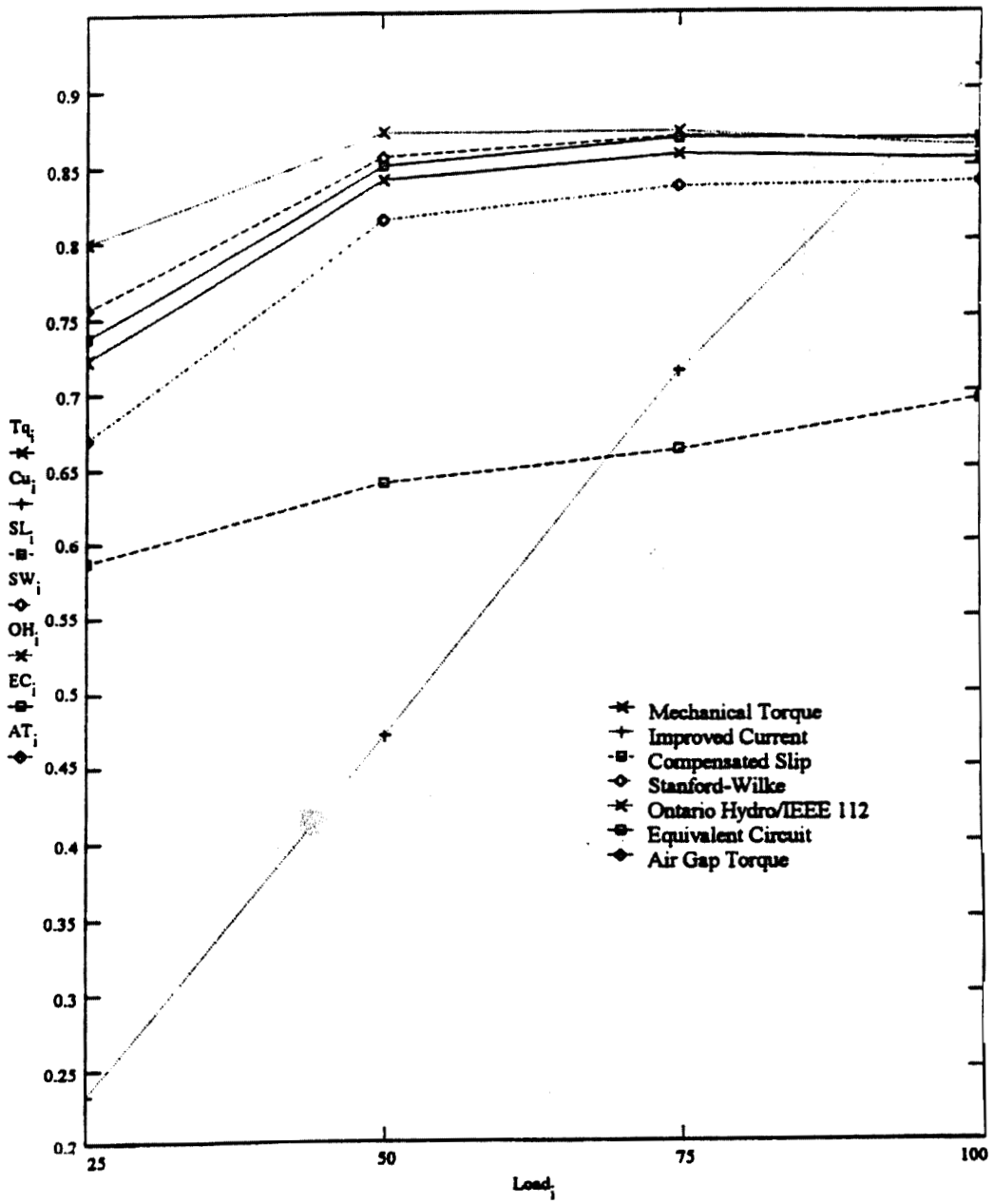

Fig. 3.16 Efficiency vs. Load for New Baldor High Efficiency 7.5 HP (Balanced Voltages)

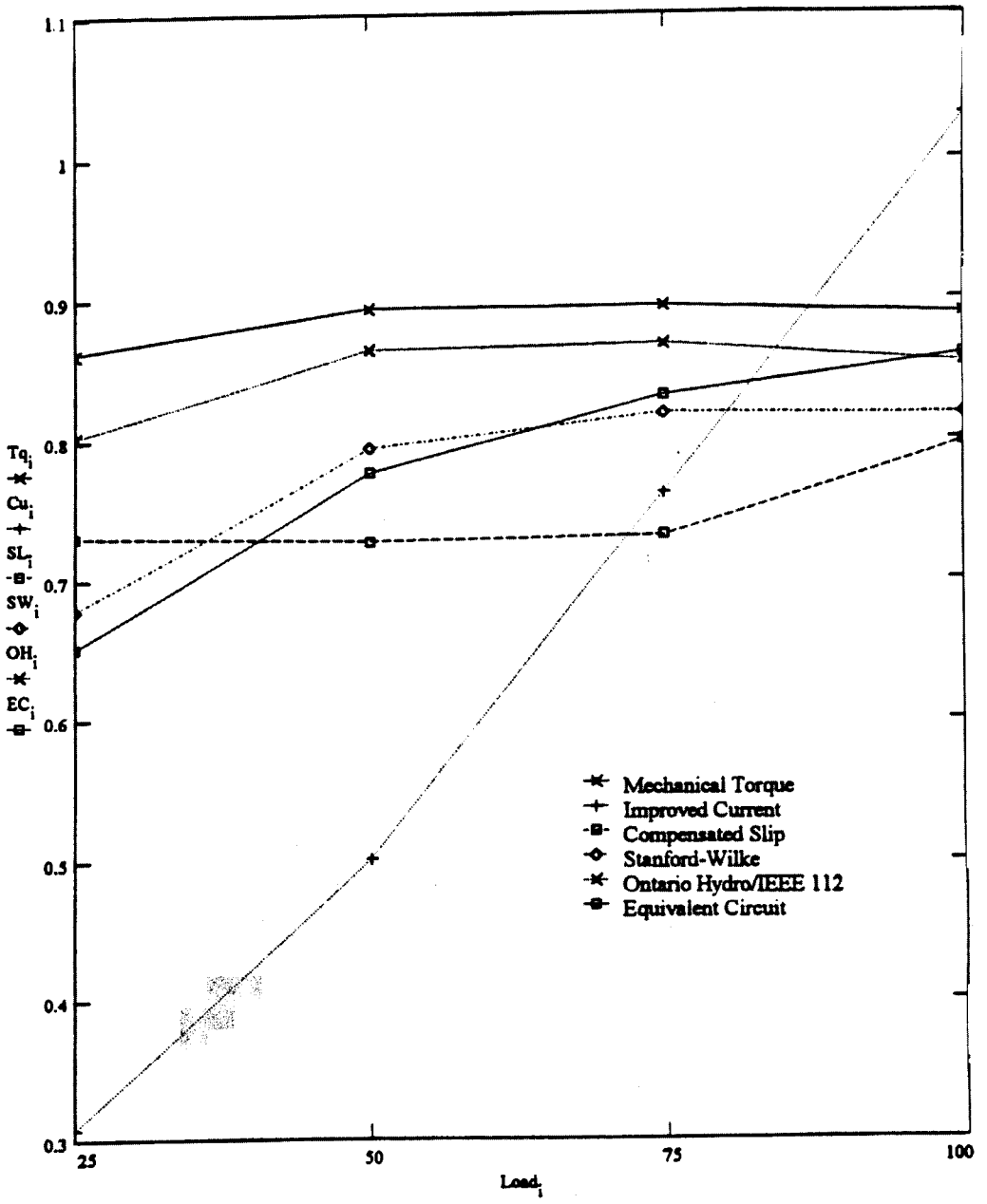

Fig. 3.17 Efficiency vs. Load for Used Baldor High Efficiency 7.5 HP (Balanced Voltages)

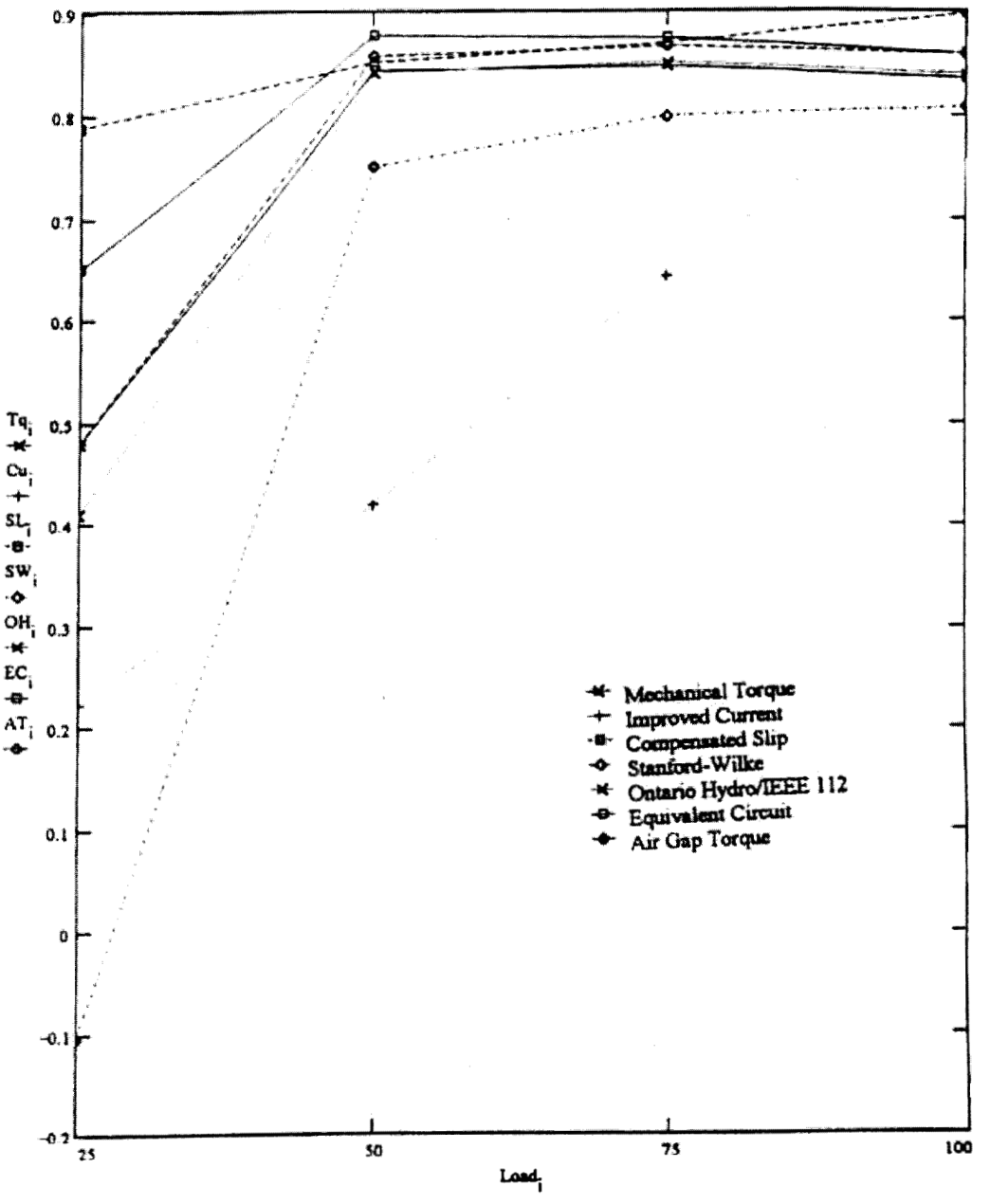

Fig. 3.18 Efficiency vs. Load for Lima Rewound Conventional 5 HP (Balanced Voltages)

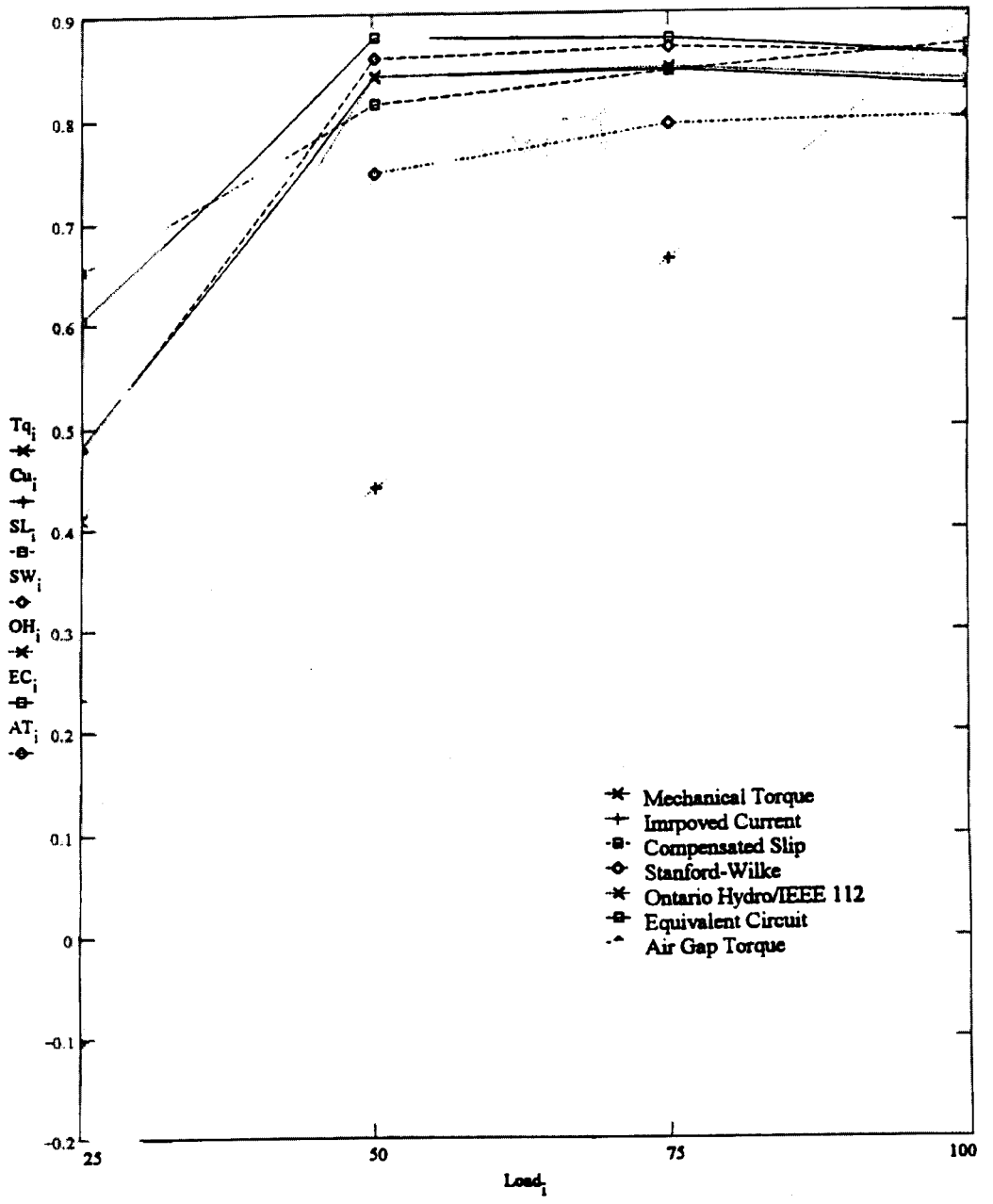

Fig. 3.19 Efficiency vs. Load for Lima Rewound Conventional 5 HP (Unbalanced Voltages)

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0.375	0.362	0.336	0.327	0.284	0.266	0.175	0.209	0.334	0.364	0.282	0.257	0	0
25% Load	0.741	0.741	0.38	0.373	0.53	0.57	0.678	0.678	0.732	0.732	0.653	0.692	0.747	0.753
50% Load	0.828	0.814	0.488	0.497	0.631	0.632	0.795	0.796	0.818	0.818	0.781	0.796	0.83	0.824
75% Load	0.843	0.831	0.654	0.678	0.695	0.697	0.833	0.832	0.838	0.835	0.824	0.831	0.848	0.841
100% Load	0.840	0.824	0.874	0.892	0.723	0.741	0.844	0.842	0.833	0.828	0.838	0.835	0.846	0.837

Table 3.: Test Results for 7.5 HP U.S. Electric Conventional Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*
Motor Load														
No Load	0.447	0.432	0.186	0.182	0.216	0.414	0.213	0.217	0.386	0.389	0.165	0.376	0	0
25% Load	0.806	0.798	0.265	0.264	0.636	0.685	0.751	0.747	0.801	0.797	0.78	0.794	0.835	0.784
50% Load	0.865	0.858	0.421	0.434	0.752	0.785	0.842	0.841	0.865	0.863	0.863	0.863	0.881	0.855
75% Load	0.878	0.868	0.617	0.634	0.792	0.823	0.865	0.863	0.878	0.873	0.877	0.878	0.889	0.868
100% Load	0.870	0.864	0.843	0.877	0.836	0.88	0.869	0.865	0.87	0.863	0.874	0.872	0.885	0.867

Table .2 Test Results for 1 HP GE Corventional Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*
Motor Load														
No Load	0.48	0.494	0.241	0.227	0.403	0.497	0.142	0.188	0.492	0.521	0.329	0.41	0	0
25% Load	0.769	0.763	0.294	0.281	0.609	0.642	0.629	0.633	0.773	0.776	0.66	0.68	0.798	0.8
50% Load	0.843	0.844	0.416	0.412	0.713	0.706	0.764	0.768	0.844	0.846	0.78	0.786	0.854	0.853
75% Load	0.861	0.863	0.585	0.585	0.738	0.763	0.805	0.807	0.859	0.859	0.814	0.819	0.867	0.87
100% Load	0.869	0.853	0.787	0.801	0.77	0.839	0.818	0.816	0.855	0.85	0.824	0.823	0.864	0.857

Table 3.3 Test Results for 5 HP GE Conventional M222

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0.345	0.375	0.408	0.385	0.384	0.382	0.084	0.082	0.386	0.378	0.351	0.351	0	0
25% Load	0.702	0.72	0.438	0.417	0.598	0.502	0.581	0.578	0.711	0.713	0.663	0.631	0.783	0.716
50% Load	0.804	0.816	0.523	0.514	0.645	0.619	0.734	0.735	0.805	0.806	0.764	0.764	0.832	0.803
75% Load	0.831	0.84	0.672	0.669	0.683	0.661	0.787	0.784	0.829	0.828	0.802	0.802	0.849	0.825
100% Load	0.835	0.843	0.864	0.888	0.724	0.713	0.805	0.8	0.828	0.823	0.812	0.812	0.846	0.826

Table 3.4 Test Results for 5 HP GE Conventional Motor M223

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*
Motor Load														
No Load	0.128	0.061	0.11	0.114	0	0	-0.546	-0.481	-0.38	-0.324	0.086	0.086	0	0
25% Load	0.891	0.882	0.226	0.246	0.714	0.686	0.84	0.844	0.852	0.854	0.888	0.888	0.883	0.878
50% Load	0.926	0.912	0.426	0.456	0.792	0.77	0.899	0.899	0.898	0.897	0.925	0.925	0.917	0.913
75% Load	0.932	0.912	0.671	0.685	0.803	0.832	0.912	0.911	0.902	0.9	0.927	0.927	0.921	0.918
100% Load	0.916	0.908	0.95	0.953	0.943	0.919	0.91	0.91	0.888	0.887	0.916	0.917	0.912	0.912

Table 3.5 Test Results for Teco 50 HP Rewound Conventional Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0.029		0.152		0		-0.23		-0.23		-0.11		0	
25% Load	0.879		0.25		0.718		0.848		0.848		0.916		0.894	
50% Load	0.927		0.445		0.866		0.905		0.905		0.949		0.93	
75% Load	0.939		0.668		0.836		0.918		0.918		0.951		0.939	
100% Load	0.944		0.919		0.947		0.919		0.919		0.946		0.94	

Table 3.6 Test Results for Reliance 100 HP High Efficiency Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0.456		0.188		0.459		-0.334		0.026		0.554			
25% Load	0.9		0.33		0.638		0.789		0.842		0.928			
50% Load	0.922		0.601		0.686		0.854		0.885		0.931			
75% Load	0.918		0.661		0.711		0.858		0.886		0.929			
100% Load	0.911		0.905		0.756		0.86		0.881		0.914			

Table 3.7 Test Results for 10 HP GE High Efficiency Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*	*Balanced*	*Unbalanced*
Motor Load														
No Load	0.529		0.352		0.277		-0.45		0.239		0.358			
25% Load	0.865		0.768		0.337		0.578		0.772		0.883			
50% Load	0.9		0.827		0.47		0.737		0.85		0.909			
75% Load	0.902		0.875		0.681		0.781		0.865		0.907			
100% Load	0.901		0.918		0.916		0.792		0.861		0.894			

Table 3.8 Test Results for 5 HP GE High Efficiency Motor M222

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0.577		0.256		0.509		-0.484		0.195		0.332			
25% Load	0.871		0.327		0.607		0.58		0.764		0.714			
50% Load	0.909		0.463		0.693		0.739		0.842		0.817			
75% Load	0.91		0.657		0.747		0.785		0.857		0.844			
100% Load	0.899		0.887		0.719		0.798		0.853		0.847			

Table 3.9 Test Results for 5 HP GE High Efficiency Motor M223

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0	0	0.153	0.157	0.647	0.565	-0.4	-0.389	0.186	0.192	0.325	0.336	0	0
25% Load	0.721	0.722	0.225	0.232	0.607	0.587	0.67	0.669	0.801	0.8	0.717	0.737	0.752	0.756
50% Load	0.847	0.841	0.447	0.471	0.643	0.64	0.818	0.815	0.875	0.872	0.841	0.85	0.857	0.856
75% Load	0.864	0.857	0.676	0.714	0.667	0.661	0.841	0.836	0.877	0.872	0.867	0.868	0.871	0.869
100% Load	0.862	0.854	0.884	0.914	0.672	0.694	0.843	0.838	0.868	0.862	0.872	0.867	0.869	0.866

Table 3.10 Test Results for New Baldor 7.5 HP High Efficiency Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0.54		0.199		1.013		-0.374		0.19		0.301			
25% Load	0.861		0.308		0.73		0.678		0.802		0.65			
50% Load	0.893		0.501		0.728		0.794		0.864		0.777			
75% Load	0.895		0.763		0.732		0.819		0.868		0.832			
100% Load	0.888		1.03		0.797		0.817		0.853		0.859			

Table 3.11 Test Results for Old Baldor 7.5 HP Used High Efficiency Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Motor Load														
No Load	0	0.033	0.218	0.228	0.749	0.82	-1.165	-1.172	-0.152	-0.157	0.487	0.468	0	0
25% Load	0.479	0.483	0.223	0.232	0.788	0.651	-0.104	-0.101	0.409	0.411	0.65	0.604	0.48	0.48
50% Load	0.843	0.841	0.42	0.439	0.851	0.814	0.751	0.748	0.841	0.84	0.877	0.877	0.857	0.857
75% Load	0.847	0.845	0.644	0.663	0.869	0.844	0.8	0.793	0.851	0.848	0.874	0.874	0.866	0.866
100% Load	0.835	0.829	0.859	0.894	0.897	0.868	0.807	0.8	0.839	0.834	0.858	0.858	0.858	0.858

Table 3.12 Test Results for Lima 5 HP Rewound Conventional Motor

Efficiency Method	Torque/ Mechanical		Improved Current		Slip Compensated		Stanford-Wilke		Ontario-Hydro IEEE 112 Meth. E		Equivalent Circuit		Air Gap Torque	
Input Voltages	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced	Balanced	Unbalanced
Avg. Difference			0.279	0.268	0.146	0.117	0.069	0.062	0.025	0.014	0.033	0.030	0.020	0.017

Table 3.13 Summary of Average Performance of Efficiency Estimating Methods

4. RECOMMENDED LOW INTRUSION METHOD-NAMEPLATE EQUIVALENT CIRCUIT METHOD

4.1. Method Technique

A modified version of IEEE Std 112 method-F has been used. In it an extra resistance has been added to the rotor circuit to account for stray losses since they are mostly dependent on rotor current (Figure 4.1). Once the values of each of the equivalent circuit components is known accurately, as shown below, efficiency may be obtained from the measurement of motor speed.

4.1.1. Determination of the Equivalent Circuit Parameters

Two low-intrusion approaches can be followed to determine the values of the seven components in the equivalent circuit. Both rely on the motor's Name Plate data and NEMA standards. The first approach requires the measurement of stator resistance (r_1) at rated load temperature. The second approach estimates r_1 using generic relationships based on the number of poles (**Np**), horsepower rating (HP_r), and rated line Voltage (V_r) of the motor.

The following applies to type B motors:

$$r_1 = 1.1 * 10^{-4} * Np^{0.52} * HP_r^{-1.26} * V_r^2$$

Thus, this second approach does not require any measurements specific to the motor of interest: all motors with the same nameplate data will be found to have the same Equivalent Circuit. Consequently, their efficiency in the field will be estimated differently only if their speed is different. It is this approach that is used in the NEQ method.

Once r_1 is known the rest of the parameters are found as follows:

The nameplate's rated horsepower, Voltage, Current and either Power Factor or Efficiency allow the computation of the rated Power Input and overall motor impedance Z_T and Efficiency or Power Factor respectively.

2. From the rated Power Input and IEEE 112 p.17 the load-dependent Stray Losses can be estimated as a percentage (**SL%**) of the Power Output at rated load weighted by the ratio of rotor-current-to-rated-rotor-current squared. Thus the equivalent loss resistance r_2SL in series with the rotor circuit is a constant given by the formula:

$$r_2SL = SL\% * (PowerOutRated/3)/RotorCurrentRated^2$$

Note that **SL% =1.8%** for motors of less than 125 HP, and that the Rotor Current at Rated conditions can be initially estimated to be a factor (i.e., 80%) of the nameplate Rated stator current. Once the equivalent circuit is found, if the resulting factor is far from the initial guess the computations can be repeated using the newly obtained value.

3 The Friction and Windage losses are taken as a constant percentage (FW%) of the rated Power Output, i.e.,

F&WLoss = FW%*PowerOutRated

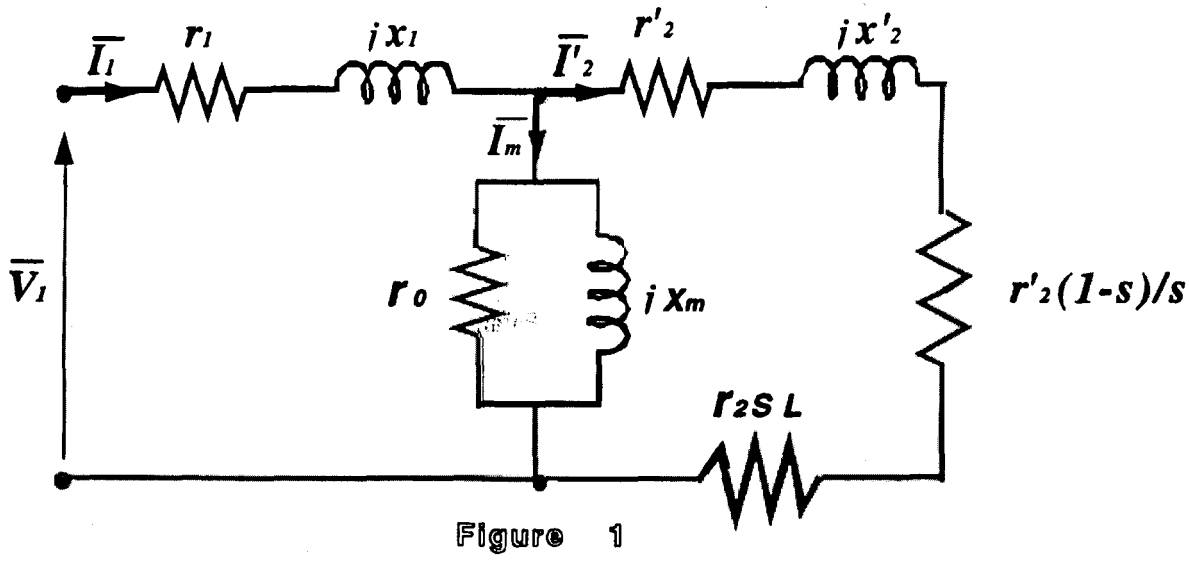

Figure 1

Single-Phase Schematic of the Equivalent Circuit for Electric Induction Motors

where,

r_1 = Stator Resistance
x_1 = Stator Leakage Inductance
r'_2 = Rotor Resistance (stator referred)
x'_2 = Rotor Leakage Inductance(stator referred)
r_0 = Core Loss Resistance
x_m = Magnetizing Inductance
s = slip Ratio = **1 - rotor Speed/synchronous Speed**
r2SL = Stray Loss Rotor Resistance (stator referred)
I_1 = Stator Current
I_2 = Rotor Current (stator referred)
I_m = Magnetizing Current
V_t = Line Terminal Voltage

where **FW% = 1.2%** for 4 pole motors below 200 HP. This loss allows the appropriate raw-efficiency for the equivalent circuit of the motor at rated conditions, to be determined as follows:

rawEffRated = Efficiency Rated + F&WLoss/PowerInRated

4 The nameplate speed and number of poles yields the rated slip (s_r) which links the power output to the rotor's ohmic loss.

5 The nameplate NEMA Class - A, B, C, or wound rotor - provides a value for the ratio between the stator and rotor leakage inductances (**x1-to-x2-ratio**) - 1.0, 0.67, 0.43,1.0 respectively.

6. The nameplate NEMA Code letter - D, E, ... L - brackets the value of the locked rotor current - from 5 to 12.5 times horsepower rating. It was decided to use the mid point of the range corresponding to the motor's Code letter. This, together with the rated Voltage, allows the computation of the magnitude of the motor's impedance under locked rotor conditions ($|Z_tLR|$).

7 The rated slip, overall resistance and inductance, x1-to-x2-ratio and magnitude of the locked rotor impedance can then be used to iteratively find the values of x_1, x_2, r_2 and Z_m that yield the raw efficiency for rated conditions and satisfy the locked rotor current condition simultaneously.

8. Finally the magnetizing impedance Z_m yields readily the values of its constituents: the Core resistance (r_0) and the magnetizing inductance (x_m).

4.1.2. Use of the Equivalent Circuit to Compute Efficiency

The values of the equivalent circuit components found above : r1, x1, r0, xm, r2, x2, and r2SL - can then be used to compute the motor's raw efficiency at any load and voltage from the measurement of motor speed only by means of the following formula:

$$\text{rawEfficiency}[s] = \text{Magnitude}[Z_g/(Z_2+R_L)]^2 * R_L/\text{RealPart}[Z_T],$$

where **s** is the slip corresponding to measured speed and the **Z** parameters are complex numbers related to the motor's equivalent circuit parameters as shown in Figures 4.2, 4.3, an 4.4.

The net efficiency is found by subtracting the friction and windage losses from the motor's raw power output. Net efficiency is thus computed by subtracting from the raw efficiency the ratio of the friction and windage losses to the power input as follows:

$$\text{netEfficiency}[s] = \text{rawEfficiency}[s] - \text{F\&WLoss} / \text{PowerIn},$$

when power input to the motor is known, or alternatively by the formula

$$\text{netEfficiency}[s] = \text{rawEfficiency}[s] - \text{F\&WLoss} / (3 * \text{Magnitude}[V_t/Z_T]^2 * \text{RealPart}[Z_T]),$$

where V_t is the motor's terminal line voltage, or, if unavailable, the nameplate line voltage.

4.2 Recommended Practice Application of Method

Using the LabView software package a virtual instrument was developed to apply the Nameplate Equivalent Circuit Method. The self-standing code (i.e., the user does not need to have LabView

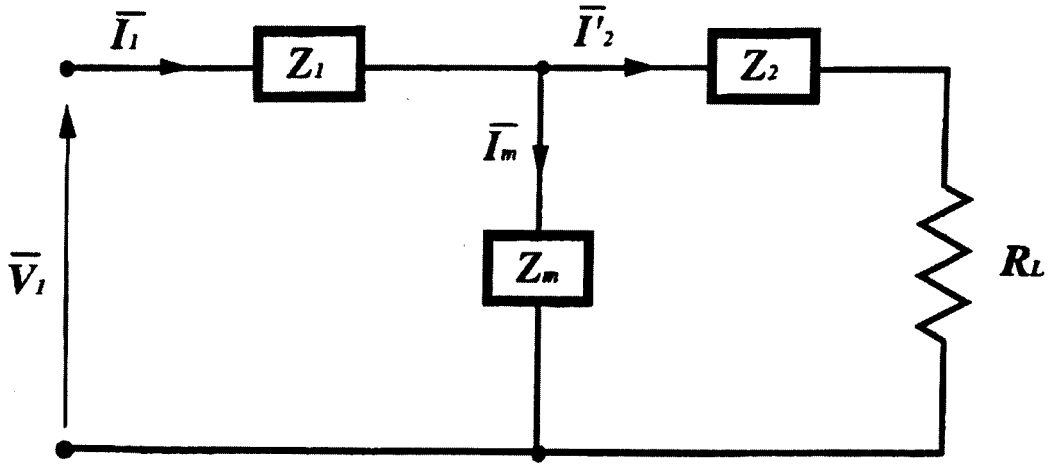

Figure 2

Schematic of Circuit Condensed to Basic Functional Impedances

where,

$Z_1 = r_1 + j\,x_1$	Stator Impedance
$Z_2 = r'_2 + r2SL + j\,x'_2$	Rotor Impedance (stator referred)
$R_L = r'_2\ (1-s)/s$	Load Resistance (stator referred)
$Z_m = 1/(1/r_0 + 1/(j\,x_m))$	Magnetizing Impedance

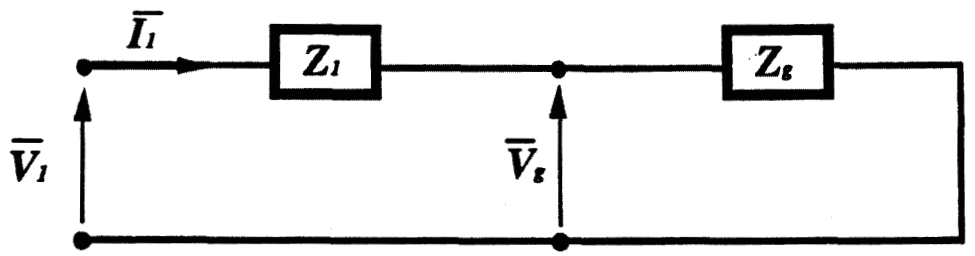

Figure 3

Schematic of Circuit Condensed to the Stator and Gap Impedances

where,

$Z_g = 1/(1/Z_m + 1/(Z_2 + R_L))$ Gap Impedance

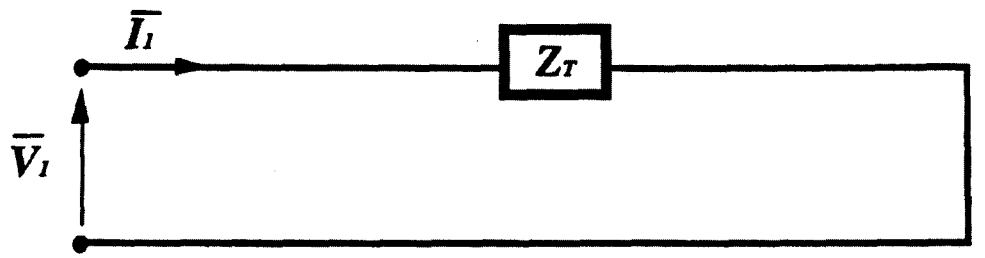

Figure 4
Schematic of Circuit Condensed to a Single Impedance

where,
$Z_T = Z_1 + Z_g$ Total Impedance

on their computer) requires nameplate information as input. This includes: number of phases and poles, motor size (in horsepower), phase-to-phase voltage, and full-load current, speed, and power factor. In addition, the user inputs the NEMA design class and code. Once this information has been entered, the code calculates the equivalent circuit. Estimation of motor efficiency and load require only the motor speed, which can be measured using an optical tachometer.

5. MEDIUM INTRUSION METHOD - ONTARIO HYDRO MODIFIED (OHM) METHOD

5.1 Method Basis

The method developed as the medium intrusion method is a modification of the Ontario Hydro version of IEEE 112 Method E Segregated Loss Method. The method will be referred to as the OHM method (Ontario Hydro Modified). Although this method has been selected for the category of medium intrusion, it has actually been found to provide quite reasonable accuracies. It can provide accuracies within two or three percentage points when the empirical factors used in estimating the losses are selected based on test results for a representative population of motors. The method becomes less reliable as loads approach 50% because it uses an approximation for no load losses, and the impact of this approximation when determining losses becomes more significant at low loads.

Ontario Hydro uses an empirical value of 3.5% to find the no load losses rather than actually performing no load testing. A factor of .035 is multiplied times the full load watts in to the motor to estimate the no load watts loss. This value was revised for motors less than 50 hp by using the same ratio as is used in the table of stray load loss approximation provided in IEEE Standard 112. This revision results in an empirical factor of .042. As a further refinement, this value could be optimized by testing samples of motors at different horsepower levels. The stray load loss is estimated simply using the method provided in IEEE 112. Because the watts in at full load are not known, this value is estimated using the nameplate current and voltage with a power factor of 0.8. The stator resistance at load is estimated based on a simple approximation using the motor current to estimate the temperature rise.

5.2 Recommended Practice Application of Method

The only measurements needed are the voltage, current, power factor, RPM and cold stator resistance. The motor does not have to be determinated to measure the stator resistance. The total resistance of the motor and feeder may be measured from the motor control center (MCC), and then the feeder resistance estimated based on the length of the cable run and wire gauge. The feeder resistance would then be subtracted from the total resistance to find the motor resistance. This technique will not result in unacceptable errors. For a 7 1/2 horsepower and a feeder of number 12 wire, an error of 100 feet in estimating the feeder length would result in an error in determining efficiency of about 1%. Thus, all measurements except RPM may be taken from the MCC bucket. In the event that the motor is inaccessible, even the RPM may be determined from an analysis of the motor current waveform.

A MathCad program was developed to produce the load and efficiency estimate using the data previously described. The algorithm includes the following steps:

1. Measure and record motor current, voltage, power factor and RPM
2. Calculate input power
3. Calculate No Load Loss
4. Calculate Stray Load Loss
5. Calculate Joule Heating Loss
6. Calculate the Temperature Corrected Slip and the Rotor Loss
7. Calculate Efficiency; Efficiency = (Input Watts - Losses) / Input Watts

The no load loss is assumed to be the sum of the friction and windage and core loss. If the no load power input cannot be measured, we set the no load losses equal to 4.2% of the power into the motor at rated load, as explained above. If the power input at rated load is not known, use the rated current and voltage and a power factor of 0.8.

The stray load loss is assumed to 1.8 percent of the motor input watts for motors less than 125 horsepower. This is in accordance with Table 2 of IEEE Standard 112. The stray load loss at loads less than rated is corrected by the square of the ratio of motor current to rated current.

The Joule heating loss in the stator is found by multiplying the stator winding resistance by the square of the motor current. The motor winding resistance is corrected by an approximated temperature. The approximated temperature is determined by using the ratio of change in motor current above no load to the rated change times the rated temperature rise. (If the resistance with the temperature rise is measured and used in this calculation, the temperature correction should not be used.)

The power in the rotor is the power into the motor minus the sum of the no load losses, stray load losses and the joule heating losses. The rotor loss is found by multiplying the temperature corrected slip times the power into the rotor. The temperature corrected slip is found using a rotor conductor temperature with the same approximated temperature as discussed above.

The rotor loss is added to the no load loss, the stray load loss and the joule heating loss to find the total losses. The efficiency is simply the ratio of the input watts minus the total losses to the watts in.

6. RECOMMENDED HIGH INTRUSION METHOD - AIR-GAP TORQUE METHOD

6.1 Method Basis

The air-gap torque method for motor efficiency field assessment is a new method developed at the Oak Ridge National Laboratory **[Hsu;Scoggins, 1995]**. Table 6.1 is a self-explanatory tabulation for motor losses and efficiency. As indicated the basic losses are rotor copper loss, stator copper loss, friction and windage loss, core loss, and the stator and rotor stray losses that constitute the stray-load loss. The rotor copper loss for induction motors is represented by the slip.

Table 6.1 Tabulation of Motor Losses and Efficiency Definitions

Stator input power	
	Stator copper loss
	Core loss
	Stator stray loss
	Total stator loss
Rotor intake power	(Corresponding to: Air-gap torque)
	Rotor copper loss
	Friction & windage
	Rotor stray loss
	Total rotor loss
Output power = Stator input-stator loss-rotor loss	
Efficiency = (Output power)/(Stator input power)	

The output power of a motor is the product of the shaft angular speed and shaft output torque. This output torque is the air-gap torque less the torque losses associated with friction, windage, and stray losses caused by rotor currents.

A significant difference between the air-gap torque method and the method E1 of IEEE 112 Standard is that the air-gap torque method considers the losses associated with the negative torques produced by the negative sequence voltages and currents, which are the products of unbalanced voltages and harmonics. Because in the real world the power supply is commonly polluted with unbalanced voltages and harmonics, the air-gap torque method has a unique advantage over the method E1 for efficiency field assessment.

6. 1 Equations of Power, Air-Gap Torque, and Efficiency

A. Power Equations

The instantaneous input power of a three-phase induction motor is the summation of products of the instantaneous phase voltages, va, vb, vc, and phase currents, ia, ib, and ic.

$$Power = v_a i_a + v_b i_b + v_c i_c \qquad (1)$$

A portion of this instantaneous power includes the charging and discharging of the energy stored in the windings. Therefore, this instantaneous power cannot represent the instantaneous torque even at a constant speed after subtracting the losses. However, the average value of instantaneous power at full load represents the input power of the motor for the efficiency calculation. The conventional single-frequency power equation using power factor, RMS current and voltage is a special case of the average instantaneous power.

B. Review of Air-Gap Torque Equations

Air-gap torque equations have been known for several decades. They can be traced worldwide in various publications. The following voltage equations are for the three-phase armature windings,

$$v_a = \frac{v\psi_a}{d_t} + r i_a, v_b = \frac{v\psi_b}{d_t} + r i_b, \frac{v\psi_c}{d_t} + r i_c \qquad (2)$$

where

Ψa, Ψb, Ψc = flux linkages of windings a, b, and c, respectively

r = the phase resistance

are substituted into (1) to give

$$Power = \left[i_a\left(\frac{d\psi_a}{dt} + r i_a\right) + i_b\left(\frac{d\psi_b}{dt} + r i_b\right) + i_c\left(\frac{d\psi_c}{dt} + r i_c\right)\right] \qquad (3)$$

From (2) the flux linkages can also be given as

$$\psi_a = \int (v_a - r i_a) dt, \quad \psi_b = \int (v_b - r i_b) dt$$

and

$$\psi_c = \int (v_c - r i_c) dt$$

Subtracting the copper losses and the terms pertinent to the energy stored in the windings, the air gap torque equation can be written for the line data as indicated in Fig. 1 where the symbols are denoted by their corresponding line identifications in the suffixes.

$$Torque[Nm] = \frac{P}{2 \cdot \sqrt{3}} \left\{ \begin{array}{l} (i_A - i_B) \cdot \int [v_{CA} - R(i_C - i_A)] dt \\ -(i_c - i_A) \cdot \int [v_{AB} - R(i_A - i_B)] dt \end{array} \right\} \quad (4)$$

Equation (4) is valid for either Y- or Delta-connected motors,
where

P	=	number of poles
iA, iB, and iC	=	line currents
R	=	half of the line-to-line resistance value.

From the definition of R, the following two expressions are for Y and delta-connected motors, respectively.

R	=	phase resistance, r for Y-connected motor
R	=	r/3 for delta-connected motor.

Equation (4) is associated with certain assumptions and simplifications. First, the three phase leakage reactances of motor are linear and identical. Second, the negative sequence winding spatial components (not the time harmonics) are negligible. Third, the torque components produced by sources that are not dependent on the armature winding currents, such as permeance cogging torque in a permanent-magnet motor, are not considered. Fourth, the instantaneous magnetic unbalances for three phases are ignored. Fifth, the effect of dc components in the flux linkages are neglected.

When using either three leads for Y-connected motors without a neutral connection or three leads for delta-connected motors, (4) can be further simplified by using

$$iB = -(iA + iC) \quad (5)$$

The above equation can be rewritten to the known format that uses only two line voltages, two line currents, and one-half of the line-to-line resistance as the input data for the calculation of the air-gap torque.

C. Numerical Evaluation of Integrals

The integrals

$$\int [v_{ca} - R(i_c - i_a)] dt$$

$$(6)$$

$$\int [-v_{BA} - R(2 \bullet i_A - i_C)] dt$$

of windings corresponding to lines CA and AB in (5) represent flux linkages. Since the time increment between data points is small, a simple trapezoidal method is used in this study. Other methods using Simpson's rule or Gauss's rule for numerical evaluation of integrals can also be used.

D. Efficiency Equations

As mentioned earlier, the shaft output power is calculated from the shaft speed (rpm) and shaft torque.

$$Output\ Power = (Shaft\ torque) \bullet 2\pi \bullet \frac{(rpm)}{60} \qquad (7)$$

where the shaft torque is the difference of air-gap torque and torque losses corresponding to mechanical loss and stray loss produced by rotor current.

$$Shaft\ torque = (Air\ gap\ torque) - \frac{(Friction\ windage\ loss)}{2\pi \bullet \frac{(rpm)}{60}} - \frac{(Stray\ load\ loss)}{2\pi \bullet \frac{(rpm)}{60}} \qquad (8)$$

From (7), (8), and the definition of efficiency, the efficiency, η, yields

$$\eta = \frac{(Air\ gap\ torque) \bullet 2\pi \bullet \frac{(rpm)}{60} - (Friction\ windage\ loss) - (Stray\ load\ loss)}{Input\ power} \qquad (9)$$

6.2 Recommended Practice Application of Method

The air gap torque method requires the acquisition of the voltage and current waveform data so that these waveforms may be used in the integrations described above. It is best if the waveform data may be acquired over a period of several cycles, preferably even one second so that oscillations in the load may be averaged. This is discussed more in the Appendix. The waveforms must be acquired with a reasonably high sampling rate so that a high accuracy of the waveform shape may be achieved. A sample rate of 5,000 hz was used in our examples. Typically, the waveform data would be stored on digital magnetic media.

In addition to the voltage and current waveforms, a measurement of no load power into the motor must be made. To do this, the motor must be uncoupled and a power meter used to measure the power input. The motor speed must also be measured; this can be done with a stroke light while the motor is in normal service. The motor resistance must also be measured; the motor must be disconnected for this measurement.

Until the method has been developed into a package unit that performs both the data acquisition and analysis, the waveform data will have to be acquired with a recording device and converted into a digital file, then this data, along with the speed, stator resistance and no load power would be used as input to software that performs the calculation.

7. SUMMARY

The purpose of this work was to assess motor efficiency estimation methods that can be used in field applications for motors running in their normal service condition; document the test results; and select a recommended method for each of three intrusion levels: high, medium, low. A low intrusion level method is one that does not significantly impact plant operations. For example, a method requiring only a speed measurement using a strobe would be considered to be low intrusion. High intrusion methods require substantial disruption of service to acquire the needed data. A locked rotor test is an example of data needs that are considered high intrusion. Medium intrusion methods are those that fall between.

Nearly 25 methods identified in the literature were screened. Qualitative screening criteria of intrusion level and accuracy were used in the screening. Within each intrusion level the methods were ranked according to their expected accuracy. Six methods were selected for further assessment. They included:

Low Intrusion level:	current method compensated slip method nameplate equivalent circuit (NEQ) method
Medium Intrusion level:	Stanford Wilke Method Ontario Hydro Modified (OHM) method
High Intrusion level:	air gap torque (AGT) method

The testing program was directed at determining the accuracy of the various methods by comparing their results with laboratory dynamometer testing. In addition, field data was taken to evaluate the accuracies of the method in actual field conditions. The laboratory testing was accomplished with 12 motors ranging in size from five to 100 hp. Seven of the motors were older standard efficiency design (two had been rewound), the other five were energy efficient designs.

All laboratory testing was performed in the ORNL Electric Machinery System Test Center. The motors were tested with no load, and at 25, 50, 75, and 100% load. Tests were conducted with two voltage conditions: phases balanced within 0.5% and unbalanced to 3%. Voltage, current, and power RMS data were acquired for each test. In addition, waveform voltage and current data were recorded.

The test data showed that the improved current method produced efficiency estimates that were, on average, different from the actual efficiency by 30%. The compensated slip method was more accurate having an average difference of 10 to 15%. The nameplate equivalent circuit method proved to be the most accurate low intrusion method. The average difference between the actual and estimated efficiency was 3.3%. All three methods showed better accuracy at higher loads. This result was anticipated because none uses no load data. Thus accuracy at low loads (below about 50%) is sacrificed.

The medium intrusion methods showed that the OHM method produced more accurate results than the Stanford Wilke method. The OHM method had an average difference of 2.5% while the Stanford Wilke method produced an estimate that differed from the actual by about 6%.

The AGT results showed an average difference of 2.5% between estimated and actual efficiency. It was felt that this did not represent the true potential of this method. In the method embodiment tested only one cycle of wave form data was used. This raises a strong possibility of introducing errors in the waveform analysis. A refinement of the model for this method was developed that used more than one cycle of data for analysis.

Based on these test results a preliminary selection of recommended practices was made. For the low intrusion category the NEQ method was selected. The OHM method was elected as the medium intrusion method and the AGT was used as the high intrusion method. These methods were further tested using a combination of field (obtained at 3M) and laboratory data. These results confirmed the accuracy of the methods. The NEQ method was within 3.6 percentage points of the actual; the OHM method produced results within 0.5 percentage points; and the AGT method was within 0.4 percentage points. These AGT results demonstrate the improvement in the accuracy of the method when more than cycle of data is used.

Based on the test results the following methods are recommended for motor efficiency estimation in the field at the given intrusion levels:

low intrusion:	nameplate equivalent circuit method
medium intrusion:	Ontario Hydro modified method
high intrusion:	air gap torque method

It is noted that the best available method of data acquisition was used in the tests. Based on the possible sources of error discussed in Appendix A, the average accuracy for the OHM method (a difference of 0.5% between the actual and estimated efficiency) is probably not representative of what is obtainable with less sophisticated data acquisition equipment. However, an accuracy of 2 to 3% is likely obtainable.

The accuracy obtained for the NEQ method, 3.6% is likely typical of what is obtainable in the field. It is also noted that the accuracy of the method improves as the load increases because the method does not use no load data. Since this method is best suited to screening studies within a plant, this does not present a serious limitation on the utility of the method. If the motor load is above 50%, the method accuracy is better than the average and reasonably accurate results are obtained. In cases where the load is less than 50% it is less important to know the actual efficiency; the key information is that the motor is lightly loaded.

The AGT refinement proved to be very accurate yielding efficiency estimates that were within 0.4% of the actual values. It is believed that the laboratory results are typical of what can be attained in the field.

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Kueck, J.D., Assessment of Available Methods for Evaluating In-Service Motor Efficiency

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APPENDIX A

Data Collection Factor Influencing Accuracy of Field Efficiency Estimate

Introduction

In order to use any of the efficiency estimating methodologies, some amount of data collection is required. There are a variety of factors which can influence the quality of measurement of analog data and its conversion to a digital format. The criticality of understanding the types and extents of uncertainties involved cannot be overstated.

The reader should understand that most of the potential error sources discussed here are primarily based on the authors' experiences in field and laboratory measurements. This chapter is not intended to be a thorough guide to appropriate measurement and transduction techniques for motor-related parameters; nor should the reader consider the referenced standards and guides to be a comprehensive list. Rather, the intent is to identify the sources and approximate magnitudes of some of the more common, but not always well-recognized, sources of error in the acquisition of motor data.

The Instrument Path

The process of transducing motor parameter information from the actual state condition to digital values for additional analysis involves several components, including:

1) The primary sensor (e.g, current transformer or shunt),
2) Analog signal conditioning (e.g., an isolation amplifier or electronic filter),
3) Conversion of the signal to a digital format (e.g., by reading graphical strip charts or meter readings or by use of an analog-to-digital conversion board in a digital computer).

Each of these three measurement processes involves energy or information transfer. Throughout the instrument path, and particularly at each point of energy/information transfer, errors *are* introduced. The effect that these errors have on the final results depends upon how well they are understood and accounted for. Brief summaries of typical parts of these processes and examples of some notable potential sources of error are provided below.

Sensors

There are several parameters which may be monitored when attempting to assess motor efficiency. Depending upon the specific model being employed, one or more of the following will be transduced (in approximate order of frequency of use):

- Current
- Voltage
- Speed
- Temperature
- Impedance
- Torque

Clearly, other parameters, such as power and power factor are also important to motor efficiency estimating. These parameters are not directly measured, but are rather indirectly determined (by either analog or digital means) from the transduced current and voltage. Field measurements normally involve current and, if power is being considered, voltage. The balance of this chapter will focus on the measurement of current and voltage, and their use in calculating power and power factor.

A.3.1 Current transducers

For purposes of supporting efficiency estimates, current is the most commonly monitored parameter. In the field, the vast majority of current measurements are performed with clamp-on current transformers or hall-effect probes. These transducers may be used either on a primary conductor or on the secondary of an installed current transformer (of course the existence of an installed current transformer may obviate the need for a clamp-on, if only the current amplitude is of interest). While there are a considerable number of performance measures for current transducers, there are four primary factors that are particularly important to consider:

1) Amplitude accuracy
2) Phase accuracy
3) Frequency response
4) Current range

Vendor literature or technical data normally provides amplitude accuracy, often as a function of frequency range and/or actual current amplitude. Typical amplitude accuracies cited for both clamp-on current transformers and hall-effect probes range from 0.5% to 5%.

Phase accuracies are less often published; phase shifts for current transformers can range from 0.5° to more than 10°. Current transformer outputs almost always lead the actual line current. Typical hall-effect phase shifts are not usually provided; the hall element itself has, from a theoretical standpoint, negligible phase shift. However, signal conditioning that is sometimes used for hall-effect probes may affect phase. Generally speaking, conditioned hall-effect unit outputs may either lead or lag the true current, normally by less than 1°, but occasionally by more.

It is important to recognize that both amplitude and phase accuracies depend upon current amplitude and frequency. For standard induction motors used in direct line feed applications, the obvious focus should be on the accuracy at 60 hz. However, if the current measurements involve variable speed devices, or if the current measurements are being used to characterize the spectral distribution of the current (e.g., for harmonic distortion) or to detect the presence of spike-type energy in the current, careful attention should be given to frequency response characteristics.

Current range ratings for both current transformers and hall-effect probes typically encompass a couple of orders of magnitude, for example 4 to 500 amps. In some cases, four or more orders of magnitude are cited (e.g., 50 mA to 1000 A).

The factors noted above are not the only factors that can influence the quality of field data; for example, hall-effect unit measurements are sensitive to the alignment/orientation of the conductor in the jaw opening. One manufacturer of high quality probes cites as high as a 1.6% influence associated with conductor position within the hall-effect jaw.

A.3.2 Examples of potential errors associated with current transducers

There are any number of ways that significant errors can be introduce by current measurements with clamp-on probes. Two common, but often unrecognized potential pitfalls are:

failure to account for transducer phase errors when using current transducers (particularly clamp-on current transformers) for power and power factor determinations, and
failure to ensure that the jaws are fully closed when the measurement is made.

The potential effects of these pitfalls are discussed below.

A.3.2.1 Effect of transducer phase error

It is important to first of all note that if the current is being measured for its own sake only, phase error is of no consequence. For example, if a clamp-on current transformer is being used simply to indicate, via a built-in readout or by the readout of an attached multimeter, the current amplitude, an error in phase does not affect the reading. However, if the current signal is being used in conjunction with a voltage signal to determine power or power factor, error in the phase does affect the result.

The power factor in a circuit is defined as the ratio of the total active power to the total apparent power[1]:

$pf = \frac{P}{S} = \cos(\theta)$, where

θ is the phase angle between the voltage and current

pf = power factor

P = active power = $V_{rms} \bullet I_{rms} \bullet \cos(\theta)$

and S = apparent power = $V_{rms} \bullet I_{rms}$

As noted previously, power factor is not directly measured, but rather is deduced from the current and voltage signals (by either analog or digital means). There are fundamentally two means for making the calculation: (1) by the ratio of active to apparent power (hereinafter referred to as the rms method) and (2) by a zero-crossing detector. The rms method provides a "true" measure of the effective power factor over the full cycle. The zero-crossing method is normally employed by digital phase angle meters which compare the time between when two signal waveforms (voltage and current in this case) cross zero. For standard induction motors run directly from the line (i.e., not variable-speed devices), the two methods will normally closely agree, unless there is considerable harmonic or other spectral content in the voltage and/or current.

Current transformers typically cause a phase error in the leading direction - meaning that the indicated current phase angle leads the true current phase angle. The amount of phase error may be affected somewhat by the current amplitude, but the change in phase error with amplitude is normally relatively small compared to the overall phase error fundamentally associated with the transducer.

The effect that a given phase error has upon power or power factor measurements is strongly influenced by the actual power factor. This can be demonstrated from trigonometric relationships. For a motor operating at relatively near its rated load condition, for example, with a true power factor of 0.900, the true phase angle between voltage and current will be:

Phase angle = arccos (power factor)= arccos (0.900) = 25.84°.

If the motor is operating at a lightly loaded condition, with a true power factor of 0.300, the true phase angle between voltage and current will be:

arccos (0.300) = 72.54°

In both cases, the voltage is leading the current by the noted angle.

To illustrate the variability of the effect that a given phase angle error has on power/power factor measurements, a phase angle error of 2° in the leading direction will be assumed for the current transducer (and with no error in the voltage transducer). For the case where the motor is running near rated load conditions with a power factor of 0.90, the true phase angle is 25.84°. With a 2° (lead) error in the indicated current, the indicated angle will be 23.84°. The calculated power factor is then:

pf = cos (23.84°) = 0.915,
and the error in indicated power factor (and indicated power) will be:

$$\text{error } (\%) = \left(\frac{0.915}{0.900} - 1\right) \cdot 100 = 1.6\ \%.$$

For the case where the true power factor is 0.300 and the true phase angle is 72.54°, the measured, or indicated phase angle will be 70.54°. The calculated power factor is then:

pf = cos (70.54°) = 0.333,
and the error in indicated power factor (and indicated power) will be:

$$\text{error } (\%) = \left(\frac{0.333}{0.300} - 1\right) \cdot 100 = 11.0\ \%.$$

It is thus seen that almost an order of magnitude difference in power factor/power error results as the motor load is changed from near rated conditions to a relatively lightly loaded condition.

Figures A.1a and A.1b graphically indicate the error in calculated power or power factor that results from six current transducer phase angle errors, plotted as a function of true power factor (Figure A.1b is the same data as shown in A.1a, but on a narrower range scale). It should be noted that the data shown in the figures are for errors associated with current transducers for which the indicated current leads the true current. For cases where the indicated current lags the true current, the error that results is slightly different than that shown in Figures A.1a and A.1b.

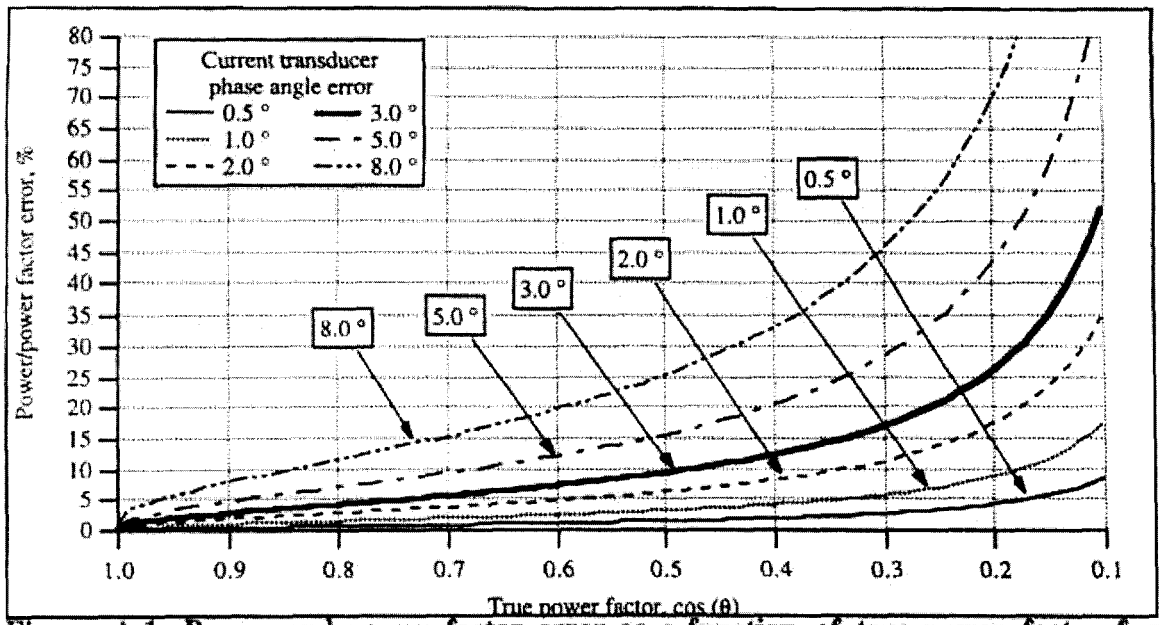

Figure A.1a Power and power factor error as a function of true power factor for six current transducer phase angle errors; true power factor range from 1 to 0.1.

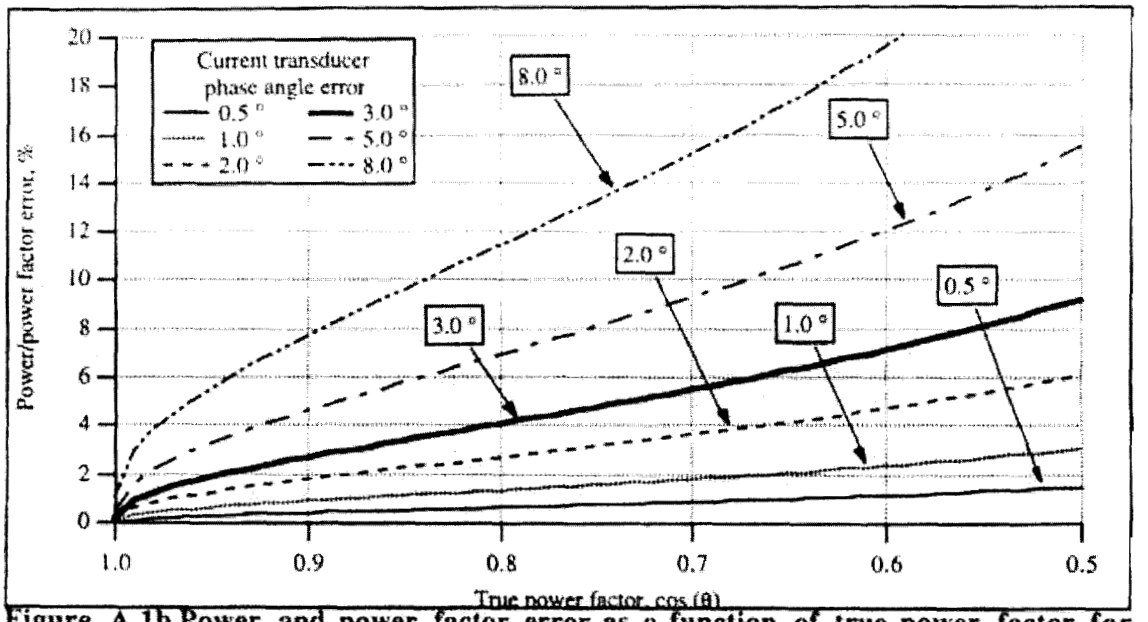

Figure A.1b Power and power factor error as a function of true power factor for six current transducer phase angle errors; true power factor range from 1 to 0.5.

These figures demonstrate that significant errors in indicated power/power factor can result, even with high phase accuracy transducers (e.g., less than 1 ° phase angle error), at low power factors. It is important to note that the phase angle errors are systematic, and therefore correctable. If the direction and amplitude of the transducer phase angle error of the are known, the direction and magnitude of the resultant error in power/power factor can be accounted for. There are a variety of ways in which the current transducer phase angle error can be addressed to minimize or eliminate the error that results in calculated power or power factor. The corrections can be made either before or after calculation of power. If the only purpose of acquiring the power or power factor signal is to determine a single average value (as opposed to analyzing the instantaneous fluctuations in the signal on a continuous basis), the simplest way of correcting the phase angle error is to adjust after the indicated power factor is calculated. **[IEEE 120-1989]** provides a phase angle correction factor which addresses phase angle errors associated with not only the current transducer, but the voltage and wattmeter as well. Rather than detail the IEEE correction methodology here, the reader is referred to section 3.1.5 of that standard.

If more than a single average value of power and/or power factor is needed, as for example, when acquiring continuous data on a motor whose load is fluctuating (even "constant" load devices can cause significant load fluctuations - see the discussion in section A.5.3), alternative methods are necessary. There are a variety of methods that can be employed through analog conditioning of the transduced signals or through control of the analog-to-digital conversion process that can be very effective in reducing the error *before* the power or power factor are calculated. For example, if the indicated current is known to lead the true current by 2° (and the voltage is known to have no phase error), the use of a sequential sampling methodology in the digitization process can correct for the error by simply sampling the current at a time corresponding to 2° before the voltage signal is sampled. For a 60 hz signal, 2° corresponds to 9.26×10^{-5} seconds. If the data acquisition hardware and software will support such control, sampling of the voltage signal 9.26×10^{-5} seconds after the current signal will allow the digitized arrays of data to be directly multiplied to yield an active power with phase angle-related error already corrected. This method is particularly

valuable where reconstruction of the power waveform from digitized current and voltage waveforms is desired.

A.3.2.2 Effect of improper clamp-on jaw closing

In section A.3.1, it was noted that hall-effect elements are often somewhat sensitive to the precise positioning of conductor relative to the clamp-on window. Another area of sensitivity which can significantly affect the accuracy of measured current is clamp-on closure.

Clamp-on current transducers are, by their very nature, intended for portable service, and although generally fairly rugged, do not always close with perfection. In many cases, clamp-on probes are used in relatively tight quarters where it is difficult to visually verify proper closure. In other cases, the probe may be left hanging on a conductor.* Depending upon the physical design of the probe, its weight may tend to cause the jaws to separate. Yet another potential problem is the accumulation of dust or dirt on the jaw faces.

Regardless of the specific cause of improper jaw closure, the effect can be significant. Table A.1 compares the current amplitude and phase differences for two identical clamp-on transformers used to transduce the same current (7.5 hp motor-driven pump). For both tests, the "A" pickup was properly closed. For test 1, the "B" pickup was properly closed, while for test 2, the jaws were slightly separated by a single sheet of fine paper. Figure A.2 shows x-y type plots of the transducer signals for the two tests. The test 1 results show that the amplitudes of the two transducers were the same when both were properly closed, and that there was less than a 1° phase difference. There was minimal effect in the amplitude when the jaws were separated, but phase was significantly changed.

Table A.1 Summary results of clamp-on jaw separation test

Test	Condition	A amplitude, rms amps	B amplitude, rms amps	A to B phase angle, degrees (B leads A)
1	Both pickups fully closed	6.33	6.33	0.6°
2	B pickup jaws ~3 mils open	6.33	6.22	5.7°

As was shown in Figures A.1a and A.1b, a phase error of 5 ° results in a power or power factor error that is very large, compared to other typically experienced errors, particularly at low power factors.

It is quite easy, in field use, to experience problems due to either tight quarters or other causes that result in greater gaps than that shown above. In one experience, the author measured all three phases of a 75 hp pump motor, with the motor operating at about 80% of rated load. The analysis indicated that one phase had an apparent power factor of about 0.95, while the other two phases had power factors of about 0.8. When retested, the anomalous phase closely matched the other two phases. In this particular case, an error was avoided, primarily because all three phases were monitored; however, had only the one anomalous phase been monitored (and a balanced motor assumed), a significant error would have been introduced.

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* As an aside, it is hopefully obvious that great care and discretion should be exercised when hanging clamp-on probes. While the conductor onto which the clamp-on is attached should be well secured, the weight of some probes is not insignificant. If there is any question at all about the ability of the lead on which the clamp-on is being attached to support its weight, don't do it. This caution applies not only to primary conductors but to the secondaries of permanently installed current transformers as well.

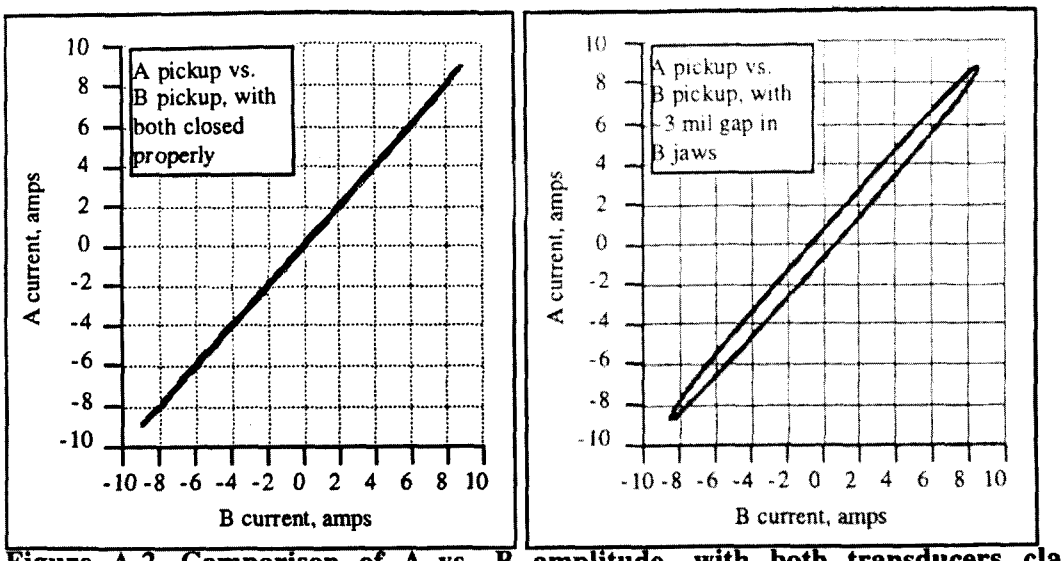


Figure A.2 Comparison of A vs. B amplitude, with both transducers clamped onto the same wire. The oval shape in the right-hand plot indicates phase difference.

A.3.3 Examples of possible errors associated with voltage measurements

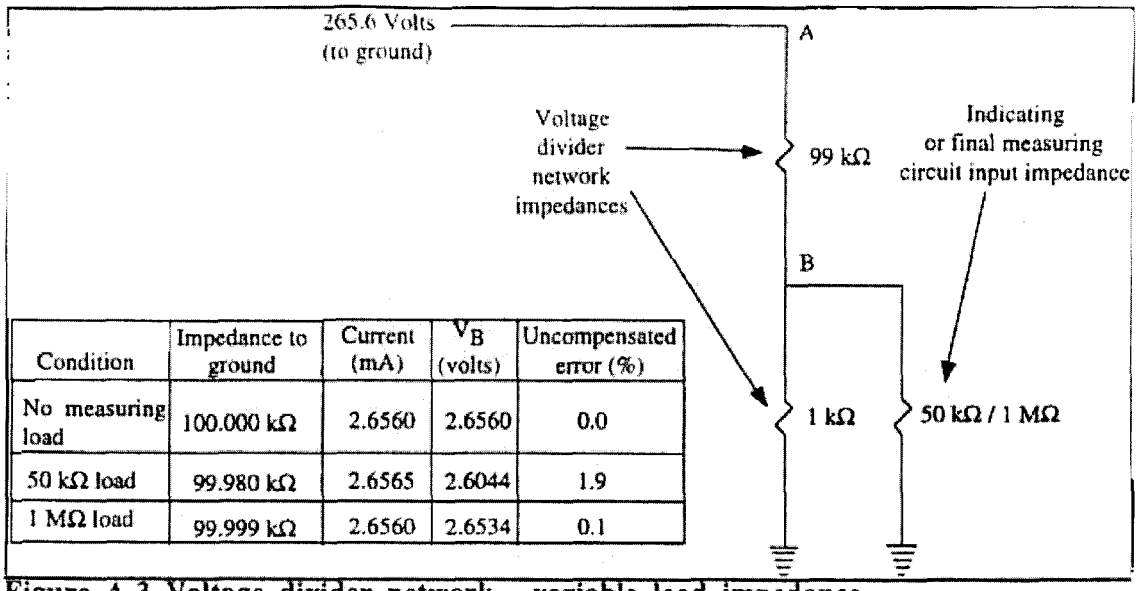
Voltage transformers or divider networks are normally used for transducing voltage signals. The phase angle considerations discussed for current transducers also applies to voltage transducers and will not be repeated here.

When voltage divider networks are used to transduce voltage, a consideration that may be overlooked is the relative output impedance of the network compared to the input impedance of the final measuring or indicating circuit. For example, if the divider network output impedance is 1 kΩ, and the measuring circuit input impedance is 1 MΩ, the uncompensated error would be only 0.1% ($10^3 \div 10^6$). However, if the input impedance is 50 kΩ, the uncompensated error would be 2% [$10^3 \div (50 \times 10^3)$]. Normally, digital multimeters have high input impedances, and this is not a concern. However, some recording devices (such as tape recorders) may have low enough input impedance that some error can be introduced, unless correction factors are applied.

For illustration purposes, Figure A.3 shows a voltage divider network which is designed to reduce the line to ground voltage by a factor of 100 before insertion into the measuring circuit. As noted in the table in Figure A.3, an amplitude error of almost 2% can be introduced by a low measuring circuit impedance.*

It is important to note that the error can be compensated by simply modifying the scaling factors applied, as long as the circuit impedances are known. Alternatively, the insertion of a high input impedance, unity gain amplifier at the output of the voltage divider network can avoid the error.

* The number of significant figures shown here is for illustration purposes only; normal field monitoring would obviously not support such precision.



Condition	Impedance to ground	Current (mA)	V_B (volts)	Uncompensated error (%)
No measuring load	100.000 kΩ	2.6560	2.6560	0.0
50 kΩ load	99.980 kΩ	2.6565	2.6044	1.9
1 MΩ load	99.999 kΩ	2.6560	2.6534	0.1

Figure A.3 Voltage divider network - variable load impedance.

There are a variety of portable power measuring devices which may be used on either single or three-phase circuits. It is important to recognize the limitations associated with the voltage signal that is used on these devices when they are used for three phase power measurement. A common usage of such meters involves measuring power in one phase (by connecting one voltage lead to one phase of the motor power supply, and the other lead to ground, and placing the clamp-on current probe on the phase lead), reading the indicated power, and then multiplying by three. There are two commonly experienced conditions that can result in error when using this method for power measurement:

1) Fundamentally, the voltage measurement in such a mode inherently assumes that the phase to ground voltage is the same as the phase to neutral voltage of the motor (or in other words, the neutral is at the reference ground). This is not always the case.

2) Individual phase powers are not always identical. Imbalanced voltage supplies, motor feeder lead resistance differences, or imbalance in the motor itself can result in unequal power distribution among the three phases.

If either of these conditions exist, the total power estimated from an individual phase will be erroneous. The IEEE 120-1989 methods for measuring three phase power involve multiple meters. The most common three-phase configuration is three wire (floating neutral); for this configuration, two wattmeters are required by the IEEE methodology. This implementation is commonly referred to as the two wattmeter method, and it assures that the total measured power will be correct.

An equivalent application of this method, using a single power meter, can be made by measuring and summing the three individual phases. Of course, the use of the single meter precludes simultaneous measurement. Changes in motor power as the individual phases are measured is a fundamental limitation to using this approach.

Three phase monitoring systems are available which monitor and indicate (through digital displays and/or analog outputs) individual phase voltage, current, power factor, and power. Some systems also measure other parameters, such as harmonic content, crest factors, etc. It is important to

recognize that these systems, like the single phase monitoring system, are inherently limited when the motor neutral is not available. In some systems, the device can create its own artificial neutral; but it is just that - an artificial neutral. If the motor is not balanced, the reported individual phase parameters, such as power and power factor, will not necessarily be accurate.

Analog signal conditioning

Analog conditioning of transduced signals is almost always necessary when acquiring motor data. In a loose sense, the fundamental transduction of the acquired signal involves signal conditioning, whether desired or not. For example, the use of a current transformer inherently involves the insertion of an RL filter circuit in the instrument path. Hall-effect elements are sensitive to ambient magnetic fields, and as a result, some conditioning of the signal is often necessary to minimize high frequency noise.

The output signals from some current sensors are relatively low amplitude and require amplification prior to digitization. As noted in section A.3, amplifiers may be used in voltage measuring circuits to prevent the dropping network signal from being affected by low input impedance monitoring devices. Typical phase errors for commonly used amplifiers are insignificant at line frequency, and are normally not a concern. Likewise, gain accuracy is relatively insignificant for calibrated amplifiers.

Analog conditioning, such as low-pass filtering may be used in some cases to avoid aliasing of digitized signals. As a general rule, it is a good practice to apply the same conditioning to all related signals to avoid introducing phase errors. For example, if the voltage signal for a variable speed drive system (which tends to have high frequency content) is passed through an anti-alias filter prior to digitization, the current signals should receive the same filter treatment, unless the anti-alias filter is known to cause no phase shift. The same general rule applies for other types of conditioning, such as ac-couplers. It is worth noting here that analog conditioning can be used to compensate for inherent phase errors associated with the transducer (for example, by introducing a phase lag to compensate for phase lead effects associated with current transformers). When applying such techniques, it is important to understand the effect of the conditioning on other factors that may be of interest (e.g., harmonic content).

Signal analog to digital conversion

The conversion of analog signals to digital values is the final portion of the instrumentation process. Although additional processing of the digitized data may be performed, errors that are introduced subsequent to the analog-to-digital (A/D) conversion are of an entirely different nature, and will not be treated here.

A.5.1 Signal resolution

There are a variety of A/D converters that are applied in motor parameter measurements. These range from the human eye conversion of an analog meter reading to a single digital value to a high speed computer data acquisition board that continuously digitizes an input signal. There are some fairly straightforward limitations, such as the resolution with which the A/D process can be made. Signal resolution in the human eye conversion of an analog meter indicator is a function of several parameters, including meter readability, avoidance of parallax in making the reading, and visual acuity. For electronic A/D converters, resolution is normally expressed in bits. The resolution, as related to the measured parameter, depends upon the bit resolution and the range over which the board can measure (in volts). For example, a 12-bit board is capable of resolving 2^{12}, or 4096 discrete values. If the range of the converter is -5 to +5 volts, the resolution in volts is 10 volts ÷

4096 = 0.00244 volts. A 16-bit converter is capable of resolving 65536 discrete values. For the same 10 volt range, it would be capable of resolving the measured signal to within 0.00015 volts.

To show the significance of the digitization resolution for an example signal, consider the measurement of phase to ground voltage on a 460 volt (phase-to-phase) system, where the phase to ground voltage will be 265.6 volts. If the line voltage is dropped, via a voltage divider network or transformer by a factor of 100, the measured voltage will be 2.656 volts (rms). Assuming no harmonic content (a pure sinusoidal waveform), the peak voltage (of either polarity) will be:

$2.656 \bullet \sqrt{2} = 3.756$ volts.

For the 12-bit A/D converter on the $\pm$ 5 volt range noted above, all values of the dynamic signal would be within range. As noted above, the signal resolution will be 0.00244 volts. Since the measured signal is 1/100th of the actual line voltage, the actual resolution referenced to line voltage will be 0.00244 • 100 = 0.244 volts, or about 0.1% of the rms voltage. The use of a 16-bit converter would improve the line-referenced resolution to 0.015 volts, or about 0.006% of the rms voltage.

It is important to note that true resolution of the measured parameter is related to not only the A/D converter's inherent bit resolution, but to the range of the converter relative to the signal being measured. For example, if the 12-bit board range was $\pm$ 10 volts instead of $\pm$ 5 volts, the line referenced resolution would be 0.488 volts, or almost 0.2% of the rms voltage.

It is evident from the foregoing discussion that even 12 bit boards are capable of relatively high resolution measurements, particularly when compared to other sources of measurement uncertainty. It is critical, however, that the signal being measured be scaled such that a significant fraction of the board range is used. For example, if the same divider network (1/100) were used on a 12 volt (ac rms) signal, and then digitized over a range of $\pm$ 10 volts, the line referenced resolution of 0.488 volts would be over 4% of the rms amplitude. Thus, when the amplitude of the signal being acquired is small relative to the range of the A/D converter, consideration should be given to amplifying the signal before digitization.

A.5.2 Sequential vs. simultaneous A/D conversion

When multiple signals are being digitized, it is important to understand the digitization sequence. Some A/D boards utilize simultaneous digitization in which multiple A/D converters are simultaneously triggered to digitize multiple signals concurrently. Some other A/D boards utilize sequential sampling in which multiple signals are multiplexed and digitized by the same A/D converter.

If simultaneous digitization is used, the arrays of digitized data will be sequenced such that direct power and power factor calculations can be made. If, however, the A/D conversion process is sequential (multiplexed), each array will be slightly offset in time from the other arrays. As a result, extensive digital manipulation may be required. For example, if eight channels of data are sequentially sampled, with an overall board maximum sampling rate of 40,000 Hz (i.e., 5,000 Hz per channel), the interchannel delay time will be approximately 1/40,000 sec., or about 25 μsec. On a 60-Hz basis, this corresponds to 0.54 degrees. Tables A.2 and A.3 show hypothetical acquisition configurations, and the timing sequences associated with two different sampling sequences.

Table A.2 Hypothetical scan sequence 1

Channel	Signal	Scan time, µsec	Delay in degrees (for 60 Hz reference frequency)
1	Phase A voltage	0	0.00
2	Phase B voltage	25	0.54
3	Phase C voltage	50	1.08
4	Torque	75	1.62
5	Phase A current	100	2.16
6	Phase B current	125	2.70
7	Phase C current	150	3.24
8	Speed	175	3.78

Table A.3 Hypothetical scan sequence 2

Channel	Signal	Scan time, µsec	Delay in degrees (for 60 Hz reference frequency)
1	Phase A current	0	0.00
2	Phase B current	25	0.54
3	Phase C current	50	1.08
4	Torque	75	1.62
5	Phase A voltage	100	2.16
6	Phase B voltage	125	2.70
7	Phase C voltage	150	3.24
8	Speed	175	3.78

For hypothetical scan sequence 1, the current for each phase is sampled 2.16 degrees after the voltage. This has the effect of causing the array of current data to appear to be advanced by 2.16 degrees relative to the voltage signal. For the scan sequence 2, however, the sampling sequence is changed so that the voltage for each phase is sampled 2.16 degrees after the current. This has the opposite effect - the voltage is advanced by 2.16 degrees. The effect of various levels of phase shift was illustrated in section A.3.2.1 (see Figures A.1.a and A.1.b). The phase shift being discussed here is of a different origin, but has the same effect.

The scan sequence for a sequential sampling device can either worsen or improve any effects associated with transducer phase shift. Assume, for example, that current transformers are being used which have phase lead errors of 2.20°. If hypothetical scan sequence 1 above is used, the net effect is a 4.36° total phase shift (in the digitized data). However, if scan sequence 2 is employed, the phase shift effect of the current transformer is almost exactly offset by the phase shift in the opposite direction associated with the sampling sequence, resulting in a total error of 0.04°.

The scan sequence is thus an important consideration for data acquisition equipment that utilizes sequential sampling. While simultaneous sampling boards eliminate this as a factor of concern, such boards are usually more expensive, and may not provide the capability to sample as many channels. Also, the ability to effectively negate other phase shift components is lost with simultaneous sampling conversion processes.

A.5.3 Length of data sample

Most test personnel recognize that motor loads may fluctuate from time to time due to changes in system conditions. The recording of *system* conditions when a motor is tested is a standard good practice. Shorter duration load fluctuations that may exist due to the fundamental nature of the device being driven are not always as well recognized or understood, but the effect can be significant.

Many motors drive devices which, although at a constant load in a system sense, experience significant load variations due to the inherent design of the device. For example, devices such as fans are frequently connected to the motor by a belt drive. In such a configuration, the load experienced by the motor, and as a result, the current and power utilized, will normally be modulated by several fundamental frequencies, including the fundamental belt rotational frequency and harmonics, the fan rotational speed, and the motor rotational speed. In other words, the motor power and current are constantly fluctuating because of these load modulations. The fundamental sources of these modulations are such things as eccentric sheaves and looseness or irregularities in the belt(s).

Figures A.4 and A.5 show time the raw current waveforms for a direct-drive pump (Fig. A.4) and a belt-driven fan (Fig. A.5). Even the appearances of the raw waveforms are clearly different, with a clear modulation pattern for the fan. Figure A.6 shows the rms amplitudes for the same motors; the modulation for the fan is even more apparent in the rms current waveform. The source of the low frequency modulation for the fan is the fan belt, whose fundamental frequency is 3.8 Hz. The overall average rms current for the fan is 5.13 amps, but swings from 4.73 to 5.45 amps. The pump rms running current fluctuates between 6.35 and 6.54 amps, with an average of 6.45 amps. Thus the fan rms current swings (min-to-max) are about 14% of the average, while the pump rms current only swings by about 3%.

Of course, not only the current, but the power and power factor are fluctuating. Figures A.7 and A.8 show power factor and power fluctuations for the fan. The power factor fluctuates (between extremes) by about 8.5% (average power factor is 0.85), and the power fluctuates by almost 22%.

There are a number of portable (as well as stationary) power analyzers which digitize a few cycles of current and voltage (as few as two, for example), then calculate and report a variety of parameters, such as current, voltage, power, power factor, harmonic distortion, etc. A single set of data collected, based on a such a short sample period, may indicate a motor load that is significantly different than the average. For example, the pairs of start and end points shown in Figure A.8 correspond to 0.033 seconds (two cycles at 60 Hz). The average power in the period banded by the first pair is 2690 watts; for the interval banded by the second pair, the average power is 3280 watts. Since the long-term average power is 3002 watts, the error that would result if data were acquired during either interval, and assumed to be representative, would be about 9%.

If short duration samples are the only available option, averaging of multiple samples can reduce the potential error. To provide an indication of the merits of averaging, one thousand random samples of fan data were acquired. Two sample periods were used - 2 cycles (0.033 seconds), and 10 cycles (0.167 seconds). Summaries of the results are provided in Tables A.4 through A.7. The data in Table A.5 is based on the average of five randomly selected samples, each of which is of the designated duration. Tables A.6 and A.7 represent averages of ten and twenty samples, respectively. There is an obvious value to collecting multiple samples; the benefit of acquiring additional data is dependent upon the nature of the signal being measured and the length of time represented by a particular sample. While there is an obvious benefit to collecting multiple samples and averaging, there are also practical limitations. At the very least, when the data collection equipment is capable only of very short samples, multiple samples should be collected and a statistical analysis performed to provide an insight into the uncertainty of the measurements.

Table A.4 Short sample period power estimates and errors, based on 1000 random sets of data selected from within a long term sample.

Sample Period	Minimum sample value, watts (Percent Error)	Maximum sample value, watts (Percent Error)	Mean sample value, watts	Sample std. deviation (Percent of average power)
2 cycles (0.033 sec)	2605 (13.2%)	3310 (10.3%)	3002	191 (6.4%)
10 cycles (0.167 sec)	2845 (5.2%)	3163 (5.4%)	3002	90 (3.0%)

Table A.5 Short sample period power estimates and errors, based on averaging of 5 sample periods (values reported are for 200 groups of 5 sample periods each)

Sample period	Minimum sample value, watts (Percent Error)	Maximum sample value, watts (Percent Error)	Mean sample value, watts	Sample std. deviation (Percent of average power)
2 cycles	2719 (9.4%)	3207 (6.8%)	3002	90 (3.0%)
10 cycles	2913 (3%)	3108 (3.5%)	3002	41 (1.4%)

Table A.6 Short sample period power estimates and errors, based on averaging of 10 sample periods (values reported are for 100 groups of 10 sample periods each)

Sample period	Minimum sample value, watts (Percent Error)	Maximum sample value, watts (Percent Error)	Mean sample value, watts	Sample std. deviation (Percent of average power)
2 cycles	2779 (7.4%)	3167 (5.5%)	3002	65 (2.2%)
10 cycles	2922 (2.7%)	3078 (2.5%)	3002	3041 (1.0%)

Table A.5 Short sample period power estimates and errors, based on averaging of 20 sample periods (values reported are for 50 groups of 20 sample periods each)

Sample period	Minimum sample value, watts (Percent Error)	Maximum sample value, watts (Percent Error)	Mean sample value, watts	Sample std. deviation (Percent of average power)
2 cycles	2827 (5.8%)	3073 (2.4%)	3002	48 (1.6%)
10 cycles	2948 (1.8%)	3045 (1.4%)	3002	22 (0.4%)

Section A.6 Summary

The process of acquiring data of any kind has inherent, unavoidable sources of error and uncertainty. This universal observation certainly applies to the monitoring of motor parameters. It is, however, often the case that the major sources of errors that occur in field data acquisition are either avoidable or can be corrected as long as the exact nature and limitations of the equipment being used is well understood.

The importance of understanding just how accurately the transduced, conditioned, and recorded data reflect the *real world condition* cannot be overstated. The use of measurement equipment with 0.1% accuracy, certified by traceable calibrations, do not guarantee that the recorded data is accurate to within 10%, let alone 0.1%. Similarly, analytical models that are capable of predicting

performance within 1% are of minimal value when the data provided to the models is in error by 5%.

This appendix has attempted to identify some of the more common, in our experience, potential sources of error that are not always commonly recognized. The examples cited are by no means comprehensive. They do, however, provide some indication of just how significant some of the potential errors are, and help to illustrate the merits of thoroughly understanding not only the full instrument train, but the nature of external influences.

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