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Assessment of Available Methods for Evaluating In-Service Motor Efficiency

J. D. Kueck
J. R. Gray
R. C. Driver
J. S. Hsu

Prepared for the
U.S. Department of Energy
Bonneville Power Administration
under DOE Interagency Agreement
and for the Pacific Gas and Electric Company

MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
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Abstract

This is a report of a literature survey of methods for evaluating the efficiency of an operating motor The survey looked for methods that could be used during motor operation without removing the motor from service. In general, these methods determine the motor's efficiency by measuring some combination of the current, voltage, power in and speed as well as other parameters. The motor's efficiency is calculated using an equivalent circuit model or other mathematical representation of the motor.

The literature survey found approximately 30 methods. These methods are each discussed briefly and rated in a number of categories such as accuracy, user friendliness, etc. These ratings are not based on test data, but only on an educated opinion.

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Glossary

f	=	frequency of current
hp_l	=	motor output power at load (hp)
hp_r	=	rated motor output power (hp)
I	=	average input line current at full load (amps)
I_2	=	rotor current
I_2'	=	rotor current at rated load
I_n	=	average line current at no load (amps)
I_r	=	rated full load current
L_1	=	X_1/ϖ
L_3	=	X_3/ϖ
L_4	=	X_4/ϖ
L_m	=	X_m/ϖ
P_a	=	air gap power
P_i	=	motor input power at full load (watts)
P_n	=	total input power at no load (watts)
P_o	=	motor output power at load (watts)
P_r	=	rated power output
k	=	234.5 for 100% IACS conductivity copper or 225 for aluminum. These values are specified by the IEEE Standard 112-1991
R	=	average line-to-line stator resistance (ohms)
D	=	estimated fraction of rated full load power that is equal to stray load losses
R_f	=	average line-to-line stator resistance after loaded tests (ohms)
R_n	=	average line-to-line stator resistance after no-load tests (ohms)
R_s	=	average line-to-line stator resistance at specified temperature
s	=	slip at load = (synchronous speed - full load speed)/synchronous speed
s'	=	slip corrected to specified stator temperature
s_n	=	slip at no load
s_γ	=	slip at rated output power
t_s	=	specified temperature of stator winding
t_t	=	temperature of stator winding during motor test
V	=	average full input line-to-line voltage (volts)
V_p	=	phase voltage
V_r	=	line-to-line voltage during manufacturer's full load test
ϖ	=	$2Bf$
W_1	=	stator losses at full loads (watts)

W_{1n} = stator losses at no load (watts)
W_2 = rotor loss
W_f = windage and friction losses
W_h = core losses
W_{LL} = stray load losses
$W_{LL'}$ = stray load losses at rated load
X_1 = per phase leakage reactance of the stator winding
X_2 = per phase rotor reactance with rotor blocked referred to stator
X_3 = rotor parallel reactance in first rotor loop of two rotor loop equivalent circuit
X_{34} = rotor series reactance of two rotor loop equivalent circuit
X_4 = rotor parallel reactance in second rotor loop to two rotor loop equivalent circuit
X_s = synchronous reactance in reduced two rotor loop equivalent circuit
X_m = per phase magnetizing reactance
r_1 = per phase resistance of the stator winding
r_2 = per phase rotor resistance with rotor blocked referred to stator
r_3 = rotor resistance in first loop of two rotor loop equivalent circuit
r_4 = rotor resistance in second loop of two rotor loop equivalent circuit
r_c = per phase equivalent core-loss resistance
r_i = equivalent circuit effective input resistance
K_{1s} = per phase resistance of the stator winding of specified temperature
r_i = equivalent circuit effective input impedance
Z_g = equivalent circuit input impedance less r_1 and X_1 (see figure 2)
Z_2 = rotor impedance of two rotor loops equivalent circuit (see figure 4)
Z_{AB} = rotor impedance of reduced two rotor loops equivalent circuit (see figure 5)

1. Introduction

The topic of this study is the estimation of the efficiency of electrical motors in the field. The authors attempted to locate and review every available efficiency estimation method that could be found in a literature search. The ratings assigned to the efficiency estimation methods in this study are summary judgements only and are not based on test data. Time did not permit a rigorous analysis of the theoretical methods employed in the various methods, and the discussions are simply summaries or digests of the papers that were reviewed. It may be discovered that actual accuracy or durability, etc. are much better than these ratings, and we apologize for any misconceptions that may appear in these reviews.

Methods are discussed for estimating the efficiency of motors already installed and driving operating systems. It is assumed throughout this study that the motor will be tested in place. This restriction places several severe demands on the method of determining efficiency. It may not be possible to perform certain desired tests because of operational requirements. Some methods of determining efficiency require name plate or other manufacturer provided data. Because of the motor's age, this data may no longer be available. In some cases the nameplate may no longer exist or may be unreadable. Even when the nameplate exists and is readable, the data may no longer be applicable because the motor has been reworked or rewound. Several safety issues[1] arise when field testing installed motors. These will likely dictate how motor efficiency is measured in the field. Thus in many cases, making a highly accurate determination of motor efficiency in the field may face significant obstacles.

What can be done under these circumstances? First, a number of good field methods can be identified. It is unlikely that any one method will be the best for every situation in the field. Second, the purpose for measuring motor efficiency can be carefully thought through.

Nailen (57) concludes, "Evidently, then, efficiency test methods readily usable in the field are not likely to yield accurate results capable of `proving' the economics of a motor replacement program." This conclusion is correct in some, but not all, situations. There are many situations where highly accurate efficiency determinations are not necessary. The accuracy and other specifications required of a field test method depend on the objective of determining motor efficiency.

Therefore, this study assumes that the user has a simple objective: to determine whether or not it is economically advantageous to replace an existing electrical motor with a more efficient one. There are, of course, other purposes for performing field efficiency tests. However, it is worthwhile to have a simple, straightforward objective in mind as available methods are evaluated.

---

[1] Brown mentions several such safety concerns and how these concerns were handled when describing his program to measure motor efficiencies for a large firm.

While this is somewhat of an oversimplification, the important point is that efficiency estimati is merely a means to an end. The first requirement of a good field method for estimating moto efficiency is, if possible, to provide an accurate estimate of power losses in that motor. Failing that, an acceptable method must provide us with a good lower bound on the losses of the existi motor.[2]

If possible, it is desirable to have an accurate estimate of power losses when the replacement motor is operating in the same environment and at the same load as the existing motor. This is one of the key advantages of performing in-service testing.

There are several factors, such as motor reliability, expected motor life, and motor load factor that directly effect the motor replacement decision analysis, and other factors that have more subtle effects. For instance, as explained by the Arizona Department of Commerce Energy Office (2) and Krishnan (46) the affinity law on centrifugal loads[3] can negate the gains obtaine by increasing motor efficiency. Krishnan also notes that changes to the overall power factor o the factory can be reflected as substantial changes in capital investment and distribution systen maintenance. Nailen (57) points out that unbalanced phase voltages can have disastrous effect on motor efficiency. This complicates the decision analysis because unbalanced voltages may have different effects on the losses of motors of different designs. And Bonnett (4) (10) discusses the energy and cost advantages of using motors with higher rated voltages or lower starting currents. For additional discussion regarding the decision analysis see Bonnett (9), Evans (24), and Montgomery (53) (54).

However, these considerations are beyond the scope of this study. Our purpose here is merely evaluate field methods for determining the efficiency of motors to determine whether it is economically advantageous to replace an existing motor with a more efficient one. For this project, it is assumed that problems related to voltage unbalance and harmonic distortion are tc be corrected prior to applying any methods for determining motor efficiency.

The ideal test method, as presently envisioned, might look something like this: (1) accuracy of or - 3% to allow a reasonable economic evaluation; (2) low invasiveness, such that it could be performed in the plant without shutting down the motor driven process; (3) utilization of commonly available test equipment which do not require the motor to be taken off-line; (4) limited to 1 to 200 HP induction motors, 600 volts or less; (5) adequate equipment safety features; and (6) good personnel safety provisions.

---

[2] Suppose it is assumed that the losses of an existing motor equals a known lower bound and it is found that economical to replace the motor. Clearly it will be economical to replace the motor if its losses are actually hi than this lower bound.

[3] The affinity law requires that the power used by a centrifugal load increases in proportion to the cube of the rotational speed

2. Study Procedure

The literature search included database searches for relevant journal articles, patent searches, and requests of industry leaders at the cutting edge of this technology. The databases searched for articles included IEEE, NTIS, Compendex, EPRI, and DOE. Key words (some of which were truncated as necessary for maximum output) included electric, induction, motor, efficiency, test, and method. Searches were also done on the names (and variations of) Austin Bonnett, Helen Sam, Vern Nielsen, Roger Daugherty, and Richard Nailen. A number of searches employing various combinations of these key words with the above databases led to a total of 252 citations from which the abstracts were chosen. Sixty-one abstracts were printed. This, plus twenty-nine citations from other sources, produced the sixty-nine articles.

The patent search was conducted using the MicroPatent software/CD at the Central Research Library, Oak Ridge National Laboratory. Key words employed (also truncated to maximize output) included shaft torque measurement, output power measurements, General Electric, electric motor, motor shaft, electric motor losses, and efficiency test. A number of searches using different combinations of these terms and different years back through 1987 produced 418 titles. Twenty-three of these were selected and printed in abstract form. Complete patent texts for six of these were ordered.

3. Discussion

The discussion will be confined to field efficiency tests for three phase electrical induction motors with rated capacities greater than one horsepower (hp). Any of these tests can be easily adapted to test electrical induction generators or other polyphase motors. Several of the tests were not necessarily intended by their originators as field tests. However, each of the tests discussed can probably be used in the field with some modifications.

As stated in the introduction, a good method provides an accurate estimate of or a lower bound for total motor losses. There are five components of these losses:

Stator resistance losses (W_1) are the losses in the stator windings equal to $1.5 \times I^2 \times R$ for a three-phase motor where I is the average input line current and R is the average dc resistance between the line terminals.

Rotor resistance losses (W_2) are the losses in the rotor windings equal to $3 \times I_2^2 \times r_2$ for a three-phase motor where I_2 is the rotor phase current and r_2 is the rotor dc resistance.

Core losses (W_h) constitute the hysteresis and eddy current losses in the iron. These losses vary approximately with the square of the input voltage, but for fixed input voltage these remain approximately constant from no load to full load. A common practice is to use no load measurements to estimate these losses. However, as explained by Nailen (57), these losses decrease slightly with increasing loads.

Windage and friction losses (W_f) are mechanical losses due to bearing friction and windage. These losses are also approximately constant from no load to full load. It is also a common practice to use no load measurements to estimate these losses. These losses are a component of the power crossing the airgap (P_a) separating the stator and rotor.

Stray load losses (W_{LL}) are fundamental and high frequency losses in the structure of the motor, and circulating current losses in the stator winding and harmonic losses in the rotor conductors under load. These losses are proportional to the square of the rotor current. Stray load losses are a difficult problem for any efficiency determination method, in the field or elsewhere.

Nailen (59) introduces this difficulty by asserting, "Handling this (*stray load losses*) has provoked worldwide controversy among engineers for half a century." He also advises that evaluating the stray load losses is a major obstacle in any field test of motor efficiency. In fact, there does not appear to be any useful means for directly measuring stray load losses in the field. Nevertheless, certain methods discussed below require an estimate of stray load losses. In all such cases this obstacle is overcome by using an

assumed value. Typical of these assumed values are those used by IEEE Standard 112-1991 (98) shown in Table 1.

Table 1
Assumed Values for Stray-Load Loss
from IEEE Standard 112-1991

Machine Rating	Stray-Load Loss (Percent of Rated Output)
1-125 hp	1.8
126-500 hp	1.5
501-2499 hp	1.2
2500 hp and greater	0.9

Nailen provides a good discussion of the difficulty one encounters in determining stray loa losses. He illustrates how extremely complex these losses are by noting that from six t twelve major components of the losses exist within the stator and rotor of the motor. H includes a plot of typical stray load losses versus rated horsepower taken from the AN standards for large motors. The values of Table 1 form a piecewise linear approximatio that fits his curve well. However, for the most part, the values in Table 1 are somewh greater than those of Nailen's plot. Of course the values of Table 1 are standard values, s for any particular motor, the table values may be significantly over or under estimate th actual stray load losses.

There is another small difficulty with stray load losses. These losses are more properl divided into two additional classes of losses. As explained by Say in (65), the fundament frequency stray load losses occur mainly in the stator, while the high frequency harmon losses occur mainly in the rotor. Thus, the fundamental frequency stray load losses oug to be subtracted from the input power along with stator resistance losses and core losses determine the air gap power when a method requires an estimate of air gap powe Otherwise, when a method estimates rotor resistance losses as a fraction of air gap powe these losses will be slightly over estimated. None of the field methods discussed in th paper separate the stray load losses into their stator and rotor components.

Figure 1 depicts the flow of energy through a motor from input, across the boundaries of the motc and out to useful mechanical power and to various losses. The flows are scaled to depict the typic sizes of the various flows in a motor with 1,000 input units. The actual loss distribution in any giv motor can vary greatly from these typical values.

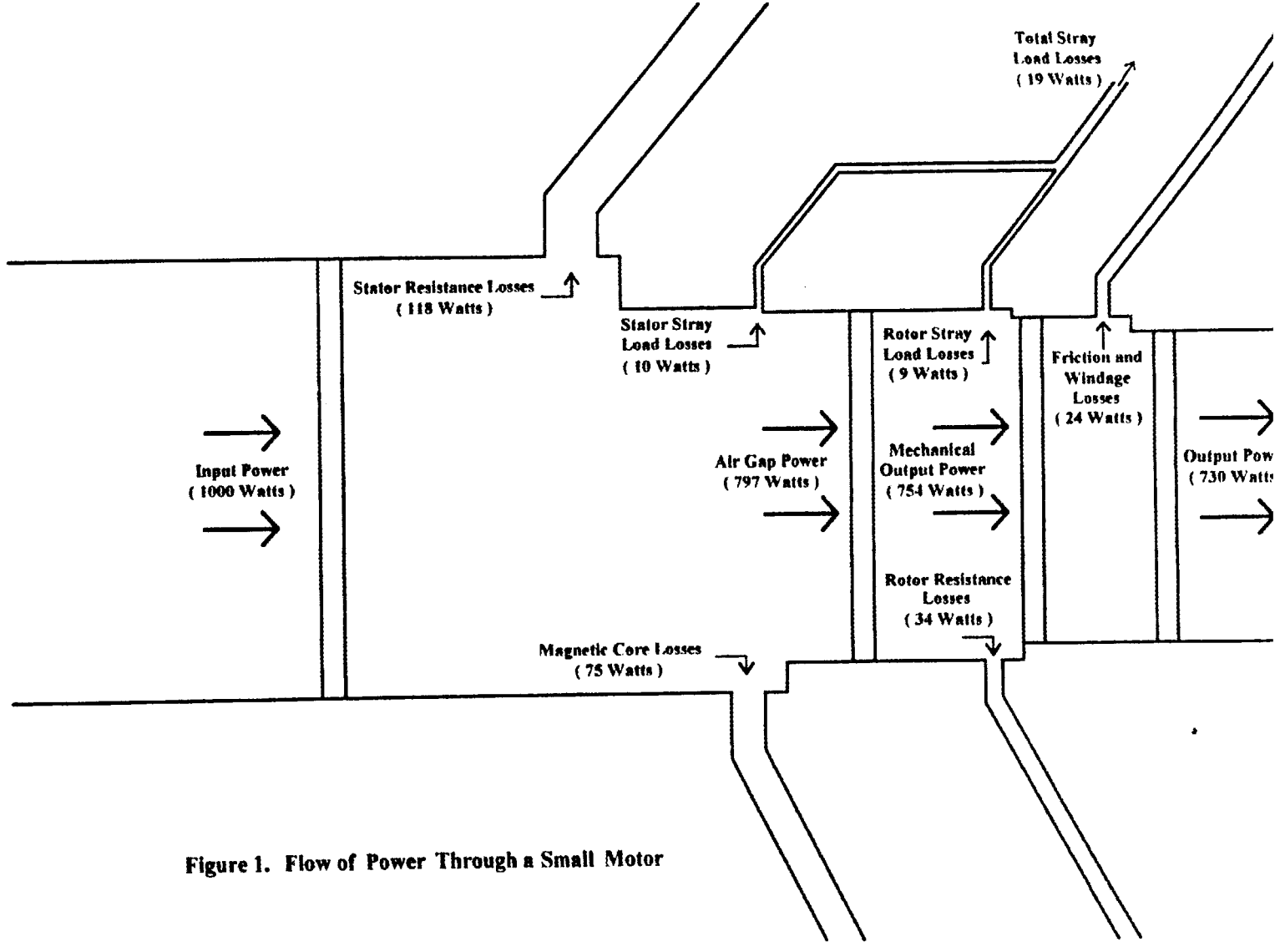

Figure 1. Flow of Power Through a Small Motor

3.1 Summary of Methods

The characteristics of the test methods are summarized in two ways, a matrix summary, and a method by method discussion. Section 3.2 provides the matrix summary of the methods versus their evaluation criteria. The first nine columns of the matrix address the nine criteria for a desirable field test of efficiency. The entries in these columns are the ratings of each of the test methods. The next seven columns describe the field measurements that are required for each method.

The ratings in the matrix summary are based only on subjective judgments made with limited data, and in no way should be considered as determining that one method is "superior" to another. The ratings are only provided to reflect estimated differences in accuracy, invasiveness, etc. between methods.

A "Grade Point Average" or "GPA" table is provided after the matrix summary. In determining the "GPA" for each method, the rating for "accuracy" was multiplied by 2 because of the need to properly weight the importance of accuracy in the evaluation of the methods. The reader will note that some highly accurate methods have a relatively low GPA. This is because the high level of instrusion or high cost pulled down the GPA. A useful field method will be simple to use without a high level of intrusion.

After the GPA table, another table is provided that shows which methods are commercially available, which are in prototype form, and which are purely theoretical or are described only in technical papers or standards.

The matrix and tables are followed by a method-by-method discussion (in Section 3.3), to expand, where necessary, on the information provided in the matrix. The discussion of each method ends with consideration of the nine evaluation criteria. The nine evaluation criteria are: invasiveness, economy, portability, durability, user friendliness, accuracy, human safety and equipment safety. These nine test characteristics were provided by the report sponsors.

The evaluation and discussion of the tests presume, <u>unless noted otherwise</u>, that:

1. The tests are conducted by competent, experienced personnel; although ignorance can be deadly it is not considered in the evaluations.

2. Applicable standards and best working practices governing electrical testing and those related to equipment and personnel safety procedures are followed during all tests;

3. All power sources provide balanced phase voltage closely approximating a sinusoidal waveform;[4]

4. All voltage and current measurements are root mean square (rms) values;

5. All instruments are properly calibrated, highly-accurate instrumentation; and

6. If necessary, proper adjustments are made for the instrument transformer and the connection points of the instruments; that is, any error caused by these factors does not play a part in the evaluation or discussion. It must be noted that the errors caused by the measurement devices can be quite significant.

Where it is important to the evaluation of a method, it will be pointed out when that method does not require or satisfy one of the above assumptions.

---

[4] Nailen (57) points out that unbalanced phase voltages can have disastrous effects on motor efficiency. Furthermore, unbalance voltages may cause different effects on the losses of motors of different designs. His Figure 6 shows that, in some cases, more good may come from a project to balance line voltages within a factory than one to replace inefficient motors. However, this is beyond the scope of this study. Here it is merely assumed that line voltages will be balanced.

3.2 Matrix Summary of Methods

List of Methods

1. IEEE Standard 112, Method E1
2. Hirzel's Modified Method E1
3. Ontario Hydro's Simplified Method E1
4. Nielsen's Modified Method E1
5. Becnel, Kilgore, and Merrill's Modified Method E1
6. Vogelsang & Benning Motor Analyzer Method
7. ECNZ Method
8. ANGUS Electronics Method
9. IEEE Standard 112, Method F1 (Standard Equivalent Circuit)
10. Ontario Hydro's Simplified Method F1 (Standard Equivalent Circuit)
11. Locked Rotor Method (Two Rotor Loop Equivalent Circuit)
12. ORMEL96
13. Standard Slip Method
14. Ontario Hydro's Compensated Slip Method
15. Slip Upper Bound Method
16. Motor Master+ (Slip)
17. Current Method
18. Motor Master+ (Current)
19. Air Gap Torque Method
20. Silex
21. Shaft Torque Methods
22. SENTECH
23. Stanford Empirical Method
24. Ho and Chen's Method
25. Colin Grantham Method
26. Motor Master + (Power)
27. SAVO's Modified IEEE 112 Method
28. Grantham and Rahman's Artificial Dynamometer Method

3.2 Matrix Summary of Methods Segregated Loss Methods

TEST CHARACTERISTICS									
Method	Invasiveness A=best D - worst	Economy A=best D - worst	Portability A=best D - worst	Durability A=best D - worst	Dependability A=best D - worst	User Friendliness A=best D - worst	Accuracy A=best D - worst	Human Safety A=best D - worst	Equipment Safety A=best D - worst
1. IEEE Standard 112, Method E1	D	D	D	C	A	C	A	C	C
2. Hirzel's Modified Method E1 (see comment 1)	C	C	A	A	B	B	B	B	B
3. Ontarios Hydro's Simplified Segregated Loss Method	B	B	A	A	B	B	B	B	B
4. Nielsen Engineering Motor Performance Analyzer (MPA)	C	B	B	B	A	A	A	B	B
5. Becnel, Kilgore, and Merrill's Modified IEEE Standard 112, Method E1	C	B	A	A	B	B	B	B	B
6. Vogelsang & Benning	1C/2B	B	B	B	B	A	1A/2B	B	B
7. ECNZ	C	B	A	A	A	A	A	B	B
8. ANGUS	C	A	A	B	B	C	B	B	B

3.2 Matrix Summary of Methods Segregated Loss Methods

MEASUREMENTS							
Method	Input Power (Pi)	Terminal Voltage (V)	Input Current (I)	Current Full Load/ No Load	Power Factor Full Load/ No Load	Stator Resistance Hot/Cold	Speed (rpm)
1. IEEE Standard 112, Method E1	Yes	Yes	Yes	Both	Both	Cold	Yes
2. Hirzel's Modified Method E1 (see comment 1)	Yes	Yes	Yes	Both	Full Load	Hot	Yes
3. Ontarios Hydro's Simplified Segregated Loss Method	Yes (see comment 1)	Yes (see comment 1)	Yes	Full Load	Full Load	Hot	Yes
4. Nielsen Engineering Motor Performance Analyzer (MPA)	Yes	Yes	Yes	Both	Both	Hot (see comment 1)	Yes
5. Becnel, Kilgore, and Merrill's Modified IEEE Standard 112, Method E1	Yes	Yes	Yes	Both	Both	No (see comment 1)	Yes
6. Vogelsang & Benning	Yes	Yes	Yes	Both	Yes	Hot	Yes
7. ECNZ	Yes	Yes	Yes	Both	Yes	Hot	Yes
8. ANGUS	Yes	Yes	Yes	Both	Yes	Hot	Yes

3.2 Matrix Summary of Methods
Equivalent Circuit Methods

TEST CHARACTERISTICS									
Method	Invasiveness A=best D - worst	Economy A=best D - worst	Portability A=best D - worst	Durability A=best D - worst	Dependability A=best D - worst	User Friendliness A=best D - worst	Accuracy A=best D - worst	Human Safety A=best D - worst	Equipment Safety A=best D - worst
9. IEEE Standard 112, Method F1	D	D	D	C	A	C	A	C	C
10. Ontarios Hydro's Simplified Method F1	C	C	A	A	B	B	B	B	B
11. Locked Rotor Method	D	D	D	C	A	C	A	C	D
12. ORMEL96	A	A	A	A	C	A	C	A	A

MEASUREMENTS							
Method	Input Power (Pi)	Terminal Voltage (V)	Input Current (I)	Current Full Load/ No Load	Power Factor Full Load/ No Load	Stator Resistance Hot/Cold	Speed (rpm)
9. IEEE Standard 112, Method F1	Yes	Yes	Yes	Both	Both	Cold	Yes
10. Ontarios Hydro's Simplified Method F1	Yes	Yes	Yes	Both	Both	Hot	Yes
11. Locked Rotor Method	Yes	Yes	Yes	Both	Both	Both	Yes
12. ORMEL96	No	No	No	No	No	Optional	Yes*

3.2 Matrix Summary of Methods
Slip Methods

TEST CHARACTERISTICS									
Method	Invasiveness A=best D - worst	Economy A=best D - worst	Portability A=best D - worst	Durability A=best D - worst	Dependability A=best D - worst	User Friendliness A=best D - worst	Accuracy A=best D - worst	Human Safety A=best D - worst	Equipment Safety A=best D - worst
13. Standard Slip Method	B	C	A	A	C	A	D	B	B
14. Ontario Hydro's Compensated Slip Method	B	C	A	A	C	A	D	B	B
15. Slip Upper Bound Method	A	C	A	A	C	A	D	A	A
16. Motor Master+									
Slip	A	A	A	A	C	A	C	A	A
Current	A	A	A	A	C	A	C	A	B
Input Power	B	B	A	A	B	A	B	B	B

MEASUREMENTS							
Method	Input Power (Pi)	Terminal Voltage (V)	Input Current (I)	Current Full Load/ No Load	Power Factor Full Load/ No Load	Stator Resistance Hot/Cold	Speed (rpm)
13. Standard Slip Method	Yes	Yes	Yes	Yes/No	Yes/No	No	Yes
14. Ontario Hydro's Compensated Slip Method	Yes	Yes	All Phases	Yes/No	Yes/No	No	Yes
15. Slip Upper Bound Method	No	No	No	No	No	No	Yes
16. Motor Master +							
Input Power	Yes	Yes	Yes	Full	Yes/No	No	No
Current	No	No	Yes	Full	No/No	No	No
Slip	No	No	No	No/No	No/No	No	Yes

3.2 Matrix Summary of Methods
Current, Air Gap Torque, Shaft Torque and Other Methods

TEST CHARACTERISTICS									
Method	Invasiveness A=best D - worst	Economy A=best D - worst	Portability A=best D - worst	Durability A=best D - worst	Dependability A=best D - worst	User Friendliness A=best D - worst	Accuracy A=best D - worst	Human Safety A=best D - worst	Equipment Safety A=best D - worst
17. Current Method	B	C	A	A	C	A	C	B	B
19. Air Gap Torque Method	C	B	B	B	A	B	A	B	B
20. Silex	B	A	B	A	B	A	B	B	B
22. Sentech	D	C	C	A	A	C	A	B	B
24. Ho and Chen's Method	C	C	B	C	B	B	B	B	B

MEASUREMENTS							
Method	Input Power (Pi)	Terminal Voltage (V)	Input Current (I)	Current Full Load/ No Load	Power Factor Full Load/ No Load	Stator Resistance Hot/Cold	Speed (rpm)
17. Current Method	No	No	Yes	Full Load	No	No	No
19. Air Gap Torque Method	Yes	Yes	Yes	Both	No	Hot	Yes
20. Silex	Yes	Yes	Yes	Full	Yes	Hot	Yes
22. Sentech	Yes	Yes	Yes	Full Load	Yes	No	Yes
24. Ho and Chen's Method	All Phases	Yes	All Phases	Both	Both	Hot	Yes

NOTE: Method 25 through 29 are not included in the Matrices because sufficient information is not available.

METHOD	TEST CHARACTERISTICS "GPA*"
Segregated Loss	
1. IEEE Standard 112, Method E1	2.3
2. Hirzel's Modified Method E1	3.0
3. Ontario Hydro's Simplified Method E1	3.2
4. Nielsen's Method E1	3.3
5. Becnel, Kilgore & Merrill's Method E1	3.2
6. Vogelsang & Benning Motor Analyzer Method, Option 1	3.3
6. Vogelsang & Benning Motor Analyzer Method, Option 2	3.3
7. ECNZ Method	3.5
8. ANGUS Electronics Method	3.0
Equivalent Circuit	
9. IEEE Standard 112, Method F1 (Standard Equivalent Circuit)	2.3
10. Ontario Hydro's Simplified Method F1 (Standard Equivalent Circuit)	3.0
11. Locked Rotor Method (Two Rotor Loop Equivalent Circuit)	2.1
12. ORMEL96 - Basic	3.4
Slip	
13. Standard Slip Method	2.9
14. Ontario Hydro's Compensated Slip	2.9
15. Slip Upper Bound Method	3.2
16. Motor Master+	3.4
17. Current Method	2.9
18. Motor Master+	3.4
19. Air Gap Torque Method	3.3
20. SILEX	3.3
21. Shaft Torque	
22. SENTECH	2.9
Other Methods	
24. Ho and Chen's Method	2.7
26. Motor Master+ (input power)	3.3

NOTE: Accuracy rating is given a double weight in the calculation of this GPA.

METHOD	TYPE
Commercially Available	
4. Nielsen's Modified Method E1	Segregated Loss
6. Vogelsang & Benning	Segregated Loss
7. ECNZ Motor Monitor	Segregated Loss
8. Angus Electronics	"IEEE standard 112 methods E & F"
12. ORMEL96[5]	Equivalent Circuit
16. WSEO's Motor Master+	Statistical/Empirical
20. SILEX	Air Gap Torque
22. Sentech Systems	Torque Gauge
27. SAVO	Modified IEEE 112 Method
Prototype or Under Development	
2. Hirzel's Modified Method E1	Segregated Loss
3. Ontario Hydro's Simplified Method E1	Segregated Loss
10. Ontario Hydro's Simplified Method F1	Standard Equivalent Circuit
11. Locked Rotor Method	Two Rotor Loop Equivalent Circuit
19. Air Gap Torque	Air Gap Torque
Theoretical/Paper Study	
1. IEEE Standard 112, Method E1	Segregated Loss
5. Becnel, et al's Modified Method E1	Segregated Loss
9. IEEE Standard 112, Method F1	Standard Equivalent Circuit
13. Standard Slip*	Slip
14. Ontario Hydro's Compensated Slip*	Slip
15. Slip Upper Bound*	Slip
17. Current Method*	Current
23. Stanford Empirical Method*	Stanford Empirical
24. Ho & Chen	Ho & Chen
28. Grantham & Rahman's	Artificial Dynamometer

*Although this method is listed as theoretical, only simple, commonly available equipment is needed to use it.

[5] Presently available only through the US DOE Motor Challenge Program.

3.3 Discussion of Methods by Category

3.3.1 Segregated Losses Methods

The segregated losses methods discussed in this section and equivalent circuit methods discussed in the immediately following section belong to a common class. In the segrated loss approach, each of the motor losses is approximated, or segregated, and then the sum of the losses is subtracted from the measured input power to find the output power. As Oesterlei (62) explains, these methods are among a class of preferred summation of losses methods for determining electrical motor efficiency. Methods from this class are usually quite accurate. For instance, a study conducted for Ontario Hydro (95) found that this class of efficiency evaluation methods gives acceptable accuracy nominally within 2 percent. However, as noted by the Ontario Hydro study, most methods of this class suffer the disadvantage of requiring both no load and full load measurements. The no load measurement requires uncoupling the motor and paying a penalty in invasiveness and economics of testing. Nevertheless, as concluded in the Ontario Hydro study, when accuracy , not simplicity of method, is of great concern, a member of this class of methods will likely be the best choice, assuming it is possible to make the required no load and full load measurements.

The segregated loss methods are the most straightforward of the efficiency testing methods because they are designed to directly measure motor power losses. These methods do not suffer the disadvantage of determining losses in a round about way, so they ought to give the most accurate and precise result. For this reason these methods will be discussed first.

1. **IEEE Standard 112-1991, Method E1**--The standard of the segregated losses methods are IEEE's Methods E and E1. Procedures for these tests are given in (98) so a detailed description will not be given here.

Except in extraordinary circumstances, method E is not a useful field test for efficiency. Its additional removed-rotor and reverse-rotation tests used to directly measure the fundamental frequency and high frequency stray load losses are too invasive and user unfriendly. Therefore, attention will be restricted to method E1. Even a literal interpretation of Method E1 would be impractical for field use, but the method is included here for completeness. Method E1, in its IEEE 112 format, as discussed here, is probably seldom used in the field because it requires a variable load and a variable voltage power supply.

1. Method E1 specifies a comprehensive no load test. This requires that the motor be connected to a variable voltage power source and disconnected from the shaft load. Measurements are taken of voltage, current and power input while operating at no load and at voltages ranging from 125 percent of rated voltage down to the point where further voltage reduction increases the current. This requires a graphical technique to separate friction and windage losses from core losses.

2. Method E1 requires test under load at six equally spaced load points with four between 25 percent and 100 percent of full load and two greater than 100 percent and less than 150 percent. This requires attaching the motor to a variable load. However, this makes it possible to determine best-fit curves of line current, speed, efficiency, and power factor versus output power. This improves the accuracy and usefulness of Method E1 because, with these curves, one can determine a smoothed value of each of the output characteristics for any load between 25 percent and 150 percent of rated full load.

3. Method E1 specifies an assumed value for stray load losses at rated load. This assumed value is a standard percentage of rated power where the percentage depends on the output rating of the machine. These standard values are shown in Table 1. For other than rated load Method E1 adjusts the stray load losses in proportion with the square of the rotor current.

   Using assumed values of stray-load losses rather than direct measurement is the difference between Method E and Method E1. This greatly reduces Method E1's invasiveness, however, it clearly introduces a potential source of error.

4. The Method E1 procedure for estimating stray load losses means that, like almost all other efficiency tests, the fundamental frequency stray load losses can not be separated from the high frequency stray load loss. As noted in (65), the fundamental frequency stray load losses occur mainly in the stator and should be subtracted from the input power along with stator resistance and core losses to determine the air gap power. This causes a high estimate of the rotor resistance losses because these losses are a computed fraction of the air gap power.

5. The repeatability of Method E1 is improved by requiring the adjustment of all resistance and slip measurements to a specified temperature. This specified temperature is adjusted to an ambient temperature of 25 degrees C.

rion	Comment
;iveness	Method E1 requires variable load tests, so the motor being tested must be connected to a variable load. Furthermore, during the no load test the motor must be disconnected from its load and connected to a source of variable voltage. In most circumstances in the field this would be quite disruptive to normal operation of the system to which the motor is connected. Hence, this method has the lowest invasiveness rating (D).

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4. The Method E1 procedure for estimating stray load losses means that, like almost all other efficiency tests, the fundamental frequency stray load losses can not be separated from the high frequency stray load loss. As noted in (65), the fundamental frequency stray load losses occur mainly in the stator and should be subtracted from the input power along with stator resistance and core losses to determine the air gap power. This causes a high estimate of the rotor resistance losses because these losses are a computed fraction of the air gap power.

5. The repeatability of Method E1 is improved by requiring the adjustment of all resistance and slip measurements to a specified temperature. This specified temperature is adjusted to an ambient temperature of 25 degrees C.

Criterion	Comment
Invasiveness	Method E1 requires variable load tests, so the motor being tested must be connected to a variable load. Furthermore, during the no load test the motor must be disconnected from its load and connected to a source of variable voltage. In most circumstances in the field this would be quite disruptive to normal operation of the system to which the motor is connected. Hence, this method has the lowest invasiveness rating (D).

Economy	This method requires extensive work in the field and receives the lowest economy rating (D).
Portability	The portability of method E1 is determined primarily by the portability of the variable load, its associated hardware and the variable power source. This, in turn, depends on the size of the motors being tested. However, except for small motors, this equipment is hardly portable and earns Method E1 the worst portability rating (D).
Durability	Most of the equipment used with Method E1 is quite durable. But, again, the variable load equipment largely determines the durability rating of Method E1. Frequent damage to this equipment seems likely as it is transported from site to site, connected and disconnect to the motors under test, and placed under stress during the load test (C).
Dependability	Method E1 is one of the recognized standards for efficiency tests within the United States. If performed correctly with proper equipment, it should yield very reliable results. Of most concern regarding dependability is whether one can set the variable load reasonably close to the six equally spaced loads required by the method. If so, then the curve fitting procedure of the method should yield dependable measures of efficiency (A) and the other fitted motor characteristics.
User Friendliness	The computation of Method E1 can be easily performed on a personal computer, so this is not a significant handicap. Therefore, the need to obtain and connect a variable load and a variable voltage source and to disconnect the motor from its load are the primary determinates of Method E1's rating (C).
Accuracy	Method E1 is one of the most accurate tests for motor efficiency (A). We would predict its accuracy to be within +/- one percent. Its negatives in this regard derive primarily from its treatment of stray load loss. The IEEE Standard 112 (98) values in Table 1 closely agree with ANSI Standard C50.41-1982. Therefore, these values certainly represent the consensus judgement of experts on induction motor losses. Nevertheless, in a particular instance, the standard value may be quite erroneous. For instance, as shown in Table 1, in the 1 to 125 horsepower range, Method E1 sets stray load losses at 1.8 percent of rated output. However, Nailen (57) points out that the American National Standards Institute sets the losses at 1.2 percent of rated output for motors sizes

in this same range. Gilmour (27) notes that Europe's International Electrotechnical Commission Publication 34-2, Part 2 sets stray load losses at full load to 0.5 percent of rated load for motors of all sizes. Even the standards do not agree on the proper value for this loss.

The problem is even worse than it seems. Neilson (60), while summarizing typical energy losses, asserts that the stray load losses of machines with standard design and high efficiency design are approximately 3 and 0.5 percent, respectively, of rated load. If this is correct, the standard stray load losses used by Method E1 cause the efficiency of standard design machines to be significantly overstated. The reverse is true for high efficiency machines.

Method E1 also suffers from its inability to separate stator from rotor stray load loss. As explained above, this causes an overstated estimate of rotor resistance losses. This, in turn, causes the estimate of motor efficiency to be understated.

Human Safety — Testing machines under high stress while connected to high voltage offers a number of hazards to the humans involved. Hazards particular to Method E1 derive from the need to change the input power source and the output load connections. Such hazards should be manageable with careful test practices (C).

Equipment Safety — The comments made for Human Safety are applicable here(C).

2. Hirzel's Modified IEEE Standard 112, Method E1--Hirzel (33) describes a modified Method E1 which, among other things, reduces its invasiveness and increases its user friendliness. Hirzel's method differs from the standard Method E1 (98) in the following ways.

1. Measurements at load are only taken at one load, not at the six loads required by the standard Method E1. For simplicity the one load used is the operating load of the motor being measured. This means that the fitted curves of the standard Method E1 are not available. Thus, Hirzel's method will not be as accurate as the standard.

2. The no load measurement taken is at rated voltage. This greatly simplifies the no load test because it is not necessary to obtain a source of variable voltage power nor to change the line connections of the motor. However, this means it is not possible

to use Method E1's graphical procedure to separate core losses from friction windage losses. Also, one must forego the benefits of smoothing the no load val with a fitted curve of no load power versus input voltage. The inability to sepa core losses from friction and windage losses brings about an underestimate of r loss. This is because Hirzel's procedure implicitly underestimates air gap power subtracting friction and windage losses from the usual estimate of air gap power, as determined by Method E1. Rotor losses are then estimated as a fraction of underestimated air gap power.

3. Resistance and slip measurements are not corrected to a specified temperature required by the standard Method E1. Therefore, results from Hirzel's method will be as repeatable as the standard method. On the other hand, if we are willing ignore the effects of changing ambient temperature, Hirzel's method gives us estimate of efficiency under the actual operating conditions of the motor.

4. The stray load losses at rated full load are estimated as 1.2 percent of rated output specified by the American National Standard Institute (ANSI) standard C50.41 effect in 1983. Consideration may be given to using the values specified by Ta 1. This is easily done, and, if present consensus opinion regarding stray load los is correct, should improve the estimate of stray load loss.

5. In the standard Method E1 stray load losses are estimated to be proportional to square of the rotor currents. In an approximately equivalent manner, Hirzel's meth sets these losses proportional to the square of motor output torque. Either meth ought to yield about the same results, if done correctly.

6. In an effort to reduce measurement error, Hirzel's procedures require that measurements at both no load and full load be repeated five times. He then specif that the average of the five readings for each parameter be used as the value of t parameter during the calculations required by his procedure. This is an excellent i because the load may be of an oscillatory nature, due to a loose belt, etc. Pov factor would then be oscillating also. Averaging readings will provide a much be measurement of the input power.

Criterion	Comment
Invasiveness	By eliminating the requirement to test the motor at several loads, Hirzel's modified Method E1 removes the need to connect the moto to a variable load. Furthermore, the requirement to connect the moto to a source of variable voltage during the no load test has also been eliminated. These modifications greatly reduce the invasiveness and increase the user friendliness of Hirzel's method. However, it is still

necessary to disconnect the motor from its load to perform the no load test. In some circumstances in the field this would be quite disruptive to normal operation of the system to which the motor is connected. Overall, this method receives a medium invasiveness rating (C).

Economy

The economy of this method would receive a poor rating. The tools required are inexpensive, but the down time required for uncoupling is a significant economic disadvantage. (C).

Portability

For the reasons discussed under invasiveness, the portability of Hirzel's Method E1 is greatly improved over that of the standard Method E1. As noted above, the portability of the standard method is largely determined by the portability of the variable load, its associated hardware, and the variable power source. Because none of this special equipment is required for Hirzel's method, it has earned the best portability rating (A).

Durability

All of the equipment used with Hirzel's Method E1 is standard equipment and ought to be quite durable. Thus, the durability rating of this method is the best (A).

Dependability

The exact dependability of Hirzel's method is open to some question. However, it is a modified version of a recognized standard for efficiency tests within the United States. If performed correctly with proper equipment, it should yield very reliable results. The improvements suggested in the discussion above should increase the dependability of this method to at least a medium rating (B).

User Friendliness

The computations of the modified Method E1 are much simpler than the standard method. In any event, either can be performed on a personal computer so these computations are not a significant handicap. The only significant burden this method places on the user is the need to disconnect the motor from its load. Therefore, this method receives a medium rating for user friendliness (B).

Accuracy

Like the standard Method E1, Hirzel's modified version is, perhaps, one of the more accurate tests for motor efficiency (B). We would predict its accuracy to be within +/- 2 percent. Its negatives in this regard derive primarily from its treatment of stray load loss. The IEEE Standard 112 (98) values in Table 1 closely agrees with ANSI Standard C50.41-1982. Therefore, these values certainly represent the consensus judgement of experts on induction motor losses. Nevertheless, in a particular instance, the standard value may be quite

erroneous. For additional information on this topic, see the discussion under **Accuracy** for the standard Method E1.

Like the standard Method E1 Hirzel's version also suffers from its inability to separate stator from rotor stray load loss. As explained above, this causes an overstated estimate of rotor resistance losses. In turn, this decreases the estimate of motor efficiency.

However, perhaps the greatest source of error in Hirzel's method comes from its inability to separate core losses from friction and windage losses. This leads to an underestimation of air gap power and, in turn, an underestimation of rotor resistance loss. The final result is an overestimation of the motor efficiency.

In spite of this, Hirzel's method can still provide reasonably accurate estimates of motor efficiency. The Ontario Hydro (95) study compares a similar segregated losses method against a dynamometer method when applied to a set of 17 motors ranging in size from five to 100 horsepower. The average difference in efficiencies obtained by the two methods was 0.3 percent while the worst case difference was slightly over one percent.

Human Safety — Testing machines under high stress while connected to high voltage offers a number of hazards to the humans involved. There are no hazards particular to Hirzel's modified Method E1. This method should be among the safer test methods (B).

Equipment Safety — The comments made for Human Safety are applicable here (B).

3. Ontario Hydro's Simplified Segregated Loss Method--The Ontario Hydro study (95 proposes a segregated loss method that is the same as Hirzel's modified Method E1. In addition, thi study proposes a method that simplifies this technique much further. As pointed out in this stud it is not always possible to interrupt a process long enough to decouple a motor from its load an conduct a no load test. The study suggest that one way around this obstacle is to assume a value fo the combined windage, friction and core losses. The study recommends that these combined losse be set to 3.5 percent of input power. Except for this modification, which means a no load test is no required, the method is conducted exactly as Hirzel's modified Method E1.

The stray load losses are estimated as a standard 1.2 percent of the input power, less the stator losses friction and windage losses, and the core losses. As an option, the estimate of these losses could b estimated by the procedure suggested in the discussion of Hirzel's Modified Method E1. Also, th standard percentage of Table 1 could be used in these calculations. These changes would give a estimate of stray load losses more nearly equal those specified by the IEEE Standard 112 (98).

The Ontario Hydro study compared the efficiencies determined by this method for seventeen motors with the results obtained by dynamometer tests. This comparison showed the simplified method gave results within ±3 percent. However, the study cautions that the test motors were all new motors. Furthermore, it cautions if a change is expected in the friction and windage losses or the core losses, then this method is not recommended.

Criterion	Comment
Invasiveness	By eliminating the no load test the Ontario Hydro's Simplified Segregated Loss Method removes the need to disconnect the motor from its load. This modification greatly reduce the invasiveness and increases the user friendliness of this method as compared with Hirzel's Modified Method E1. In some circumstances in the field this method would be usable where Hirzel's method would not. This method will cause little or no disruption to normal operation of the system to which the motor is connected. The user still has to measure winding resistance, so we give this method a (B).
Economy	Because this method uses only standard power, resistance and speed measurement equipment, the cost of the measurement equipment is low. Also, the method does not require extensive field work. One drawback that increases the cost of this methods is the requirement to measure stator resistance. The method provides a good accuracy value for a small investment in measurement (B).
Portability	For the reasons discussed under invasiveness of Hirzel's Method E1, the portability of the Ontario Hydro Simplified Method is greatly improved over that of the IEEE Standard 112, Method E1 (98). As noted above, the portability of the standard method is largely determined by the portability of the variable load, its associated hardware, and the variable power source. Because none of this special equipment is required for Ontario Hydro's method, it has earned the best portability rating (A).
Durability	All of the equipment used with Ontario Hydro's Simplified Method is standard equipment and ought to be quite durable. Thus, the durability rating of this method is the best (A).
Dependability	The exact dependability of Ontario Hydro's method is open to some question because it assumes a value for two of the important types of losses (B). These assumed values may be quite incorrect in the case of rewound motors.

User Friendliness	This method has not been provided in commercially available softwa and must be calculated either by hand or by "home made" softwa (B).
Accuracy	This method loses some accuracy because it uses a standard value f stray load losses and an assumed value for the friction, windage, a core losses. As discussed above, its treatment of stray load losses c easily be improved to more closely agree with the IEEE Standard 1 (98). Like the standard Method E1 and Hirzel's Modified Method E1, th method also suffers from its inability to separate stator from rotor str load loss. We have experimented with a version of this method and found th with reasonable loss estimation, average accuracies of two percent m be obtained (B).
Human Safety	Testing machines under high stress, while connected to high voltag offers a number of hazards to the humans involved. There are n hazards particular to Ontario Hydro's Simplified Segregated Lo Method (B).
Equipment Safety	The comments made for Human Safety are applicable here (B).

4. Nielsen Engineering's Motor Performance Analyzer (MPA)--Nielsen Engineering (9 (94) offers a device for measuring the efficiency of installed motors. This device is based o modified version of the IEEE Standard 112, Method E1 (98). Nielsen's method is very similar Hirzel's modified Method E1. There are four differences.

1. Stator resistances are measured once at normal operating condition. The average these line-to-line resistances is used to compute the stator resistance losses at b no load and normal load. Hirzel measures the resistance after the no load test a uses these to compute stator resistance losses at no load. Thus, the friction a windage losses of Nielsen's method may be slightly smaller than those of Hirz method. This may reduce Nielsen's estimate of total losses and increase his estim of efficiency as compared to Hirzel's method.

2. A proprietary estimate of the ratio of stray load losses to rated full load power is u to estimate the stray load losses at full load. This proprietary ratio is an empiri

estimate that, according to Nielsen's marketing information, is "...based on hundreds of actual dynamometer tests conducted by approved labs throughout North America." The value of this ratio varies with the size of the motor and whether or not the motor is classed as high efficiency. The values for this ratio specified by IEEE Standard 112 (98) also depend on motor sizes. However, the standard values do not vary with the efficiency class of the motor. Nielsen's procedure for handling stray load losses appears to be a logical improvement over the standard values.

3. Nielsen's method, like Hirzel's method, estimates the stray load losses at normal operating load by adjusting the rated full load losses according to the ratio of the square of output power. The output power in Nielsen's method is input power less all losses except stray load losses. Therefore, Nielsen's adjustment ratio is somewhat greater than Hirzel's. This tends to increase the estimate of total losses and reduce the estimate of efficiency.

4. Nielsen's method uses the MPA, a proprietary manufactured device, to perform all measurements. Assuming that clear instructions come with this device, this ought to have beneficial effects on all of the test characteristics of Nielsen's method except accuracy. The ratings presented here depend on this assumption.

Criterion	Comment
Invasiveness	By eliminating the requirement to test the motor at several loads, Nielsen's modified Method E1 removes the need to connect the motor to a variable load. Furthermore, the requirement to connect the motor to a source of variable voltage during the no load test has also been eliminated. These modifications greatly reduce the invasiveness and increase the user friendliness of Nielsen's method. However, it is still necessary to disconnect the motor from its load to perform the no load test. In some circumstances in the field this would be quite disruptive to normal operation of the system to which the motor is connected (C).
Economy	Use of this method obviously requires the purchase or lease of the MPA (B).
Portability	For the reasons discussed under invasiveness the portability of Nielsen's is somewhat better than Hirzel's Method E1, but it is still much more cumbersome than just individual instruments (B).
Durability	In Nielsen's method all measurements and calculations are performed with one commercially available package that ought to be quite durable, but is computer based (B).

Dependability	The exact dependability of Nielsen's method is open to son question. However, it is a modified version of a recognized standa for efficiency tests within the United States. Because all tl measurement are made with a packaged unit, this method considered somewhat more dependable than Hirzel's method (A).
User Friendliness	All measurements and computations in Nielsen's method are made b one commercially available device. This ought to make the metho user friendly if the instructions for using the device are clear (A).
Accuracy	Like the standard Method E1, Nielsen's modified version is, perha one of the most accurate tests for motor efficiency. Primarily, negatives in this regard derive from its treatment of stray load loss. T IEEE Standard 112 (98) values in Table 1 closely agrees with AN Standard C50.41-1982, therefore, these values certainly represent t consensus judgement of experts on induction motor loss Nevertheless, in a particular instance, the standard value may be qu erroneous. As discussed above, Nielsen uses a set of proprietary rati to improve his estimate of stray load losses. In private conversatic Nielsen reports that his estimates of stray load losses agreed well wi lab results. Like the standard Method E1, Nielsen's version also suffers from i inability to separate stator from rotor stray load loss. As explain above, this causes an overstated estimate of rotor resistance losses. turn, this decreases the estimate of motor efficiency. However, perhaps the greatest source of error in Nielsen's method comes from its inability to separate core losses from friction and windage losses. This leads to an underestimation of air gap power and, in turn, an underestimation of rotor resistance loss. The final result may be an overestimation of the motor efficiency. Nielsen believes that accuracy within +/- 1% is expected. We believe this expectation is reasonable (A).
Human Safety	Testing machines under high stress while connected to high voltage offers a number of hazards to the humans involved. Having a single device and a standardized procedure to perform all tests ought to reduce these hazards. This method should be among the safer test methods (B).
Equipment Safety	Having a packaged device with an instruction manual should help to eliminate the learning curve associated with acquiring and analyzing

data with an assortment of data acquisition devices (B).

5. **Becnel, Kilgore, and Merrill's Modified IEEE Standard 112, Method E1**--Becnel, et al (3) tailored the standard Method E1 to provide a method for measuring the efficiency of large induction machines in the field. Their method is a modified version of IEEE Standard 112, Method E1 (98) that differs little from Hirzel's method described above. Both of these methods, among other things, reduce their invasiveness and increase their user friendliness when compared to the standard Method E1. They accomplish this by simplifying the load test to require measurements only at the normal operating load. This eliminates the variable load and measurements taken while operating at six distinct loads required by the standard Method E1. The no load test is also simplified to require measurements only at rated voltage. Most of the comments made when discussing Hirzel's Modified Method E1 are applicable here. However, Becnel, et al's and Hirzel's methods differ in the following ways.

1. In Hirzel's method, the inability to separate core losses from friction and windage losses brings about an underestimate of rotor loss. This is because Hirzel's method implicitly underestimates air gap power by subtracting friction and windage losses from the usual estimate of air gap power, e.g. as determined by Method E1. In Becnel, et al's method this error is compounded by also subtracting stray load losses from air gap power. Rotor losses are then estimated as a fraction of this underestimated air gap power. This, in turn, leads to an overly large estimation of efficiency.

   In spite of this, Becnel et al's method can still provide reasonably accurate estimates of motor efficiency. The authors applied their method to field test an installed 5000 hp motor. The data from a factory which conducted duplicate machine tests of the efficiency of this motor were available. When the actual friction and windage losses from the factory test were assigned to the rotor (i.e., added to the authors' estimate of air gap power), the estimate of rotor losses changed less than one percent.

   In this particular case, the stray load losses are approximately equal to the friction and windage losses so subtracting these losses from the air gap power also caused less than a one percent underestimation of the rotor losses. In spite of the smallness of the error in this particular case, there are no compelling reasons for ignoring the IEEE Standard 112 (98) specified method for handling stray load losses. Becnel's method could be revised to assign these losses to the rotor (i.e., to treat these losses as a component of air gap power and may result in increased accuracy, especially for smaller motors).

2. Resistance measurements were not made during the authors' field application of this method. Instead, the stator temperature was measured with an embedded detector and adjusted the factory determined resistance value to obtain an estimate of stator resistance at test temperature. To compare their results with factory results, the authors' adjusted both resistance and slip to the factory specified temperature as required by the standard Method E1.

3. The stray load losses at rated full load are estimated as 0.9 percent of rated output as specified for large motors by IEEE Standard 112 (98) as shown in Table 1. The authors compared their estimate of stray load losses with the estimate determined by the reverse rotation test, i.e. the Morgan method. The field estimate was almost 50 percent greater than that obtained at the factory. This underscores the difficulties associated with determining a good estimate of stray load losses in the field. Fortunately, the field estimate of total losses was only 5.6 percent greater than the factory estimate. Nevertheless, this adds emphasis to the caution to add a reasonable safety factor to the estimate of total losses of an existing motor during economic comparisons of motors.

4. In the standard Method E1, stray load losses are estimated to be proportional to the square of the rotor currents. In an approximately equivalent manner Hirzel's method sets these losses proportional to the square of motor output torque. On the other hand, Becnel, et al adjust these losses in proportion to the square of the ratio of input power to rated full load output power. Any of these methods ought to yield about the same results if done correctly.

Criterion	Comment
Invasiveness	By eliminating the requirement to test the motor at several loads, Becnel, et al's modified Method E1 removes the need to connect the motor to a variable load. Furthermore, the requirement to connect the motor to a source of variable voltage during the no load test has also been eliminated. These modifications greatly reduce the invasiveness and increase the user friendliness of this method. However, it is still necessary to disconnect the motor from its load to perform the no load test. In some circumstances in the field this would be disruptive to normal operation of the system to which the motor is connected. Overall, we give this method a medium invasiveness rating (C).
Economy	Only conventional instruments are required to make all measurements, but instruments must be supplied to measure power, resistance, and speed (B).
Portability	For the reasons discussed under invasiveness, the portability of this version of Method E1 is greatly improved over that of the standard Method E1. As noted above, the portability of the standard method is largely determined by the portability of the variable load, its associated hardware, and the variable power source. Because none of this special equipment is required for this method, it has earned the best portability rating (A).
Durability	All of the equipment used with Becnel, et al's Method E1 is standard equipment and ought to be quite durable. **Footnote:** (To measure

input power the authors used a three-element watthour meter because such instruments are more accurate for low power factor loads. Perhaps, this instrument is not really standard, nevertheless, it ought to be durable.) Thus, the durability rating of this method is the best (A).

Dependability

Like Hirzel's method, the exact dependability of Becnel, et al's method is open to some question. However, it is a modified version of a recognized standard for efficiency tests within the United States. If performed correctly with proper equipment it should yield reasonably reliable results (B).

User Friendliness

The computations of both Hirzel's and Becnel, et al's modified Method E1 are much simpler than the standard method. In any event, either can be performed on a personal computer so these computations are not a significant handicap. Therefore, this method received a medium rating for user friendliness (B).

Accuracy

Like the standard Method E1 and Hirzel's modified version, this test is, perhaps, one of the more accurate tests for motor efficiency. We would predict its accuracy to be within +/- 2 percent. Its negatives in this regard derive primarily from its treatment of stray load loss. This test uses the IEEE Standard 112 (98) values in Table 1 that closely agree with ANSI Standard C50.41-1982. Therefore, these values certainly represent the consensus judgement of experts on induction motor losses. Nevertheless, as shown by the authors' test, in a particular instance, the standard value may be quite erroneous. For additional information on this topic see the discussion under **Accuracy** for the standard Method E1.

Like the standard Method E1 Becnel, et al's version also suffers from its inability to separate stator from rotor stray load loss. As explained above, this causes an overstated estimate of rotor resistance losses. In turn, this decreases the estimate of motor efficiency.

However, perhaps the greatest source of error in this method comes from its inability to separate core losses from friction and windage losses. This leads to an underestimation of air gap power and, in turn, an underestimation of rotor resistance loss. The final result is an overestimation of the motor efficiency.

Despite these problems, the efficiency the authors obtained with th method for one large motor in the field was only 0.14 percent less tl that obtained during a factory test. However, the use of a collection available instruments for field data measurement could introduce err For this reason, we only give a rating of (B).

Human Safety — Testing machines under high stress while connected to high volta offers a number of hazards to the humans involved. There are hazards particular to this modified version of Method E1. This meth should be among the safer test methods (B).

Equipment Safety — The comments made for Human Safety are applicable here (B).

6. Vogelsang & Benning Motor Analyzer Method --In Germany, this method is referre as "Motor Check" and is distributed by Status Pro.

The Motor Analyzer is an instrument that has been commercially available in Germany for 3 y and in the United States for about 1 year. The unit is a self-contained package weighing abou lbs. and comes complete with current, voltage, power factor, speed, and temperature measu devices. The Motor Analyzer contains a computer complete with hard and floppy disks. calculations and data evaluation are completed automatically by the computer and all data are st on the hard disk. Reports and graphs are generated automatically and are shown on the scr immediately after the tests are completed. Hard copies of the results are generated by a printe

The Motor Analyzer comes standard with several methods for evaluating motor efficiency. The up procedure that is common to all of the available test methods is outlined below:

1. Motor nameplate data are input into the program. This data includes rated voltage, curr frequency, power factor, speed, number of poles, and operating temperature. A power fa data base is included in the program in case this information is not available on the m nameplate.

2. The resistance between phases is measured with an accurate bridge. The measured resist values are input into the nameplate data window.

3. Voltage leads and current clamps are connected to the unit and motor leads or terminal l An optical speed sensor is aimed at the motor shaft for speed measurements.

There are two test options available that are viable for in-the-field testing of motor performance efficiency. Option 1, which requires both a no load and a load test, is more invasive but is accurate (±1% error). Option 2 requires a load test only, but is less accurate (±3% error).

Option 1
Under no load conditions, line voltage, current, power factor, input power, and speed are measured at a single instant in time. Using this one data point and nameplate data, the Analyzer computes the losses through the motor under full load conditions and the full load efficiency.

The motor is then connected to its load and started. The Analyzer then monitors and records line voltages, currents, power factor, input power, and speed. Torque, output power, efficiency, energy consumption, and energy costs are computed internally at each data point taken using the motor loss information gained from the no load test. For cyclic loads, the unit takes data at a user specified time interval for as long as is desired by the user. In this way, motor efficiency at various load points is determined.

The error associated with the measurements of efficiency using this method is claimed by the manufacturers to be ±1%.

Option 2
Option 2 is conducted in much the same way as Option 1, but does not require a measurement under no load. Option 2 relies more heavily on the motor nameplate data in order to determine the losses in the motor.

During the test, the Analyzer monitors and records line voltages, currents, power factor, input power, and speed. Torque, output power, efficiency, energy consumption, and energy costs are computed internally at each data point. For cyclic loads, the unit takes data at a user specified time interval for as long as is desired by the user. In this way, motor efficiency at various load points is determined.

The accuracy of Option 2 depends on the "trueness" of the nameplate data. The experience of Volgelsang & Benning is that the nameplate data are slightly optimistic regarding the output power of motors. The accuracy claimed by the manufacturer for Option 2 is ±3%.

Additional Option
The Motor Analyzer also includes a third method for determining motor efficiency. This test, however, is rarely suited for in-the-field testing due to the need of a variable voltage supply. The results of this method are the quantification of all motor losses and the full load efficiency of the motor.

This third method is a no load test with the motor operated at voltages ranging from 110% to 50% of rated voltage as described in IEEE Standard 112, Method E1. By plotting this data graphically, the core and friction losses can be separated so that the air gap power (and thus the copper losses in the rotor) can be accurately computed.

Even though this option is rarely applicable in the field, it still can be useful for field service personnel if the test has been conducted in the shop before the motor is put into use. If this is the case, Option 2 is employed in the field for the efficiency measurements under load. The unit will

automatically use the loss information from the shop test for its determination of motor efficien in the field. This combination of tests provides the user with efficiency estimates, with an error less than 1% per the manufacturer.

Criterion	Comment
Invasiveness	There are two options with different intrusive levels for the fie efficiency assessment: OPTION 1: This is an invasive metho because both the no load (decoupled) and load measurements a required. Terminal voltages, currents, resistance and speed data a also needed (C). OPTION 2: The name plate data and the load measurement a required. Terminal voltages, currents, resistance and speed data a also needed. Because the resistance measurement is intrusive, w can't give an A (B).
Economy	This method requires purchasing the instrument, however, the sel contained package is available with all equipment needed fc measuring, recording, evaluating and presenting the data except fc the resistance bridge (B).
Portability	The unit is self contained in a box 20x21x8 inches and weighs abou 55 pounds (B).
Durability	Computer based instrumentation must be handled with care (B).
Dependability	The method of the Motor Analyzer is based upon a segregated los method and has proven itself to be quite dependable per th manufacturer. The Analyzer components and method have bee tested for many years in Germany and for the last 6 months in th United States. The manufacturer has noted that actual power facto at full load can often times vary as much as 2.5% from the valu listed on the nameplate of the motor. This variance in power facto is the largest source of error in the Motor Analyzer method (B).
User Friendliness	The software for the Motor Analyzer is completely menu driven, an is reported to be easy to use once familiar with the system. Al connections for voltage, current, and speed are clearly labeled on th rear of the unit. All computations are done by the computer, so ther is no need for the user to do any data processing or analysis after dat is taken. The results are readily available to the user immediatel after the test is completed (A).

Accuracy	The Option 1 accuracy claimed by Vogelsang & Benning is ±1% (A). The Option 2 resultant accuracy given by Vogelsang & Benning is ±3% (B).
Human Safety	Caution should always be exercised when connecting to live voltages. All connectors are insulated for 1000 V. Extreme caution must be used when dealing with medium voltages (i.e. 2,300 V, 4,160 V, and 6,900 V) and testing requires a special high voltage kit manufactured specifically for the Motor Analyzer (B).
Equipment Safety	Connections for voltage and current can be made when live voltages are present. The speed sensor can also be aligned when the motor is running provided that they keyway is visible and provides a readable signal (B).

7. **ECNZ Method** --This method is developed by the Electricity Corporation of New Zealand Limited (ECNZ).

The segregated loss method based on IEC34-2 (which is substantially that of IEEE 112) is used to determine the efficiency of induction motors ranging from 5.5kW through to 750kW in situ. Direct measurements can be made on low voltage machines (400V-480V) but medium voltage machines (3.3kV and above) can be tested using PTs. The IEC24-2, IEEE 112, and JEC standards differ primarily in their definition of stray load loss estimates and the motor monitor accommodates these by providing a user setable stray loss parameter. The default is 0.5% of rated power as per the IEC34-2 standard. This adjustment also permits more accurate determination of the high efficiency classes of motor which have lower stray loss estimates. If the stray loss parameter for a given design is known this too can be directly set to improve accuracy.

Simultaneous measurement of voltage, current, speed and supply frequency are made through voltage probes, clamp on CTs, and an optical pulse speed transducer. Resistance is measured in all three phases with an additional set of current injection probes.

Special techniques have been employed to ensure accuracy in all critical measurements. To preserve the accuracy of power measurement at low power factor, the measurement includes compensation for phase shift created by the clamp-on current sensors. For the same reasons full three phase power measurements are taken, although a two CT option is available if access to all phases is impossible.

Stator and rotor loss parameters are temperature compensated and the temperature of the winding can be determined using the resistance rise test if desired. The current injection connection can be left attached to the motor during power-on to enable resistance measurement to be made as quickly as is practical after a load test and to reduce the risk of physical harm. This enables the instrument to determine the value for the thermal resistance of the motor and makes it possible to allow for the

effect of temperature differences at different loads on efficiency. (This is an extension of Il and can be disabled if desired.)

Direct slip measurement (correcting for supply frequency variances) is made to a very high ac simultaneously with full three phase power measurements. These are averages over 20 s (20,000 samples are taken). In doing so load variations are accommodated and noise induced do not significantly diminish the accuracy of the results.

The instruments can be set in either "measure" or "calculate" mode once all motor parameter been acquired or manually entered into the motor monitor. In measure mode instanta information about the motor operation under the existing load conditions is displayed. information includes efficiency, voltage, current, real and reactive power, power factor, spee torque. The individual loss components are displayed along with the total loss (in kW).

In calculate mode, motor monitor calculates and displays motor performance information at th defined (adjustable) load levels based on the previously recorded parameters. The voltag frequency in the calculate mode is assumed to be the rated value for that motor. For calculate the motor need not even be connected.

This method is a four part test. These four parts are cold (or known temperature) resistance te load test, motor loaded test, and hot resistance test. The hot resistance test is used to measu winding temperature and is optional if the temperatures are known (entered manually). The test be performed in any order and the instrument has a memory facility which allows several mot be tested in parallel, and for tests to be spread over time and site visits. Motor loss paramete calculated once the resistance and load tests are performed.

The motor load test need not be at full load but best results are obtained if loading is above Also the load need not be stable. For optimum results the no load test is performed with the decoupled. However, if very low loading can be achieved and the shaft can not be decouple instrument is capable of separating the fixed losses of the motor (excepting the friction and wind from the residual load albeit with some loss of accuracy.

The stray load loss is not measured but estimated according to a user defined level according t relevant standard. The default level aligns with IEC34-2. Setting this value to 0 will alig results to the JEC standards, and setting the value with respect to motor size according to IEEE 112 permits alignment with that standard.

Criterion	Comment
Invasiveness	All measurements and calculations are simply performed by commercially available device. There is usually a requirement disconnecting the motor for a low load test so overall we give method medium invasiveness (C).

Economy	The instrument is a relatively high cost piece of equipment, but additional power supplies, transformers, etc. are not required (B).
Portability	Excellent portability is provided because everything is packaged into a brief case (A).
Durability	It is an industrial quality, well packaged instrument (A).
Dependability	This segregated loss method with sufficient input data should give dependable results (A).
User Friendliness	The system is designed for ease of use (A).
Accuracy	The manufacture claims that the instrument will produce accuracies within ± 1% (A).
Human Safety	Terminal voltage is involved. Human safety precautions must be observed (B).
Equipment Safety	The connection methods are standardized and clearly described (B).

8. **ANGUS Electronics Method** --Electronics Method: (An E/F method claimed by ANGUS)

The MET program (Motor Efficiency Test) is a procedure consisting of making certain specified field measurements on motors, and entering those values into a computer through a menu driven software package. The software performs calculations (based on IEEE standard 112 "IEEE test procedure for polyphase induction motors and generators, methods E and F") to determine the motor's operating efficiency. This program also provides the user with the capability to make economic comparisons between different motor options, and calculate economic payback.

The MET program requires actual input data at load and no load of the motor being tested. Measurement of the electrical characteristics (current voltage, watts, vars, VA, power factor) can be accomplished with the Esterline Angus PMT AC Motor/Load Surveyor or any other portable three phase power measurement instrument. Additional measurements of RPM, stator resistance, and ambient/surface temperature are also required.

Criterion	Comment
Invasiveness	This method has moderate invasion because the shaft of motor needs to be decoupled for a no load test (C).
Economy	This is a relatively inexpensive device. One only needs the software and commonly available equipment (A).

Portability	The ohmmeter, strobe, resistance meter, temperature measureme and power meter are individually quite portable. They could l placed in a case for field rounds (A).
Durability	This equipment is of average durability (B).
Dependability	The company claims that this method is based on the IEEE Standa Methods E and F. There is no information on how these two differe methods interact in the efficiency calculation (B).
User Friendliness	The program manual appears simple and even includes an economi evaluation. However, when the program cannot reach a solutio based on the input data, it does not give the user error messages wit tips on what the user may need to change (C).
Accuracy	Based on the data acquired, we would estimate the accuracy to b good (B).
Human Safety	The input power measurement that involves terminal voltages requir safety awareness (B).
Equipment Safety	Attention is required when connecting equipment to the moto terminal voltages. Using the Angus motor load surveyor should b no more difficult than using other three phase watt meter devices (B)

3.3.2 Equivalent Circuit Methods

The performance of an electric motor, at least with regard to most of those attributes effecting efficiency, can be calculated from its equivalent electric circuit (Figure 2). As a class, these methods offer a number of advantages. As explained in the discussion of segregated losses methods, equivalent circuit methods are among a class of preferred summation of losses methods for determining electrical motor efficiency. Methods from this class are usually quite accurate. Furthermore, these methods permit one to compute estimates of the efficiency of the motor when it is operating at loads other than those at which measurements were made. Such estimates can be improved by measuring the input current, input power and slip at these new loads. This capability is particularly useful if the motor routinely operates at two or more known loads.

However, a few caveats must be added. As Guru and Hiziroglu (31) warn, equivalent circuits represent induction motors on a per phase basis. It is assumed by these methods that all phases are equal. Hence, equivalent circuit methods are particularly sensitive to imbalances in phase voltages and currents. Also, as noted by Oesterlei (62), because of the nonlinear nature of equivalent circuit parameters these must be determined with great care to ensure accurate results. Often it may be difficult to perform such careful measurement in the field. In addition, Nailen (57) points out that a shortcoming of equivalent-circuit methods is that there are no circuit elements to directly account for either stray load losses or friction and windage losses. These losses may be determined by procedures separate from the equivalent circuit calculations, or estimated, and then circuit elements may be added to account for these losses.

Standard Equivalent Circuit Methods--The usual equivalent electric circuit of an induction motor is shown in the IEEE Standard 112-1991 (98).

9. **IEEE Standard 112-1991, Method F1**--The standard of the equivalent circuit methods are IEEE's Methods F and F1. Procedures for these tests are given in (98) a detailed description will not be given here.

Except in extraordinary circumstances, Method F is not a useful field test for efficiency. As is true for Method E, its additional removed-rotor and reverse-rotation tests used to directly measure the fundamental frequency and high frequency stray load losses are too invasive and user unfriendly. Therefore, we will restrict our attention to Method F1.

The basic Method F1 requires an impedance test and the complete no load, variable voltage test described in the section on the IEEE Standard 112, Method E1 (98). However, the complete no load test does not appear to offer enough improvement to warrant the additional expense and trouble of performing it in the field. Thus, it is assumed for the field test version of Method F1 that measurements will only be made at rated voltage during the no load test. The IEEE Standard 112 (98) permits this simplification.

According to IEEE Standard 112 (98), the required impedance test of Method F1 can be performe by any of four procedures. The best of these for a field test is Procedure 3, which uses a reduce voltage, reduced load test, i.e. a low voltage slip test. As is allowed by the IEEE Standard 112 (98) it is assumed that this test will be simplified for field use to a reduced voltage, no load test. Th other three impedance procedures require, in addition to other tests, a locked rotor test. Because o the invasiveness, user friendliness, human safety and equipment safety issues raised by a lock-roto test, these procedures are bypassed in favor of Procedure 3, which does not require a lock rotor test Again, this test would normally be considered impractical in the field because of the need for th variable voltage power supply. It would only be used where an extremely high confidence level is required. It is included here for completeness.

This selection of impedance procedure is also supportable on the grounds of accuracy. Cummings, Bowers, and Martiny (19) explain that the reduced voltage, no load procedure provides a more accurate determination of equivalent circuit parameters x_2 and r_2. This is because measurements are made at actual rotor operating frequency. These authors assert that the reduced voltage, no load test which is performed at rated frequency may be equal to or slightly better than the basic one-quarter rated frequency test. However, since this method depends on the expertise of the tester, the IEEE Standard 112 (98) implies that this method should be limited to cases where a reduced frequency impedance test or curve is not practical. Yet, according to Cummings, et al, the value of r_2 determined by the quarter frequency test will usually be high due to the increased skin-effects as compared to the operating frequency of approximately 1 Hz.

The three-frequency impedance test was eliminated from consideration because in most instances providing a variable frequency power source is too burdensome for a field test. Besides, even in those cases where variable frequency power can be provide, this appears to be an unnecessary burden. Moreover, adjustment to rated frequency is not required when the reduced voltage, no load procedure is used. This reasoning leads to the selection of the reduced voltage, no load procedure as the preferred impedance procedure for the field version of Method F1.

Thus, the version of Method F1 believed most suited to field use requires volts, watts, amperes, slip, stator winding temperature or stator winding resistance to be measured at two values of line voltage while operating at no load. In one case measurements are made at rated voltage while operating at no load. In the other case measurements are made while operating at no load with the voltage reduced until slip is equal to that obtained at the normal operating load. The IEEE Standard 112 (98) cautions that slip must be measured very carefully during this procedure.

Once these measurements are made an iterative procedure is used to determine the parameters of the equivalent circuit. This iterative procedure requires one to either know the design value of the ratio X_1/X_2 or to use the standard NEMA design value[6]. The proper value to use depends on the design

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[6] All of the impedance procedures of Methods F and F1 require one to know or assume a value of X_1/X_2

class of the motor being tested. The equivalent circuit is then used to compute the losses and efficiency of the motor being tested.

As shown by the Ontario Hydro study (95) Method F1 can provide an accurate estimate of efficiency if performed carefully. It offers a number of other advantages. As noted by Cummings, Bowers, and Martiny (19) Method F1 is particularly useful when it is not possible to test the machine under load. Also, the equivalent circuit can be used according to IEEE Standard 112 (98), Method C/F, E/F or E1/F1 to determine efficiency at loads other than the ones used to determine the equivalent circuit parameters. Cummings, et al conclude, "Method F, with a standardized value of stray-load loss, is essentially no more complex than JEC Standard 37 and can easily be specified by any purchaser who desires an efficiency determination with a good degree of confidence at minimum test cost".

On the other hand Method F1 has a number of weakness:

(1) One must know or assume a value for X_1/X_2. As noted in the Ontario Hydro study (95) additional errors will occur in the calculated values of motor losses and efficiency if the assumed ratio of X_1/X_2 is erroneous, but usually the user will be working with NEMA design motors which have well defined X1/X2 ratios.

(2) Both a rated voltage, no load test and a reduced voltage, no load test must be run. In turn, this requires one to obtain and connect a variable voltage power source to the motor being tested.

(3) As is true for Method E1 the motor must be disconnected from its load.

(4) An assumed value for stray load losses must be used from IEEE 112 Section 5.4.4.

Criterion	Comment
Invasiveness	Method F1 requires the tested motor to be disconnected from its load and connected to a source of variable voltage. In most circumstances in the field this would be quite disruptive to normal operation of the system to which the motor is connected. Hence, like IEEE Standard 112, Method E1 (98), this method has the lowest invasiveness rating (D).
Economy	Because of the need for a variable voltage power supply, this method is expensive and time-consuming. Thus a rating of (D).
Portability	The portability of method F1 is determined primarily by the portability of the variable power source and its associated hardware. This, in turn, depends on the size of the motors being tested.

However, except for small motors, this equipment is cumbersor (D).

Durability

Most of the equipment used with Method F1 is quite durable. B again, the variable voltage power source largely determines t durability rating of Method F1. Frequent damage to this equipme seems likely as it is transported from site to site and connected a disconnect to the motors under test (C).

Dependability

Method F1 is one of the recognized standards for efficiency te within the United States. If performed correctly with prop equipment, it should yield very reliable results. Of most conce regarding dependability is whether the measurements can be made the field with the accuracy required by this method. If so, then t iterative procedure of Method F1 should yield dependable measur of the equivalent circuit parameters (A). An accurate equivale circuit permits one to accurately determine motor efficiency and oth motor characteristics.

User Friendliness

The computation of Method F1 can be easily performed on a persor computer so this is not a significant handicap. Therefore, once agai the need to obtain and connect a variable voltage source and disconnect the motor from its load are the primary determinates Method F1's rating (C).

Accuracy

Method F1 is one of the most accurate tests for motor efficiency (A Its negatives in this regard derive primarily from its treatment of str load loss. The IEEE Standard 112 (98) values in Table 1 close agrees with ANSI Standard C50.41-1982. Therefore, these valu certainly represent the consensus judgement of experts on inducti motor losses. Nevertheless, in a particular instance, the standa value may be quite erroneous. Please see the comments under t **Accuracy** section of Method E1 above for further discussion of tl problem. The comments there are equally applicable to Method (A).

Human Safety

Testing machines under high stress while connected to high volta offers a number of hazards to the humans involved. Hazar particular to Method F1 derive from the need to change the inp power source and the output load connections (C).

Equipment Safety

The comments made for Human Safety are applicable here (C).

10. **Ontario Hydro's Simplified Method F1**--A modified version of the IEEE Standard Method F1 (98) is outlined in the Ontario Hydro study (95).

A no load test and a full load test, both at rated voltage must be run. In turn, this requires one to disconnect the motor being tested from its load. Line voltage, input power, line current, power factor, and stator line resistance at load temperature are measured while operating at no load and at full load, i.e. the normal operating load of the motor. The slip is also measured at full load.

This method eliminates the need for a variable voltage as required by IEEE Standard 112, Method F1 (98).

The equivalent circuit used by this method is slightly different from that of Method F1. In this version of the equivalent circuit the impedance elements of the magnetizing branch are shown in series while that of Method F1 is shown in parallel. This simplifies the no load version of the equivalent circuit as shown in (95).

Input data is used in an iterative procedure to determine the parameters of the equivalent circuit. This iterative procedure is different from the one used by Method F1.

This method ignores the friction and windage losses and the stray load losses. The method may be modified slightly to estimate these losses in a way similar to that used by Method F1. However, the Ontario Hydro study reported the surprising results that, during tests of a 100 hp, 1800 rpm motor, the method gave an estimate of efficiency within 0.7 percent of that from a dynamometer test. Logically one would expect that this method would be improved by including the excluded losses. However, in face of the these reported results, perhaps this is an area needing further investigation. In any event, if an estimate of stray load losses is used, this must be based on a standard value similar to IEEE Standard Method F1 (98).

Resistances and slip are not adjusted to a specified temperature as required by IEEE Standard 112 (98).

Criterion	Comment
Invasiveness	Ontario Hydro's Simplified Method F1 eliminates the requirement to connect the motor to a source of variable voltage during the full load test. This modification greatly reduces the invasiveness and increases the user friendliness as compared to the standard Method F1. However, it is still necessary to disconnect the motor from its load to perform the no load test. In some circumstances in the field this would be quite disruptive to normal operation of the system to which the motor is connected. This is exactly what is required by Hirzel's Modified Method E1. Also, the same measurements are made in

these two methods. Thus, this method receives the same medium invasiveness rating received by Hirzel's method (C).

Economy	Because ordinary power and speed measuring equipment are used, the cost of the test equipment would not be a negative, but disconnecting the motor from the load could at times be a significant economic problem (C).
Portability	For the reasons discussed under invasiveness, the portability of the Ontario Hydro Method F1 is greatly improved over that of the standard Method F1. As noted above, the portability of the standard method is largely determined by the portability of the variable power source. Because this special equipment is not required for the Ontario Hydro method, it has earned the best portability rating (A).
Durability	All of the equipment used with the Ontario Hydro Method F1 is standard equipment and ought to be quite durable. Thus, the durability rating of this method is the best (A).
Dependability	The exact dependability of the Ontario Hydro Method F1 is open to some question. However, it is a modified version of a recognized standard for efficiency tests within the United States. If performed correctly with proper equipment, it should yield very reliable results (B).
User Friendliness	The computations of the simplified Method F1 are about as complex as the standard method. In any event, either can be performed on a personal computer so these computations are not a significant handicap. The only significant burden this method places on the user is the need to disconnect the motor from its load. Therefore, this method receives a medium rating for user friendliness (B).
Accuracy	Like the standard Method F1, the simplified version is, perhaps, one of the more accurate tests for motor efficiency (B). If the simplified method is modified to account for core losses accuracy may be somewhat improved.
Human Safety	Testing machines under high stress while connected to high voltage offers a number of hazards to the humans involved. There are no hazards particular to the Ontario Hydro modified Method F1 (B).
Equipment Safety	The comments made for Human Safety are applicable here (B).

Two Rotor Equivalent Circuit Methods--The next two methods are based on an equivalent circuit that differs from the standard equivalent circuit of Figure 2. As shown in Figure 4, the revised equivalent circuit adds a second rotor loop.

11. **Locked Rotor Method**--A. Dell' Aquila, L. Salvatore, and M. Savino (20) present a procedure that uses two locked rotor tests to determine the parameters of an equivalent circuit with two rotor loops. An alternative procedure is to use a single locked rotor in conjunction with a load test to determine these parameters. In both cases a no load test must also be run. With these parameters in hand they then develop a method for computing the efficiency of the motor from the equivalent circuit relationships.

Their method is based on the equivalent circuit shown in Figure 4. The authors simplified their circuit by moving the resistance r_c to the input side of the stator reactance X_1. To reduce the number of parameters that must be determined the authors further simplified their equivalent circuit to that shown by Figure 5. The authors point out that the circuits of Figures 4 and 5 give the same results if, and only if, the impedance within the parts of the circuits to the right of points A and B are equal. The authors derive a set of equations that must be satisfied to assure these impedances are equal. These equations show it is possible to compute the parameters of the circuit in Figure 5 if the parameters of Figure 4 are known.

The following tests are conducted to determine the parameters of the equivalent circuit and friction and windage losses. There is no load at rated voltage, no load with voltage reduced to give normal operating slip, and a locked rotor test with reduced voltage and full load current. Once the equivalent circuit parameters are determined, an adaptation of IEEE Standard 112, Method F1 (98) is used to determine the losses, power output, and efficiency of the motor. The authors do not clearly explain their procedure. However, such an adaptation ought to be straightforward.

Two Rotor Loop Method--The advantages of this method are:

(1) The procedure for determining parameters of equivalent circuit is not iterative like that of Method F1. Hence, computations are simpler. With widespread availability of personal computers, this is only a small advantage.

(2) It does not require one to know or assume a value for the ratio X_1/X_2 of primary reactance to secondary reactance as does Method F1 and the other equivalent circuit methods discussed previously.

(3) According to the authors, the two reactor loop equivalent circuit represents double-cage and deep-bar rotor motor better than the single rotor loop equivalent circuits. Also, the two-loops model represents the single cage motor better over a wider range of loads or slips, according to the authors. Determining efficiencies at loads other than the ones used to determine the

equivalent circuit parameters is easily done with the two rotor loop circuit. No additional tests at these other loads are required.

(4) The two-rotor-loops circuits represents the motor better under non-sinusoidal applied voltage.

(5) The two-rotor-loops circuit can be used in other types of analysis, such as for determining breakdown torque.

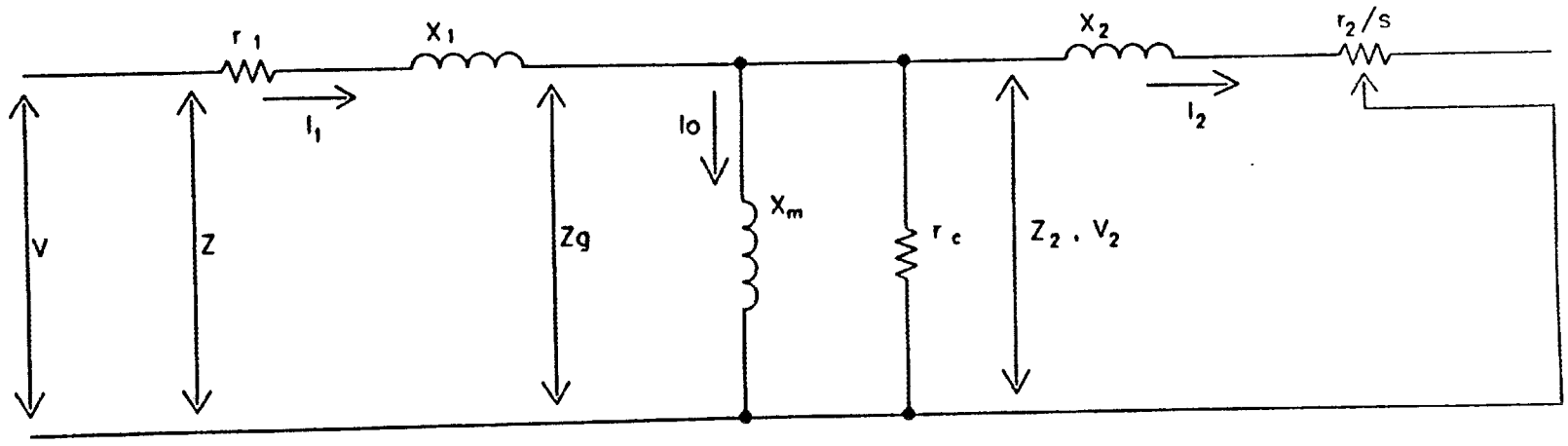


Figure 2. IEEE Standard 112 Equivalent Circuit

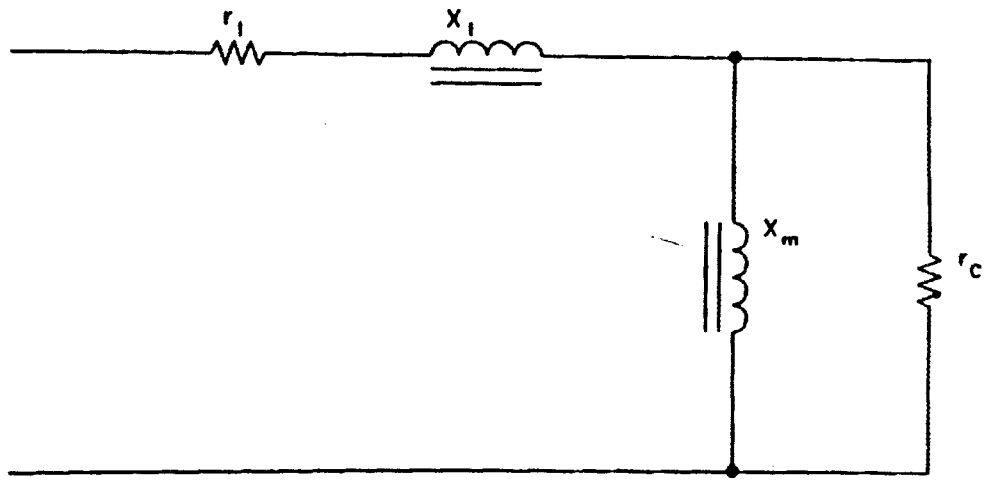


Figure 3. Standard Equivalent Circuit of Motor at No Load

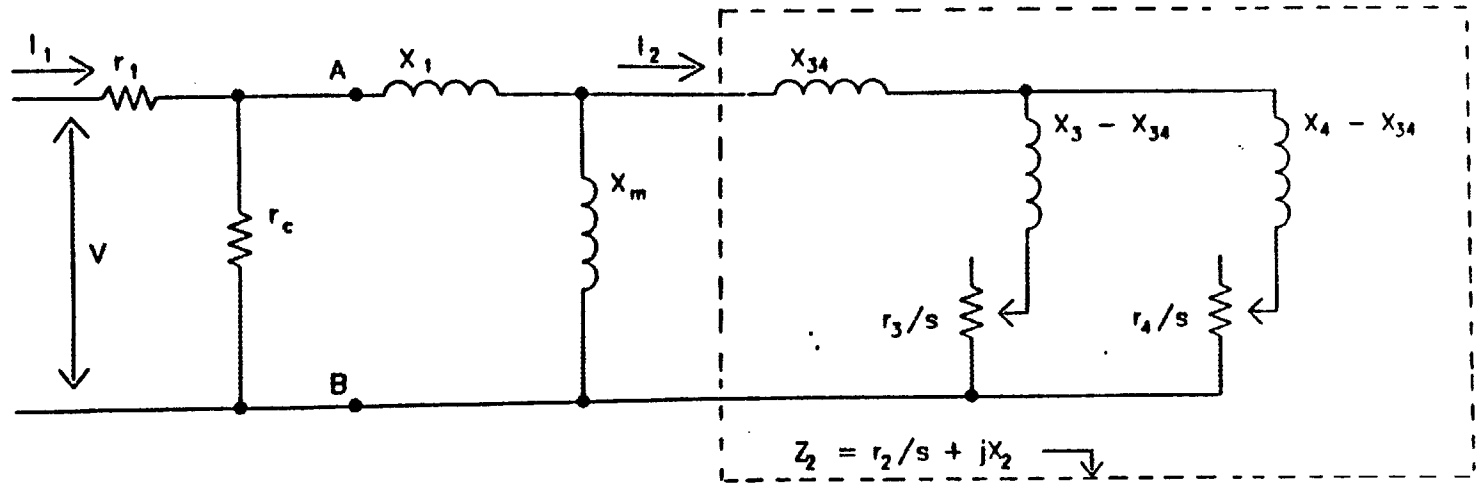


Figure 4. Two Rotor Loop Equivalent Circuit for Induction Motor

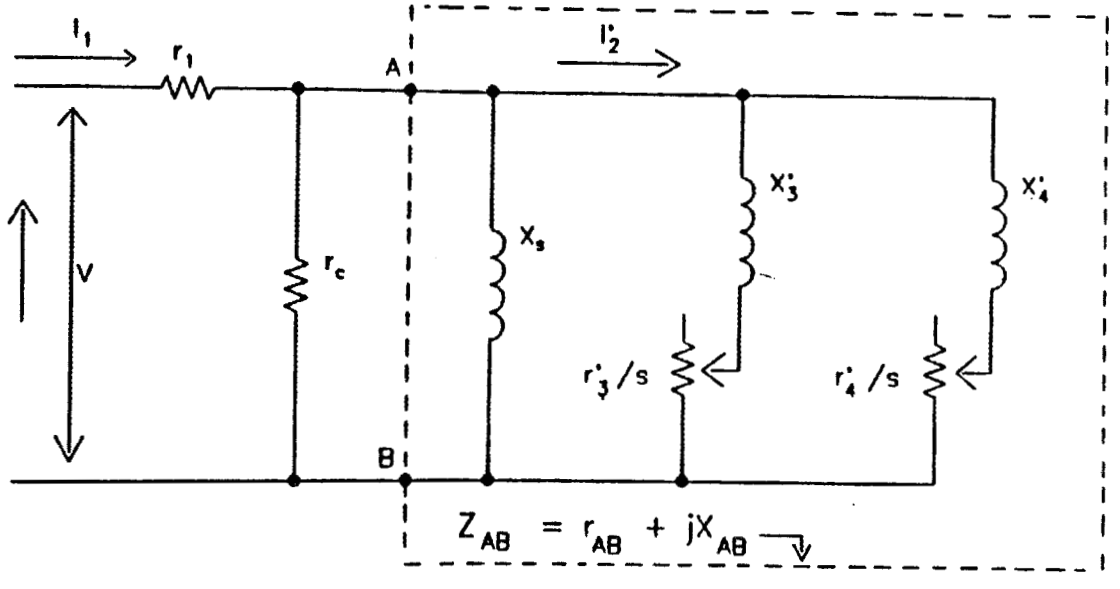


Figure 5. Reduced Equivalent Circuit with Two Rotor Loops

This method has two principal disadvantages.

(1) It requires a complete no load test as specified by IEEE Standard 112 (98). This, in turn, requires the motor to be connected to a variable voltage power source. Taking a lead from several of the other methods, it may be possible to simplify Dell' Aquila, et al's method by only running the no load test at rated line voltage. However, this makes it impossible to separate friction and windage losses from cone losses. Thus, this simplification may cause errors in the values of the equivalent circuit parameters and the motor efficiency.

(2) In addition to the no load test, the locked rotor method requires either two locked rotor tests at two distinct frequencies, or a locked rotor test at rated frequency, plus a test at normal operating load. The two locked rotor tests require connecting the motor to a variable frequency source. This is too massive and user unfriendly for a good field test. Therefore, we assume the equivalent circuit impedance will be determined within the locked rotor and normal load tests.

The authors reported the results of a comparative test that uses one 18.5 kw motor operating at eight loads. The efficiency obtained from their method agreed very well with the efficiencies obtained from dynamometer tests performed according to IEEE Standard 112, Method B (98).

Criterion	Comment
Invasiveness	This method is even more invasive than the standard Method F1 because it requires a locked rotor test as well as a variable voltage power source for the motor. It also requires the motor to be disconnected from its load to perform the no load test (D).
Economy	The economy of this method would be rated as very poor because of the need to perform extensive loading tests at various voltages and frequencies (D).
Portability	The comments made for Method F1 regarding portability are applicable to the locked rotor method (D).
Durability	The comments made for Method F1 regarding durability are applicable to the locked rotor method (C).
Dependability	The locked rotor method should be at least as dependable as method F1. The comments there are applicable here (A).
User Friendliness	This method is not user friendly because it requires a no load test, as

	well as a reduced voltage locked rotor test. It is only somewhat more user friendly than the standard method E1 (C).
Accuracy	The comments regarding accuracy under method F1 are applicable here. We rate the locked rotor methods somewhat better than the other equivalent circuit methods because it appears to give accurate efficiencies over a range of loads without additional tests. We would predict accuracy within 1% (A).
Human Safety	The comments made concerning human safety under method F1 are applicable here. However, the locked rotor method has the extra safety hazards associated with the locked rotor tests. In the field environment these hazards may be formidable (C).
Equipment Safety	The need for testing at various voltages and frequencies plus the locked rotor test raises the concern of potential equipment damage (D).

12. ORMEL96--A method which finds the motor's equivalent circuit using only nameplate data. This method was developed by Dr. P. J. Otaduy at ORNL.

ORMEL96 models a motor using a modified version of IEEE's Std 112 equivalent circuit. ORMEL96 inserts a parasitic resistance in the rotor circuit to account for stray load losses. In addition, friction and windage losses are incorporated into the computation of the equivalent circuit so that the calculated power output for rated voltage and speed matches the rated power output value.

This method uses the motor's nameplate data, standard values for X1/X2, stray load, friction and windage, and locked rotor current, and a stator resistance estimator to compute the equivalent circuit of a motor. In the field, only a measurement of rotor speed is required to obtain the load and efficiency of a running motor.

Since the values on a motor's nameplate are representative of a class of motors and thus are not guaranteed to be those of a specific motor, two modes of operation are available in ORMEL96: Basic and Advanced. The mode of operation is selected by clicking on a switch in the display screen. In the basic mode of operation the user can only change values shown in the "Nameplate Data" screen. In the advanced mode, the user can change values in the so called "Interactive Tunable Parameters" screen. This tunable screen shows the specific values the program is using to build the equivalent circuit of the motor. These values are a composite of those in the nameplate screen and those derived from standard practice and the resistance estimator. If the user has information that improves on any of the values in the tuning screen then the Advanced mode should be selected.

Measured speed data (rpm) are entered in a third screen in which "Results" are collected. For every speed entered by the user, the corresponding efficiency, load factor, and total losses are shown. The

user can in addition select viewing a breakdown of the total losses in its classic components - stator, rotor, core, stray, and friction and windage - in both absolute magnitude or percentage of losses. All values in the results screen are updated automatically as soon as a parameter is changed in the active screen (NamePlate screen in the Basic mode and Tunable screen in the Advanced mode). This allows, for instance, interactive adjustment of the stray loss until the core losses amount to some percentage (i.e., 25%) of the total losses. Similarly, the user can study the sensitivity of any output quantity to changes in any parameter in the active screen. A "Pause" button allows the user to change groups of parameters between recomputations. In addition, a "Database" button allows saving and restoring name plate data as well as time-stamped records of the rest of the data in the screens.

Criterion	Comment
Invasiveness	This low invasion method uses name plate data to construct an equivalent circuit of the motor. In the field, only a measurement of rotor speed is required. As an option, the program allows the user to enter additional design, and/or measured motor data to improve the characterization of the equivalent circuit. The invasiveness level would go up if measurement of optional motor data is conducted in the field (A).
Economy	Speed determination does not require expensive equipment other than a low invasive tachometer or strobe light (A).
Portability	Speed measurement only requires a tachometer. The portability should be good. The user should be able to judge the portability when additional motor data are collected in the field by the user (A).
Durability	Tachometers should be quite durable (A).
Dependability	The basic mode is dependent on the accuracy of the nameplate data and the estimates of friction and windage and stator resistance. These estimates are, however, not critical if the nameplate power, voltage, speed, current and power factor (or efficiency) are reasonably accurate for the motor of interest. The advanced mode facilitates accurate characterization of the motor's rated parameters (C).
User Friendliness	The software for this method is available and is user friendly. The program has two modes of operation: Basic and Advanced. The mode is selected by clicking on the screen. In the basic mode the user has access to the nameplate data and can view the values in the interactive tuning screen. Access to the interactive tuning screen is only possible in the advanced mode. In both modes the user must first enter the nameplate data for the motor of interest (A).

Accuracy	In a field trial of fifteen motors the average accuracy is ±3 percentage points of efficiency for motor loads from 25 to 100% of rated capacity. The typical accuracy for motors that fit their nameplate data is ±1% (C).
Human Safety	This method is safe because no physical contact with the motor or wiring is required. Additional hazards may be present when optional motor data are measured (A).
Equipment Safety	The comments made for Human Safety are applicable here (A).

3.3.3 Slip Methods

An interesting and well known result from induction motor theory is that slip is directly proportional to load. This linear relationship has been exploited by practitioners to develop simple field methods for measuring motor efficiency. The methods discussed in this section represent the usual forms of the slip methods found in the literature.

13. **Standard Slip Method**--Only four data elements are needed to estimate motor efficiency with the standard slip method. Two of these data elements, the power and slip at the rated load, are obtained from manufacturer's data. These data elements are often found on the motor nameplate. The standard slip method is not useful if these data elements are not available from the manufacturer or some other source separate from the field test. The other half of the data is obtained with field measurements of slip, i.e. rotational speed, and input power while the motor is operating at its normal operating load. (Slip varies with the temperature of the motor rotor). With these four data elements in hand the operating efficiency of the motor can be quickly and easily estimated using the following relationship:

$$Efficiency = \frac{746 * hp_r * s}{P_i * s_r}$$

As noted in an Ontario Hydro study (95), the main attraction of the standard slip method is its simplicity. However, several authors, e.g. (2), (37), (59), and (95), have observed that the accuracy of the method suffers badly from several causes. Nailen (59) and the Arizona Department of Commerce Energy Office (2) provide an excellent discussion of the drawbacks of the slip methods particularly the standard slip method. One of the major problems is that the nameplate speed is allowed to deviate as much as 20% from the actual rated speed by standard NEMA MG1. An

estimate of the magnitude of the inaccuracy of the method is provided by the Ontario Hydro study. This study found that in an efficiency test of 11 identical motors the procedure gave a worst case error of over 16 percent. The Ontario Hydro study concluded, "... the significant errors which can result from use of this procedure, limits the test method to applications where only a crude estimate is required." The scale of these inaccuracies is supported by the Arizona Department of Commerce Energy Office (2) which found that the slip method can differ from dynamometer results by over 40 percent.

Criterion	Comment
Invasiveness	The standard slip method requires only the availability of certain manufacturer's data and field measurement of input power and slip at the normal operating load of the motor being tested. In most cases these measurements can be made without unduly disrupting normal operations. Therefore, the invasiveness of this method is rated good (B).
Economy	Although the method is quite non-invasive, it's probability for gross-error renders it a poor economic selection because the results have so little value (C).
Portability	The portability of the standard slip method is determined by the portability of the instruments used to measure input power and motor speed. Such instruments are quite portable (A).
Durability	The comments made for portability are equally valid here (A).
Dependability	Like all the slip methods, the dependability of the standard slip method is determined in large measure by the availability and dependability of the manufacturer's data. Of course the dependability of the slip methods is also determined by the accuracy of the field measurements. In particular, the rotational speed must be measured very carefully. As noted above, the cited references explain that there are several reasons why these data elements may not be dependable enough to serve as the basis of a good field test for efficiency. This is discussed further in the descriptions of the other slip methods (C).
User Friendliness	The standard slip method is very user friendly if one assumes the manufacturer's data can be obtained without undue difficulty (A).
Accuracy	As noted in the discussion above, the standard slip method offers only a crude estimate of motor efficiency. This is discussed further

in the descriptions of	the other slip methods (D).
Human Safety	There are no unique hazards associated with the standard slip method. The tests required of this method ought to be accomplished without undue risk to personnel trained in making power measurements (B).
Equipment Safety	The comments made for Human Safety are applicable here (B).

14. **Ontario Hydro's Compensated Slip Method**--One of the drawbacks of the standard slip method mentioned above is the effects that voltage variation has on the method. At a given slip the output power of a motor is proportional to the input voltage squared. Thus, when the operating voltage of the motor differs from the rated voltage used during the manufacturer's efficiency test the output power computed with the standard slip method will be in error. The magnitude of this error grows rapidly as the difference between the two voltages increases. To gain an improvement over the standard slip method the Ontario Hydro study (95) offers a method that compensates for voltage.

The Ontario Hydro's compensated slip method is the same as the standard slip method with two exceptions: two more data elements are required and the efficiency equation is revised. The additional data elements are the rated or nameplate voltage used during the manufacturer's test and the normal operating voltage. The former is additional information that must be provided by the manufacturer or another source external to the field test. The latter is another measurement that must be made during the field test. The revised efficiency equation is:

$$Efficiency = \frac{746 * hp_r * s}{P_i * s_r} * \left[\frac{V}{V_r}\right]^2$$

Unfortunately, even with this voltage compensation the slip method can provide unsatisfactory accuracy. During the Ontario Hydro study the efficiencies of eleven motors, varying in size from five to a hundred horsepower, were determined using their compensated slip method, while the test input voltage was held equal to the manufacturers' nameplate voltage. Nevertheless, the calculated efficiencies were drastically different from efficiencies determined with dynamometer tests.

Although not reported in the Ontario Hydro study, a simple linear regression test shows that the efficiencies determined by the compensated slip method are not correlated with rated horsepower. On the other hand, there is a strong, statistically significant correlation between the efficiencies determined by the dynamometer method and the rated horsepower. Furthermore, as expected, the slip efficiencies are not correlated with the dynamometer efficiencies. The mean of the slip efficiencies is 14 percent higher than the dynamometer ones and the standard deviation of the former is about five times greater than that of the latter. The Ontario Hydro study summarizes these

observations succinctly, "Even under these ideal conditions the error resulting from calculation of efficiency from nameplate RPM is unsatisfactory."

Criterion	Comment
Invasiveness	Like the standard slip method this compensated method requires the availability of certain manufacturer's data and field measurement of input power and slip at the normal operating load of the motor being tested. The compensated method also requires the measurement of the input voltages. In most cases these measurements can be made without unduly disrupting normal operations (B).
Economy	This method is again not considered to be a good economic selection because the results are unreliable (C).
Portability	The portability of the standard slip method is determined by the portability of the instruments used to measure input power and motor speed. Such instruments are quite portable (A).
Durability	The comments made for portability are equally valid here (A).
Dependability	Like all the slip methods, the dependability of the Ontario Hydro's compensated slip method is determined in large measure by the availability and dependability of the manufacturer's data. Of course the dependability of the slip methods is also determined by the accuracy of the field measurements. In particular, the rotational speed must be measured very carefully. As noted above, the cited references explain that there are several reasons why these data elements may not be dependable enough to serve as the basis of a good field test for efficiency (C).
User Friendliness	The compensated slip method is very user friendly, if one assumes the manufacturer's data can be obtained without undue difficulty (A).
Accuracy	As noted in the discussion above the standard slip method offers, at best, only a crude estimate of motor efficiency (D).
Human Safety	There are no unique hazards associated with the standard slip method. The tests required of this method ought to be accomplished without undue risk to personnel trained in connecting such metering (B).

Equipment Safety The comments made for Human Safety are applicable here (B).

15. **Slip Upper Bound Method**--Guru and Hiziroglu (31) derive one of the most intriguing efficiency methods. They show that the efficiency of an induction motor is bounded above by:

$$Efficiency \leq (1 - s)$$

This is the ultimate in simplicity, for as Nailen (59) notes, "Of all the conditions observable in an operating motor drive, the two most easily and accurately measurable are temperature and speed." One only needs to measure the normal operating speed and to know the synchronous speed to use the upper bound method. There is a price to pay, however. To test this method, we computed an upper bound for the efficiencies of the eleven motors discussed under Ontario Hydro's compensated slip method. As ought to happen, for each motor in this set, the Guru and Hiziroglu upper bound is greater than the dynamometer determined efficiency. This is not true for the efficiencies determined by the compensated slip method. The price paid for this simplicity is that the average upper bound is 98.0 percent while the average dynamometer efficiency is 90.7 percent. The standard deviation of the upper bounds are about one-fourth of the standard deviation of the dynamometer efficiencies. In most cases, such a large difference will make the upper bound useless for economic comparisons of competing motors.

Guru and Hiziroglu assume that stator losses are zero to arrive at their upper bound. As shown in Figure 1, stator losses are about 40 percent of total losses in the typical motor. Therefore, an upper bound that includes these losses may be more useful in economic comparisons. Such a bound is given by:

$$Efficiency \leq (1 - s)\left[1 - \frac{1.5 I^2 R_f}{P_i}\right]$$

The penalty for using this upper bound is that three more operating parameters of the motor must be known or measured. This bound is certainly not as elegant as Guru and Hiriroglu's upper bound. The usefulness and reliability of this new upper bound is a subject that needs further research.

It is possible that each of these upper bounds may be improved empirically. Referring again to the eleven motors of the Ontario Hydro study, we found that the Guru and Hiriroglu upper bounds are strongly correlated with the dynamometer efficiencies. Most of the variance between these measures is explained with a simple linear model. The upper bounds are also less strongly correlated with the rated output power. It seems likely that an empirical relationship can be determined that adjusts the

above upper bounds closer to the actual motor efficiency while remaining a valid upper bound. This is an area that needs further investigation.

Criterion	Comment
Invasiveness	This method is about as un-invasive as a method can be. All that is required is a measure of the motor speed (A).
Economy	Because of the relative inaccuracy of this method, it would not make good economic sense to use it in spite of its low level of invasiveness (C).
Portability	The portability of the standard slip method is determined by the portability of the instruments used to measure motor speed. Such instruments are quite portable (A).
Durability	The comments made for portability are equally valid here (A).
Dependability	The upper bound is guaranteed to be greater than the actual efficiency so the method is very dependable. Unfortunately, this is not to say that the method is highly useful. That is an area requiring further study. It is necessary that the rotational speed be measured very carefully. For this reason the upper bound is not given the best rating (C).
User Friendliness	The slip upper bound method is very user friendly (A).
Accuracy	As noted in the discussion above, the slip upper bound method appears to offer estimates of efficiencies that are too conservative (D).
Human Safety	There are no unique hazards associated with the standard slip method. The tests required of this method ought to be accomplished without undue risk to personnel. This method is slightly less dangerous than the standard slip method because only the motor speed must be measured (A).
Equipment Safety	There should be no concern for equipment safety because only a non-contact stroke light is needed. (A)

16. **Motor Master+**–Motor Master+ offers three optional methods of operation - slip, current, and input power. Each method uses an empirical or statistically based motor load and efficiency estimation approach that makes use of nameplate information plus available measured power (kW) or voltage, slip, amperage, and power factor values. When kilowatt or power factor readings are supplied, an iterative approach is used to determine motor load

and efficiency values which are consistent with the measured input power values. The initial load estimates is determined as:

$$Load\ Estimation = \frac{Measured\ Input\ kW}{(Nameplate\ Output\ kW / Nameplate\ Full\ Load\ Efficiency)}$$

With the load estimate known, MotorMaster+ searches for the motor operating efficiency at that load point. Three part-load efficiency curves (energy-efficient, intermediate or standard) exist for each motor horsepower, speed, and enclosure class. Open or closed motors in the 1 to 600 hp size range and with synchronous speeds between 900 and 3600 RPM are covered.

"Industry Average" energy efficient motor performance is approximated through interpolation with the average performance of all motors in a selected hp-speed-enclosure class which exceeds the minimum efficiency standards expressed in NEMA MG1-Table 12-10. Standard efficiency motors are those falling below the old NEMA Table 6-B (or 12-9). "High" efficiency motors are in-between. Motors are automatically assigned to an efficiency versus load curve based on the full-load efficiency value stamped on their nameplate. If no nameplate information is available, the motor is assumed to be a standard efficiency motor.

The initial load estimate is used in conjunction with the appropriate load versus efficiency curve interpolation to obtain the efficiency at the indicated load point. The motor load is then recalculated (input kW times lookup table efficiency at the load point divided by the full-load kilowatt draw) and a new efficiency at this load point obtained. The process is repeated until convergence occurs and a load-efficiency pair consistent with the measured kilowatt draw of the motor is obtained.

Below 25 percent load, the candidate motor efficiency relationship is approximated as load divided by load plus losses at 25 percent load for the motor class under consideration. Given that line currents are about the same at the idle and 25 percent load points, losses below 25 percent load, including I^2R losses, are represented as fixed. A motor load and efficiency pair consistent with measured kilowatt values are again selected.

For rewound motors, MotorMaster+ deducts 2 efficiency points for motors less than or equal to 40hp, and one point for larger motors. The deduction occurs within the convergence routine such that a lower efficiency/higher load pair is produced, again replicating the measured power draw measurements.

While the technique accuracy is unknown, it should be best for larger, un-renewed motors, operating in the higher load ranges. Accuracy is reduced and uncertainty increases for smaller sized motors and at lower motor loads.

When kilowatt readings are not available, MotorMaster+ uses a conventional voltage corrected amperage or slip technique to estimate motor load. Efficiency at load point values are again plucked

from the appropriate empirical motor efficiency versus load curves. Rewind losses are assigned; howver, convergence to a measured kilowatt value is not possible. The amperage technique becomes increasingly suspect at loads below 40 percent due to non-linearity or flattening of the amperage versus load curve.

Criterion	Comment
Invasiveness	Motor Master+ provides three data collection options, namely: the input power, the current, and the slip approaches. Both the current and the slip approaches are low invasion approaches. The input power approach requires measurements of voltages and currents. The currents can be measured by a low invasion clamp-on meter, but the voltage measurements need to tap on to the terminal connections inside the conduit box (slip (A), current (A), power (B)).
Economy	The slip and the current approaches do not require expensive equipment other than a tachometer or a current probe. The input power approach is somewhat more expensive (B). Both the slip and current methods are inexpensive (A).
Portability	The portability of either a power meter , tachometer, or a current probe is good (A).
Durability	All the meters used should be quite durable (A).
Dependability	Motor Master+ has certain statistical data stored in the computer program. A few efficiency estimations may have larger deviations from the actual values. However, the overall dependability should be improved with the assistance of statistical data. The power method should be significantly more dependable (slip (C), current (C), power (B)).
User Friendliness	The Motor Master+ computer program is user friendly (A).
Accuracy	Accuracy of either current, slip, or input power approach without an adjustment from the statistical data is known to be low. The overall accuracy for motors that fit the samples of the statistical data should be improved (slip (C), current (C), power (B)).
Human Safety	Both the current and the slip approaches are safe. The input power approach is somewhat less safe due to the need to attach the voltage probes (slip (A), current (A), power (B)).

Equipment Safety	The comments made for Human Safety are applicable here; extra risk is involved in making current and voltage measurements (slip (A), current (B), power (B)).

3.3.4 Current Method

17. **Current Method**. The current method is another approach that uses a minimum of field measurements in conjunction with manufacturer's data to estimate motor efficiency at normal operating loads. Like the slip methods, the main attraction of the current method is its simplicity. In its basic form the current method estimates efficiencies as

$$Efficiency = \left(\frac{I}{I_r}\right)\frac{746hp_r}{P_i}$$

Also like the slip methods, the current method requires two parameters from manufacturer's data and two from field measurements. Of course, if the manufacturer's efficiency versus load curve is available only operating current must be measured.

Hsu, et al (37) and Nailen (59) summarize the advantages of the current method:

(1) The NEMA Standard MG1-12.47 permits only half the tolerance in name plate full load current as it does full load slip.

(2) Variations in input voltage affects current linearly but slip varies with voltage squared.

(3) Current is not directly related to temperature.

(4) Motor current measured by a clamp-on probe has a low intrusion level.

The disadvantages of the current method are:

(1) The tolerance allowed by the NEMA Standard causes uncertainty regarding the accuracy of the method.

(2) The manufacturer's data, if it is still available, may no longer apply because of repair performed on the motor.

(3) Most importantly, current, unlike slip, does not vary linearly [illegible] because there is a magnetizing current even when the motor is operating at no load.

In an effort to improve the current method, Nailen (59) investigated a method that corrects for the nonlinear current-load relationship. It is based on the following estimate of efficiency:

$$Efficiency = \left[\frac{2I - I_n}{2I_r - I_n}\right]\frac{746hp_r}{P_i}$$

However, one is not guaranteed improved results, for Nailen gives an example where this method does not provide better estimates than the simple current method. Also, this model requires one to measure the no load current or obtain it from manufacturer's data. Hsu, et al suggest that for the current, or the slip methods, to provide accurate results, the manufacturer's data should include data at motor loads of 50, 75, and 100 percent of full load.

Perhaps the best use of the current method is that it may give an empirical upper bound on efficiency. The Washington State Energy Office (67) reported that in an extensive analysis, using their Motor Masters' library, the current method overestimates motor loads by 10 to 20 percent. Such overestimates mean the efficiency estimate provided by the current method will be larger than the true efficiency. This is an empirical upper bound unlike those based on slip discussed above. Those are based on induction motor theory. Nevertheless, the Washington State study shows that, for a large number of motors, this bound is rarely exceeded and then not by much. Unfortunately the range between motors is large.

Criterion	Comment
Invasiveness	Like the standard slip method, the current method only requires two parameters from manufacturer's data and input line current and power from field measurements (B).
Economy	Because of the low accuracy of the current method, the estimate is not valuable, even considering the low invasiveness (C).
Portability	The portability of the current method is determined by the portability of power meters and current meters and, perhaps, current coils. Such instruments are quite portable (A).
Durability	The comments made for portability are equally valid here (A).

	Dependability
The current method may be better than the slip method, but the method appears to	dependably give an estimate that is almost always greater than the true efficiency (C).
User Friendliness	Like the slip methods, if the manufacturer's data is available and still applicable, then the current method is very user friendly (A).
Accuracy	As discussed above, the current method provides only a crude estimate of efficiency that is reported to be greater than the true efficiency (C).
Human Safety	There are no unique hazards associated with the current method. The tests required by this method ought to be accomplished without undue risk to personnel (B).
Equipment Safety	The comments made for Human Safety are applicable here. The current method appears to offer even less hazard to equipment than it does to personnel (B).

18. **Motor Master+**--MotorMaster+ offers three optional methods of operation , slip, current, and input power. The complete discussion is found at number 16.

3.3.5 Air Gap Torque Method

19. **Air Gap Torque Method**. Hsu, Scoggins, and Sorenson (37) have proposed a new field method based on well known air gap equations for determining motor efficiency. The method uses measurements of instantaneous input line voltages and line current and a set of integral equations to compute the average air gap torque. The authors note that the data required by the method can be quickly obtained with an inexpensive personal computer system. Furthermore, this same personal computer can be programmed to quickly solve the air gap equations with numerical integration routines. Once the air gap torque is obtained the efficiency is computed by

$$Efficiency = \frac{(Air\ gap\ torque)\cdot 2\pi\left(\frac{rpm}{60}\right) - W_f - Rotor\ stray\ load\ losses}{P_i}$$

The advantages of the method are:

(1) Air gap torque method has a certain advantage over method E1 when the supply is unbalanced and contains harmonics (37).

(2) Air gap torque can be measured while the motor is running.

(3) Unlike any other method discussed in this report, the air gap torque method can be used when the phase powers are unbalanced.

(4) This method can be used for non-induction motors such as the adjustable speed, brushless dc motors.

The major disadvantages of the method are:

(1) No load test is required.

(2) Specialized equipment and training will be required to conduct the field measurements.

(3) Based on Hsu, et al's reported test results, the method appears to need further development to achieve a desirable level of accuracy.

Lipo and Moreira (79) have patented a method of measuring air gap flux using stator third harmonic voltage waveforms. The claims of this patent are directed toward optimizing the control of variable voltage and frequency alternating current machines. However, it is likely that Lipo and Moreira's method can be adapted to create a new field method for measuring motor efficiency. This is an area requiring further research.

Criterion	Comment
Invasiveness	The air gap torque method only requires a sample of input line voltages and currents. Such measurement can be made in most cases without disrupting normal operations. The method, as presently conceived, requires a no load test (C).
Economy	The method appears to provide valuable information with only moderate invasiveness. The equipment cost may be higher though because of the need to acquire voltage and current waveforms (B).
Portability	The air gap torque method's portability suffers from the need to move a personal computer from motor to motor. Once the method is well

	developed it ought to be possible to produce customized instruments for this method that are more easily moved about (B).
Durability	For industrial grade, packaged electronic devices, durability can be good (B).
Dependability	In theory the method ought to be extremely dependable because very little is estimated (A).
User Friendliness	Once the system is commercialized, the method should be user friendly (B).
Accuracy	Very limited testing indicates the method is quite accurate to 1% (A).
Human Safety	There do not appear to be any significant human safety hazards associated with the air gap method (B).
Equipment Safety	Once the equipment is commercialized and packaged in industrial grade hardware, equipment safety should not be a concern (B).

20. SILEX --An air gap torque approach

This method is developed by Industrial Automation Co. Ltd, Budapest, Hungary. It uses measured voltage and current waveforms to calculate the air gap torque.

SILEX torque measuring instrument (TMI-02) is portable with a 120V power supply requirement and several built-in sensors. The torque is calculated using air gap torque equations. The measured data are displayed digitally or shown on the screen of an oscilloscope. No zero sequence component in current and voltage is allowed (i.e., motors must be delta or wye connection without a neutral to ground connection).

The torque measuring card (TMC-01) is a "Single Europe Card" version for the TMI-02 torque measuring instrument. It has to be supplied by a 15V DC from the unit's power supply. The sensors have to be connected externally. The card has only an analog output.

The principle of this method is based on the calculation of the air gap torque that is presented by the current and flux. The flux can be calculated from the measured terminal data. This method appears to be less sophisticated than the air gap torque method developed at ORNL. The core loss, friction and windage loss are not measured in the SILEX method. It is a simpler approach without un-coupling the motor. Subsequently, the accuracy is probably not as high as the ORNL air gap torque approach.

Criterion	Comment
Invasiveness	Because an un-coupled no load test is not required, this method is less invasive and less accurate than the ORNL air gap torque method. The value of stator resistance is required as an input to the equipment (B).
Economy	The SILEX torque measuring instrument, an IBM PC with A/D card, and a speed measuring device are used for the torque measurement. The analog circuit in the circuit board is used for the computation. The cost is relatively low for a method that has these features (A).
Portability	Portability is good because the device is in a packaged system (B).
Durability	For industrial grade, packaged electronics, durability can be good (A).
Dependability	This method stands as a lower intrusion option among air gap torque methods. However, the principle of air gap torque method is generally sound (B).
User Friendliness	This is a more sophisticated method than the simple slip method or the current method, but a well designed computer based system can be quite user friendly (A).
Accuracy	Because an un-coupled no load test is not required in this method, the result is a sacrifice in accuracy (B).
Human Safety	Because of the voltage and current measurements human safety is a concern and proper training must be provided (B).
Equipment Safety	Again, because of the need to connect to live terminals, there is a risk of equipment damage (B).

3.3.6 Shaft Torque Methods

21. **Shaft Torque Methods** In principle, the efficiency of a motor can be determined by measuring the torque experienced by the output shaft under load. Once this output torque is known and input power and motor speed has been measured, motor efficiency can be quickly determined from:

$$Efficiency = \frac{(Shaft\ torque)2\pi\left(\frac{rpm}{60}\right)}{P_i}$$

Hence, any procedure for measuring shaft torque in the field can be quickly adapted to create a field method for determining efficiency. Many different ways have been proposed for measuring shaft torque as evidenced by (70), (71), (72), (73), (74), (75), (76), (77), (78), (80), (81), (82), (83), (84), (85), (86), (87), and (96). However, these methods are beyond the scope of this study and are not considered further.

22. **SENTECH** --A torque gauge method.

This instrument is developed by Sentech Systems Inc.

It is commonly known that the torsional distortion of a given shaft is a direct function of the torque. The torque, power and speed (TPS) sensor system of the SENTECH device is based on a laser shaft torsional distortion measurement technology. It measures the real time interval between received optical reflections provided by tangential reflective surfaces affixed to or created on the rotating member. It also measures the shaft speed in real time.

There are three modes available for the calibration of the TPS sensor system. (A non-rotating static torque calibration method is currently under development). Two correspond to a rotating shaft, and one is used for a stationary shaft.

Because the sensor measures the shaft output torque, the motor needs to be decoupled for calibration without the influence of load friction.

Currently, according to Jim Pierson of SENTECH, the clear shaft length (i.e., without key way) is required to be not less than two inches. This becomes difficult to meet in the shaft dimension of NEMA frame size motors. The key way that is normally on the shaft that limits the clear shaft length, and in the field the coupling is normally on the shaft.

Accuracy for shaft output torque claimed by the manufacturer is ±1%

The use of this device for motor efficiency assessment in the field is at a development stage.

Criterion	Comment
Invasiveness	This is an invasive method, because the shaft of the motor needs to be decoupled for calibration and installation of the optical surfaces, and the input power needs to be measured for efficiency calculation (D).
Economy	This method has a relatively high initial cost (C).
Portability	Power measuring devices and the laser equipment can be bulky. The device was not designed to be portable (C).
Durability	Laser and power devices must be handled with care, but the system is designed for continuous operation in an industrial environment (A).
Dependability	It is commonly known that the torsional distortion of a given shaft is a direct function of the torque. The torque, power and speed (TPS) sensor system of the SENTECH device is based on a laser shaft torsional distortion measurement technology. It measures the real time interval between received optical reflections provided by tangential reflective surfaces affixed to or created on the rotating member. It also measures the shaft speed in real time. The unique advantage of this method is that the stray load loss is not assumed. The shaft output torque has already taken the stray load loss into consideration (A).
User Friendliness	Because the sensor measures the shaft output torque, the motor needs to be decoupled for calibration without the influence of load friction. Extensive training is required for the installation of the method (C).
Accuracy	Accuracy can be high depending on the accuracy of equipment and the calibration (A).
Human Safety	The input power measurement that involves terminal voltages and the laser require safety awareness. (In use the TPS system is fully optically shielded) (B).
Equipment Safety	Attention and trained personnel are required when using power device and laser equipment (B).

3.3.7 Other Methods

23. Stanford Empirical Method--Wilke and Ikuanobe (41) developed an estimating method for their own use, as Stanford University conducted an energy efficient retrofit program. Their method is similar to the Ontario Hydro simplified segregated loss method discussed earlier. There is one important difference. During their retrofit program Wilke and Ikuanobe developed a database of no load tests based on tests of 50 motors. The method uses it's own empirical factors based on this testing. Limited testing done at ORNL's Electric Machinery Systems Test Center has shown that the method has significant errors (10%) in the lower load ranges. In the later stages of the retrofit program the no load characteristics the motors being considered for replacement were estimated by examining the characteristics of similar motors in the data base. Otherwise, the discussion and matrix information for the Ontario Hydro method is applicable to the Stanford method. Therefore, the evaluation parameters will not be discussed for the Stanford method, and it is not entered in the matrix.

24. Ho and Chen's Method--This is a fascinating method based on system characterization methods of control theory. Ho and Chen apply dynamics system techniques to develop differential equations to describe an induction motor and its load as a system. Equations are derived for both the no load and normal operating load conditions. Shaft output torque at normal operating load is one of the parameters of these equations. Therefore, if the parameters of these equations can be estimated and the equations accurately represent the motor, then computing the output power of the motor is straightforward.

Ho and Chen's method uses samples of the motor dynamic behavior as input data. The input power, current, and motor speed are electronically sampled for a period of time sufficient to identify the dynamic behavior of the motor. The authors derive a recursive least squares algorithm to estimate the parameters of the model. A personal computer is used to control the data collection process and to perform the recursive algorithm to estimate the model parameters.

How well Ho and Chen's method performs depends on how well their mathematical model represents the dynamic behavior of the motor. If there is a good match then this method provides estimates of all losses, including stray load losses. However, these losses are not necessarily separated into the classical categories of motor losses.

Criterion	Comment
Invasiveness	Ho and Chen's method requires a sampled measurement of input power, line current, and motor speed at both no load and the normal operating load. This places the invasiveness of this method about equal to that of Hirzel's modified method E1 (C).
Economy	This method will require significant data acquisition capability and has not yet been prototyped (C).

Portability	This method suffers the same handicaps as the air gap torque method with respect to the required data recorder (B).
Durability	The comment under portability is applicable here Data recorders are relatively fragile (C).
Dependability	The dependability of this method is unknown. More research and testing of the method is required to ascertain its dependability. A medium rating is given for this quality for want of reasons to do otherwise (B).
User Friendliness	The tests required by this method are reasonable, however, the motor must be disconnected from its load (B).
Accuracy	The comparative tests of the method reported by Ho and Chen reveal that the method has an error of about 6% (B).
Human Safety	This method ought to be as safe as Hirzel's modified method E1 because the test required by the two methods are very similar (B).
Equipment Safety	The equipment safety of this method is determined primarily by the hazards associated with moving a personal computer from motor to motor in an industrial environment (B).

25. Colin Grantham Method --A synthetic loading of three-phase induction motors by magnetic field magnitude modulation (29)

For field efficiency measurement this technique does not contribute directly to the objective. Because in the field the motor is already loaded by its driven equipment, a synthetic load is not needed. However, this method can be used for testing motor temperature rise when the motor is not coupled to a load.

The synthetic loading technique is to vary the stator frequency about the rated frequency and to cause alternate motor/generator operation. There are three techniques available:

a) Dual frequency (DF) method. Two distinct frequencies are generated through a digital signal processor (DSP) controller. The slower field produces a load torque on the rotor.
b) Sweep frequency (SF) method. It uses DSP to rapidly change the machine's normal single supply frequency. A generator mode is established during the sweep.

c) Constant Speed of Rotating Magnetic Field varying Amplitude (CSORMFVA) method. The principle of this method is to produce a rotating magnetic field whose speed is constant, while its magnitude varies sinusoidally.

There are unanswered questions regarding the use of this method to measure motor efficiency, such as the effect of additional rotor core loss due to varying flux linkage to the rotor. There is also a concern on the accuracy of the calculated efficiency when the supply to the motor is changed from sine wave to a modulated wave such as the case under the Synthetic loading situation.

NOTE: Because this method is so novel and was not developed as a field method, it would be inappropriate to attempt to provide letter ratings for the various categories.

Criterion	Comment
Invasiveness	This is a very invasive method, because the motor supply has to be changed to provide an alternate motor/generator operation.
Economy	The rating of the power device has to match the motor rating. The initial investment is proportional to the rating of the motors that are required for tests.
Portability	Power devices can be heavy, but this method is not really designed to be moved from motor to motor.
Durability	The synthetic loading device could be manufactured to industrial standards and made quite durable.
Dependability	The method is more suitable for motor temperature rise without loading the motor mechanically. There are unanswered questions on the suitability of this method for motor field efficiency tests.
User Friendliness	Because this method allows the user to vary the motor load, it does provide some user friendly characteristics.
Accuracy	Accuracy may be low due to the effect of the variable field.
Human Safety	Reconnecting the motor terminals requires special caution.
Equipment Safety	Attention is required when using power device and sophisticated equipment.

26. **Motor Master+**--Motor Master+ offers three optional methods of operation, slip, current, and input power. The complete discussion is found at number 16.

3.3.8 Summary Discussion of Methods on Which Limited Information Is Available

The following is a brief description of other methods on which we have limited information or for which the information was received late in the process and the Matrix Summary of Methods and evaluation criteria could not be developed. These methods are included for completeness:

27. <u>SAVO's Modified IEEE 112 Method</u> - This appears to be a modified version of the IEEE Standard Method F.

SAVO holds the algorithms for this method proprietary, other than to state that the following information is provided:

Inductance of the stator, air gap and rotor
Resistance (both low and high) of the hot spot, voltage imbalance and leakage to ground
Capacitance
Voltage
Current
Phase Angle
kW in
Losses
HP out

Because of commercial reasons, SAVO is not able to provide the exact algorithms used in their methods. We believe the IEEE 112 Equivalent Circuit is used because the circuit is shown in their referenced literature. Because we do not know how the circuit is developed or what data it is based on, it is inappropriate for us to attempt to categorize the features of the method by our rating criteria. We are also not including this method in the Matrix Summary of Methods because the ratings would be based only on conjecture. We are including the method here for completeness and because it is a commercially available, portable method for field efficiency testing. Reference SAVO Beacon, August, 1993, IdL Inc., P.O. Box 1373, Corvallis, OR 97339.

3.3.9 Testing to Date

Some testing of representative methods has been conducted as an initial evaluation of their relative strengths. Attached is a plot of tests (Figure 6) that were conducted at ORNL's Electric Machinery Systems Test Center as part of the Department of Energy's Motor Challenge Program. These tests were performed on a 7.5 horsepower used motor. This figure is included only for discussion and to show qualitatively the merits are of various methods. No quantitative conclusions should be taken from this figure, it is only for one motor, and with seven efficiency estimation methods as follows:

Slip Method (14)

This method is shown from the figure to be accurate only in a very small portion of the motor load range, and that portion will vary depending on the nameplate slip value, which, as discussed previously, may be off by as much as 20%.

Current Method (17)

The particular current method shown here is one where the current vs. load plot is expressed as three slopes depending on the percentage load. As discussed above, the current method is also highly susceptible to unknowns in the nameplate value, and in the non linearity of the curve.

Actual Measured Efficiency

This is the motor efficiency as determined by an in line torque transducer, rpm meter and three phase power meter, all calibrated and traceable to the NIST.

Equivalent Circuit Method (12)

This is a modified IEEE 112 Method F equivalent circuit based solely on motor nameplate data and measurements of motor speed.

Air Gap Torque Method (19)

This is the Air Gap torque method developed by John Hsu and described in Section 3.3.5.

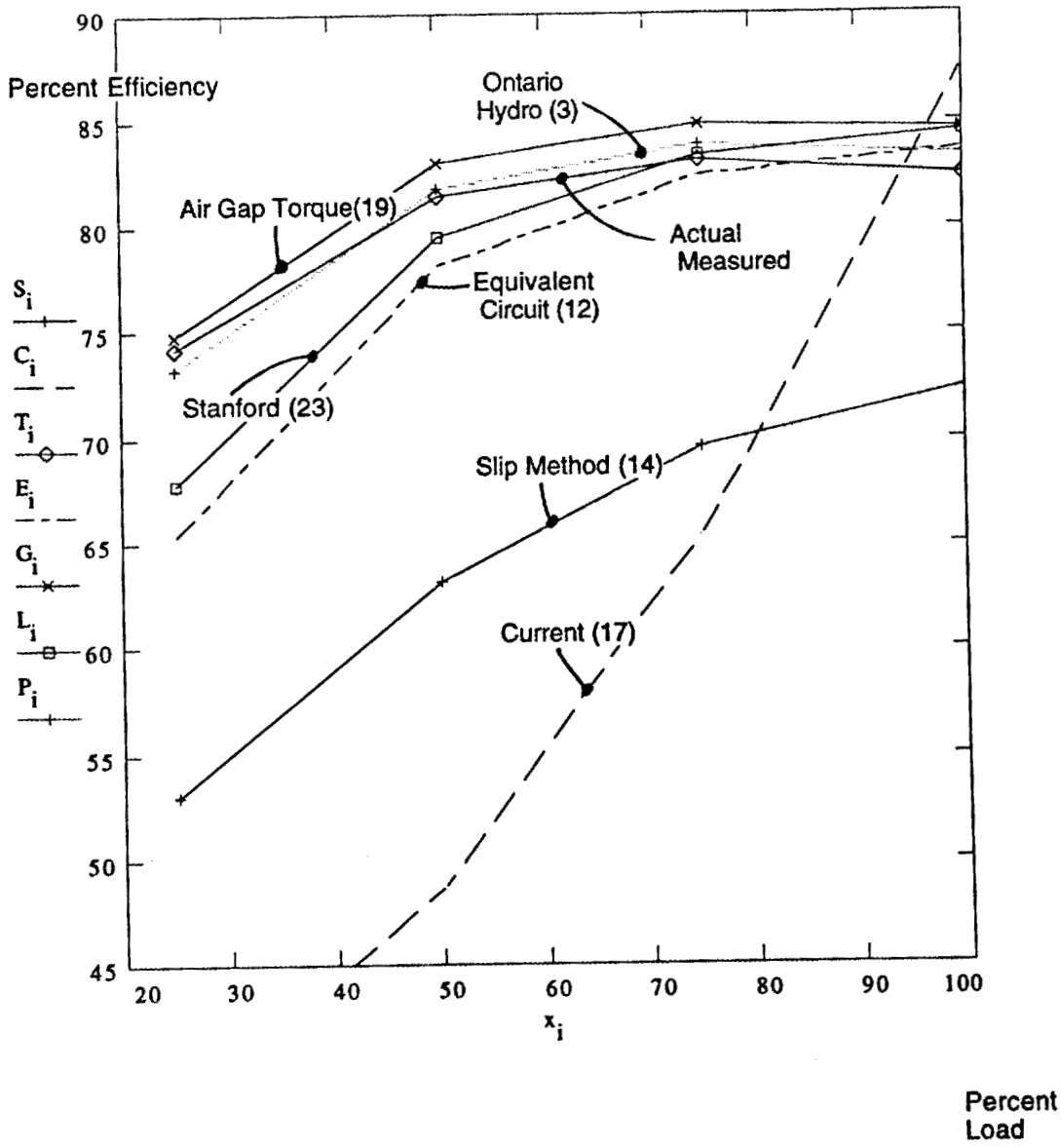
Empirical (Stanford) Method (23)

This is a method based on empirical methods, developed by K. Wilke and discussed in Section 3.3.7.

Ontario Hydro (3)

This is a variation of the Ontario Hydro simplified method E1 discussed in Section 3.3.1. In this variation, the no load losses have been approximated as 4.2% of the full load watts in rather than 3.5%. Also, the conductor temperatures have been corrected for an approximated temperature.

A report discussing tests performed of a sample of methods is titled "Assessment of Methods for Estimating Motor Efficiency and Load Under Field Conditions", J. D. Kueck, Oak Ridge National Laboratory report number ORNL/TM-13165. This report also includes an interesting Appendix discussing the influence of data collection factors on accuracy.



Tests of Various Estimation Methods on a 7.5 HP Standard Efficiency Motor

Figure 6

4. Conclusions and Recommendations

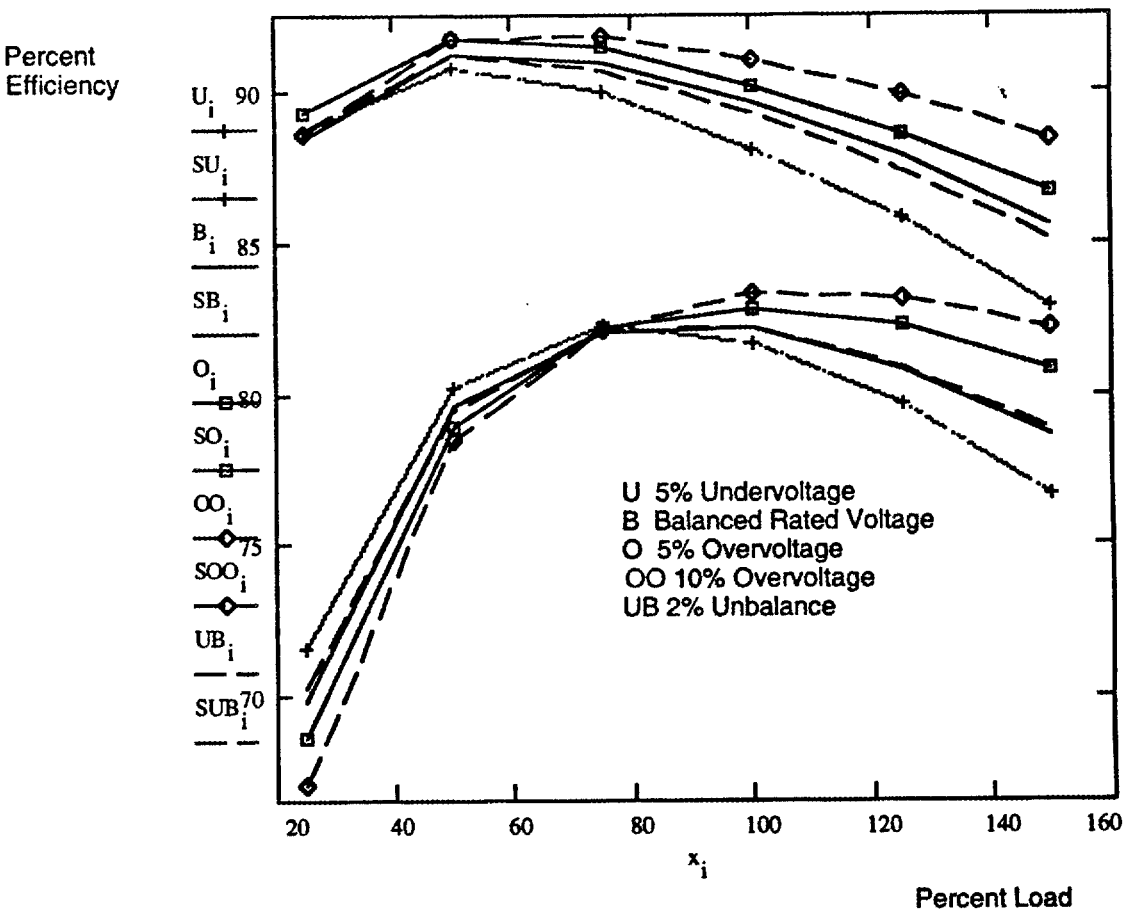
It can be seen from this study that there is an impressive spectrum of efficiency estimation methods available commercially and in the literature. In general, the more accurate methods require more data and are more intrusive, and the simpler methods are less accurate and less dependable. However, there are some low intrusion methods that provide gross errors of 40 percent (slip method), and some that have an average accuracy of about 3 to 4 percent (ORMEL96 Method).

As was stated in the introduction, it is assumed here that the user has a simple objective: to determine whether or not it is economically advantageous to replace an existing motor with a more efficient one. An accuracy of 3 to 4 percent is probably adequate for this objective in most cases.

In a recent test performed at ORNL of two 10 hp motors, one energy efficient and one standard efficiency, it was found that at 75% load, there was an efficiency difference of 9 percentage points between the two motors. The energy efficient motor was operating at 91% efficiency, and the standard motor was at 82% efficiency. See Figure 7. This significant difference in performance is typical between standard and energy efficient motors. Indeed, as can be seen from Figure 7, at low load conditions the difference grows.

In performing a cost benefit analysis of a motor replacement, many analysts just use nameplate data in determining the efficiency and load to be used in calculating energy usage. (40) Again, from Figure 7, it can be seen that merely using nameplate data can introduce significant errors because efficiency is so much a function of motor load. In the author's opinion, it is important for the user to make a field survey of their motors and perform some measurements and analysis to estimate what the motor's operating load and efficiency is.

In some cases, the user may have a need for high estimation accuracies, but for a typical motor survey, accuracies of 1% are not needed in a replacement cost benefit analysis.
In the case of a large, relatively new motor, where the difference in efficiency for the replacement motor may be relatively small, a high accuracy efficiency estimate may be required. In this case, one of the more intrusive methods such as Nielsen, ECNZ, or Motor Check may be needed. However, in the average replacement situation, where one is replacing an older motor with one that has a significant improvement in efficiency, and where one is replacing a number of motors and wants to keep the field measurement time to a reasonable minimum, an estimate with a accuracy of 3 or 4 percent would be satisfactory. For these replacement situations, just measuring the motor shaft speed, reading the motor nameplate data and using the ORMEL96 method would provide satisfactory results with minimum time and with no exposure to hazardous voltage. (For many industries, the risk of exposing workers to hazardous voltages is believed to outweigh the benefit of a field survey. For these industries, the ORMEL96 method would be especially attractive.) The ORMEL96 method also provides an estimate of the motor



Plots of Efficiency Vs. Load
for an Energy Efficient and a Standard Efficiency 10 Hp Motor
for Various Voltage Conditions

Figure 7

load, has a data base feature for record keeping, and provides a truly significant improvement in accuracy over just using nameplate data.

There are several other benefits that may be obtained from a motor field survey. A simple visual inspection of a motor will often reveal a problem such as a clogged air intake, a locally high ambient temperature, or some other condition that could be robbing efficiency and shortening motor life. In addition, when the user elects to use a method with a voltage measurement, he will obtain information about possible voltage unbalance, under or over voltage, or excessive harmonic distortion. (Many of the newer, handheld power monitors also have a feature for harmonic distortion analysis.) All these conditions can have not only an effect on efficiency, but an extreme effect on motor lifetime. Indeed, the authors are aware of many situations where motors were repeatedly replaced in service conditions where premature motor failure was guaranteed due to the voltage and or loading conditions.

Another consideration that must be stressed is that a motor survey using even a low intrusion method will provide an estimate of motor loading. Having an estimate of motor loading will make the replacement cost benefit analysis much more accurate, and may also reveal that a smaller motor, or a larger one, should be used as the replacement. A recent trend among design engineers is to use a motor that is marginally rated for its load. A problem with this philosophy is that it does not take into account changes in load during the operation of the process, inaccuracies in the calculation of the load of the driven equipment, and problems in the voltage supply to the motor. A good rule of thumb is to size motors for 75 to 85 percent of their design horsepower rating. This will allow some margin to account for unforeseen changes in the service condition, will result in longer motor life, and will actually provide 1 or 2 percent higher efficiency than operating the motor at its full load condition as seen from Figure 7.

We hope that this report has provided the reader with insight into some of the excellent methods which are available for estimating motor load and efficiency, and some of the methods that should not be used such as the slip or current method. These methods can introduce gross errors, and should never be used when much more accurate and dependable methods are available that provide trustworthy estimates for the same level of intrusion.

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