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Aleksandr S. Nagornyy for the degree of Master of Science in Electrical and Computer Engineering presented on June 13, 2003.
Title: EVALUATION OF THE STRAY LOAD LOSSES FOR A THREE-PHASE INDUCTION MOTOR

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Alan K. Wallace

The evaluation of the stray-load losses in induction motors is an important part of the efficiency estimation process. However, stray-load losses have several components which are difficult to isolate and calculate. Consequently, they are more readily determined by test. IEEE Standard 112-1996 recommends the testing of electrical induction motors at a rated mode (nominal frequency and voltage). Thus, the IEEE 112 test does not provide us with information about the motor efficiency and stray load losses at supply frequencies which are different from the rated value. At the same time, this information is very important for the correct evaluation of the efficiency of the motors, controlled by the Adjustable Speed Drives (ASDs).

This work is dedicated to the investigation of the relation between the motor efficiency, stray-load loss and the supply frequency. The voltages to be applied for the specific values of the frequency were chosen to keep the value of the relative slip constant at 100 % load torque. After performing the series of load tests, it was found that the SLL is proportional to the square of the load and the dependency between SLL and frequency for different load levels is close to linear. The comparison of the efficiency values obtained by the methods IEEE 112 B and 112 E has shown a good correlation of the results.

Evaluation of the Stray Load Losses for a Three-Phase Induction Motor

By
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EVALUATION OF THE STRAY LOAD LOSSES FOR A THREE-PHASE INDUCTION MOTOR

1. INTRODUCTION

Reduction of energy consumption, CO_2 emissions, as well as overall environmental pollution is nowadays a very important problem that exists in all industrial countries. A considerable part of this pollution is related to the production of electrical energy, especially in large power generating plants. Typically, 60 – 80 % of the electrical energy, which used in the industrial sector, and about 20 – 35 % of the electricity used in the commercial sector, is consumed by electric motors. In industry, a motor consumes an annual quantity of electricity, which corresponds to approximately up to 4 – 5 times its purchase price throughout the whole life of around 12 to 20 years [1].

Traditionally, three-phase squirrel cage AC induction motors are the most commonly used electric motors in industry. The range of the output power is from a few hundred watts up to several megawatts. The range of use for the electric motor includes a whole list of applications, such as fans, compressors, pumps, transport devices, home appliances, office equipment etc. Thus, we can make a conclusion, that the largest portion of electricity is consumed by induction motors. As a result, the efficiency of the electric motor that indicates the effectiveness of conversion of electrical energy to mechanical energy is a very significant parameter.

Actually, the importance of efficiency of electric motors is not constant with time. Generally, it depends on the economical situation and the cost of electrical energy compared to the cost of active materials: dynamo steels, wires, insulation, bearings and so on. Stable growth of the cost of electric energy during recent years is a reason for higher attention of manufacturers and users of electric motors to motor efficiency. Also, an effective way of reducing pollution, greenhouse gas emissions and reducing consumption of fossil fuels is by improving the efficiency of induction motors. Another important effect is that improving the efficiency will reduce motor operation cost. Such an improvement brings up an opportunity to increase the plant efficiency, profitability and competitiveness of the overall industry. Because of the above reasons, electric motor manufacturers and users are becoming more conscious of efficiency as a criterion for selecting and applying motors, and they need a tool which would allow them to get a precise efficiency determination using a uniform yardstick. Sometimes, this problem is not very simple because the motor manufacturers in different countries use different standards and different methods of efficiency evaluation. As a result of the different standard systems, the efficiency values of the same motor can differ in different countries. Thus, there is a probability for the buyers to get a motor from a variety of countries, where the efficiency is estimated by different methods and protocols.

Usually, it is possible to precisely identify the losses in stator and rotor conductors, magnetic core loss and friction and windage loss incurred through the rotation of the rotor and cooling fan. However, the electric motors also have an additional power loss component, termed stray load loss (SLL), that is caused by the non-ideal nature of a practical machine. It is very difficult to calculate SLL analytically, and it is hard to measure it. Usually, SLL can be evaluated by special experimental methods. Thus, one of the reasons for the differences in efficiency values from different national standards is the variation of stray load loss (SLL) evaluation methods. However, at the same time SLL is a very significant part of overall losses that may have a big influence on the temperature condition of the motor. For some motors, the level of SLL can reach several percent of the input power and have a large influence on the efficiency. All of the above indicated reasons make the evaluation of SLL in induction motors an important part of the efficiency estimation process.

Some of the important aspects of induction motor SLL evaluation are presented in this thesis. The second chapter is dedicated to the literature review of SLL in induction motors and its basic components. The third chapter highlights the most popular experimental methods of finding the efficiency and SLL that are currently in use in different countries. The fourth chapter describes the results of SLL and efficiency evaluations that have been made by different test methods, and, finally, the last chapter gives the conclusions and recommendations for the future work in this area.

2. ADDITIONAL AND STRAY LOAD LOSSES IN INDUCTION MOTORS

2.1 Conventional Load Losses

All losses occurring in the induction motors can be separated into conventional losses and additional losses. The conventional losses can be represented by

1. Stator electrical losses;
2. Rotor electrical losses;
3. Magnetic losses;
4. Mechanical losses.

The stator and rotor electrical losses are of the type I^2R (i.e. ohmic losses), and they increase with the motor load. These Joule losses can be reduced by increasing the cross-section area of the stator and rotor conductors.

The magnetic losses (or core losses) occur in the steel laminations of the stator and rotor. These losses are due to hysteresis and eddy-currents, and vary with the flux density and the frequency. Usually, the induction motor magnetic circuit can be divided by the following regions: stator core teeth, stator core yoke, air gap between the stator and the rotor, rotor core teeth and rotor yoke. For any steel core region the core loss can be found from the expression

$$P_c = P_{60}\left(\frac{f}{60}\right)^{\beta} B^2 G \qquad (2.1)$$

where:

P_{60} is a specific loss in unit mass at $B = 1$ T and $f = 60$ Hz;

f is a current frequency, Hz;

β is the power, that depends usually on the concentration of the silicon in the dynamo steel;

B is the flux density in this part of the magnetic core;

G is the mass of this part of the magnetic core.

From (2.1) it is clear that the core loss in the induction motors can be reduced by decreasing the flux density; for example, by increasing the cross-section area of the iron core in the stator and rotor, or by decreasing the specific loss by using improved magnetic materials. Also, there are a lot of technological methods for reducing magnetic losses. Among them are precision stamping with low burring, deburring, annealing the lamination sheets after stamping, regulation of the pressure during the core packing, and so on.

The mechanical losses in the induction motors are due to the friction in the bearings, ventilation and windage losses. For the wound rotor induction motor, there is a loss caused by the friction between brushes and slip rings, which the squirrel-cage induction motor does not have. Thus, finally, the summary of the mechanical losses could be found from the equation

$$P_m = P_f + P_v + P_b \quad (2.2)$$

where:

P_f is a friction loss in the bearings;

P_v is a ventilation loss;

P_b is the loss in the brushes contacts.

The ventilation loss component depends on the pressure head and, it is proportional to the speed of the air squared. The mechanical loss can be reduced by using low friction bearings and improved fan design.

The breakdown in percent of each type of loss in the total loss of induction motor 7.5 kW, four pole according to [7] is shown in the Figure 2.1.

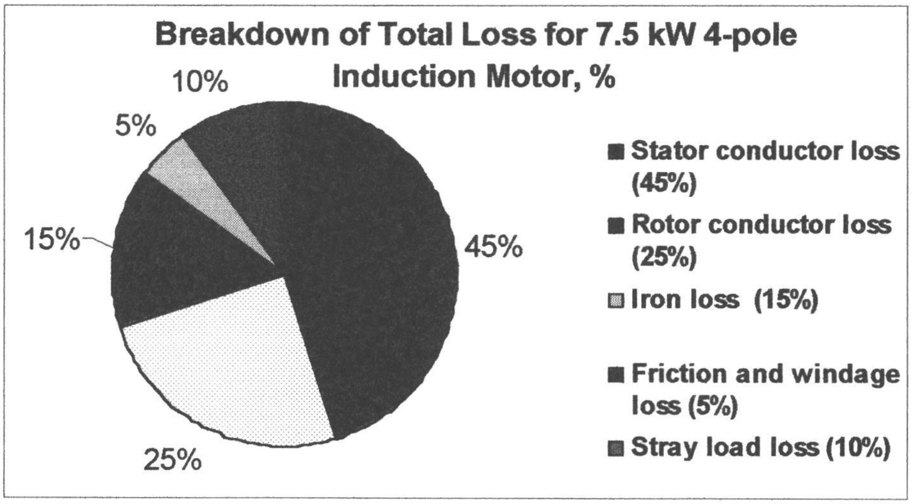

Figure 2.1 Breakdown of total loss for 7.5 kW, 4-pole induction motor.

2.2 Additional Losses in Induction Motors

There are several of literature sources that study the additional and Stray Load Losses (SLL) in polyphase induction motors. The main topics of these studies are the sources of these losses, the methods of determination (calculation and measurements), the influence of these losses on the motor output parameters, such as, efficiency, torque, thermal condition. Among such works is [1] that describes the state of the art of the SLL in the literature over a wide period of time. Ref. [1] offers the following physical origins of the SLL in induction machines:

a) The magnetic property limitations of iron material that leads to saturation at load current;
b) The geometrical structures, i.e. slots, windings and air-gap around the active region of the machine that leads to space harmonics due to such effects as ripple, tooth pulsation and leakage flux.
c) Industrial imperfections – the most prominent of which is cross-bar current due to the imperfect insulation of the squirrel cage rotor bars.

Another work [2] gives the interesting information (Table 2.1) that is connecting together the components of SLL with their origin and locations inside the machine.

Table 2.1

Components	Origin	Type and Location
1. Surface losses	Gap leakage (harmonic) flux	Stator and rotor core losses
2. Tooth-pulsation losses	Gap leakage (harmonic) flux	Stator and rotor core losses
3.Tooth-pulsation, squirrel-cage, circulating current losses	Gap leakage (harmonic) flux	Rotor I^2R loss
4. Stator harmonic, , squirrel-cage, circulating current losses	Gap leakage (harmonic) flux	Stator I^2R loss
5. Stator-slot eddy-current losses	Slot leakage flux	Stator I^2R loss
6. Rotor-slot eddy-current losses	Slot leakage flux	Abnormal rotor I^2R loss at high slip only
7. Stator-overhang eddy-current losses	Overhang leakage flux	Stator core loss
8. Rotor-overhang eddy-current losses	Overhang leakage flux	Abnormal rotor core loss at high slip only

It is usually hard to compute the additional losses by conventional methods. In practice, the additional losses could be separated into two major groups. The first group is the losses that depend on the voltage; the second group is the losses that depend on the current.

The losses of the first group can also be divided into the following categories:

1) The losses that are caused by imperfection of the steel lamination insulation;
2) Surface loss;
3) Pulsating loss.

The losses dependent on the voltage can be found experimentally from the no load test and can be taken into account theoretically by using special correction factors.

The second group of the losses is the losses that depend on no load current and cannot be added to the no load losses. This group of losses is usually termed stray load losses. It should be mentioned that until now the survey of the literature on the SLL in induction machines reveals the considerable disagreement with the definitions of these losses and their origins. This chapter contains the survey of the literature sources that are investigating the different aspects of the SLL evaluation.

The contribution of each of the SLL components to the total stray load losses according to the [8] is shown on the Figure 2.2.

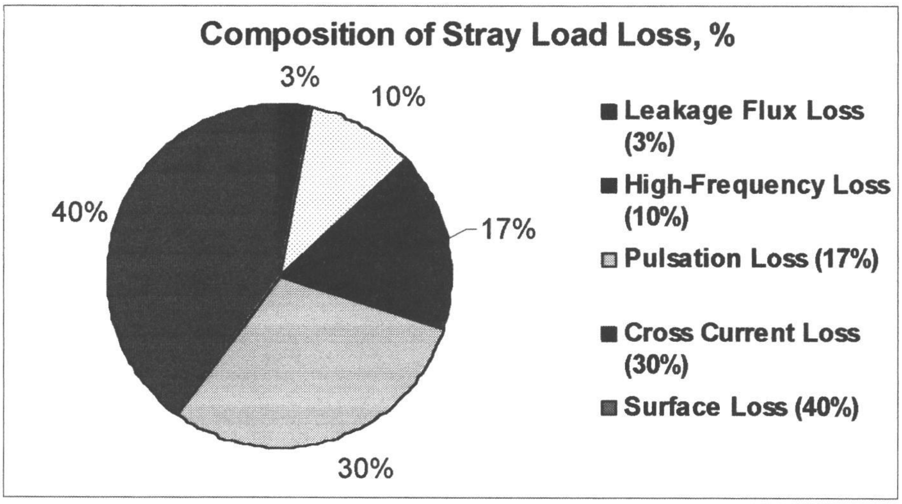

Figure 2.2 The contribution of the components to the stray load losses

One of the most fundamental works that studied the method of the SLL determination is [3]. In this paper the SLL are divided into the six following components:

1) The eddy-current loss in the stator copper due to the slot leakage flux;
2) The losses in the motor end structure due to the end leakage flux;
3) The high-frequency rotor and stator surface losses due to the zigzag leakage flux;
4) The high-frequency tooth pulsation and rotor I^2R losses, due also to the zigzag leakage flux;
5) The six times frequency rotor I^2R losses due to the circulating current induced by the stator belt leakage flux;

6) The extra iron losses in motors with skewed slots due to the skew leakage flux.

The short descriptions and formulas for those SLL components will be given below.

2.2.1 Losses Due to Stator Slot Leakage Flux

These losses are associated mainly with the increasing the resistance of the stator conductors due to the "skin-effect" or displacement the currents flowing in the stator conductor to the outer areas and increasing the resistance in consequence of this. The extra copper loss is proportional to the fourth power of radial conductor size and the square of the frequency. It is negligible in small round-wire machines. For large machines this effect can be reduced by using wire transposition. The slot leakage flux can also cause some increase in loss in the laminations, but, usually, both of these effects are negligible, and it can be assumed that the core loss has the same value for all loads.

2.2.2 Losses Due to the End Leakage Flux

These losses are created by eddy currents flowing in the end structures of the machine which are induced by end-leakage fluxes. These fluxes penetrate the end fingers, flanges, ventilating shields, end bells and other adjacent metal parts. The portion of the end fluxes in the overall resultant flux can be significant when the coil overhang is long, and when the metal parts are close to the stator and rotor windings. Because of the fact that any electric machine has some specific design parameters and dimensions, and, thus, it has a different end leakage flux path, it is very hard to derive a formula for the end loss that is based on the specific end construction. However, it has been found satisfactory to assume that the end loss is equal to that portion of the volt-amperes (VA) of the leakage reactance that is due to the flux entering the stator laminations axially (rather then radially)`, multiplied by the empirical "power factor" constant usually equal to 0.3.

The formula that may be used for the determination of the losses due to the end leakage flux is [3]:

$$P_e = 0.3mI^2\left[\frac{1.6fmN^2D_1}{p^2 10^7}\log\left(1+\frac{A^2}{4Y_1Y_2}\right)\right] \tag{2.3}$$

where: I is the phase current;

m is the number of phases;

N is the number of effective winding turns per phase;

D_1 is the inner core diameter;

p is the number of poles;

A is the slant distance between the assumed center of the stator and rotor peripheral currents;

Y_1 and Y_2 are, respectively, axial distances between the stator and rotor end-current centers to the end of the laminated core.

2.2.3 Surface Losses Due to the Zigzag Leakage Flux

The stator and rotor of the conventional induction machine usually have slots in the core laminations which cause the dips in the flux distribution around the air gap. On the other hand, the concentration of current in the slots creates the step structure in magnetomotive force (mmf) distribution. Both of these factors cause the slot frequency pulsation in the radial flux density around the air-gap. These pulsations cause eddy-current losses in the laminations, which are usually called surface losses. The peripheral air-gap flux distribution can be presented as a series of rotating harmonic fields called the stator and rotor slot harmonics with pole numbers equal to ($2s \pm 1$) and ($2r \pm 1$) multiplied by the fundamental number of poles, where s and r are the numbers of slots per pole in the stator and rotor respectively. These rotor and stator slot harmonics are caused by the slot –tooth structure of the stator and rotor and also by the stepped form of the mmf distribution curve. Harmonics due to the slot openings and due to the steps in mmf distribution have the same number of poles and the same frequency. The stator slot openings cause losses at no load, which can be counted as part of the core loss. The mmf steps cause losses under load.

The loss in the rotor surface is caused by the effect of the no load permeance variations due to the stator slot openings and can be determined by the following formula [3]:

$$W_{S0} = 2D_1L\left(\frac{B_g}{100}\right)^2 K_{pf}C_{S2}\lambda_1 \tag{2.4}$$

where D_1 is an internal stator core diameter;

L is the core length;

B_g is average flux density over the effective gap;

K_{pf} is the pole-face loss coefficient for stator slot openings;

C_{S2} is the rotor iron loss coefficient;

λ_1 is the stator slot pitch.

The equation for the rotor surface loss due to the load current is

$$W_{SL2} = 2D_1L\left(\frac{I}{sI_0}\right)^2\left(\frac{B_g}{100}\right)^2 C_{S2}\lambda_1 \tag{2.5}$$

where I is the stator load current;

s is the number of stator slots per pole;

I_0 is the stator no load current.

The total surface loss is given by adding the no-load loss W_{S0} and the stray loss W_{SL2}. In both equations the loss is proportional to the flux density squared.

The stator surface loss can be found by the equation

$$W_{SL1} = 2D_1L\left(\frac{I}{rI_0}\right)^2\left(\frac{B_g}{100}\right)^2 C_{S1}\lambda_2 \tag{2.6}$$

where r is the number of slots per pole;

C_{S1} is a rotor iron loss coefficient;

λ_2 is the rotor slot pitch.

Because there is no significant rotor current at no load the total surface losses at load will be the sum of W_{SL1} and W_{SL2}.

2.2.4 Rotor Pulsation and I²R Losses Due to the Zigzag Leakage Flux

If the stator and rotor have equal number of slots, each rotor slot pitch would be nearly equal to one period of the stator slot harmonics. In this case, no significant part of this harmonic field would penetrate into the rotor teeth, Thus, no current would be induced in the rotor winding, and the only high frequency loss in the rotor would be the surface loss. If the ratio of stator to rotor slots differs from unity, the rotor tooth pulsation increases. The losses in this case could be determined by the equation

$$W_z = CI^2(K_S R_{2B}) \tag{2.7}$$

where C is a loss factor;

K_S is the skin-effect ratio for the rotor bars at the stator slot frequency;

R_{2B} is the rotor bar resistance referred to the stator.

2.2.5 Losses Due to the Belt Leakage Flux

The low order harmonic fields due to the phase belts of the stator winding induce currents in the rotor. These currents are small in the case of wound-rotor motors but can be significant for the squirrel-cage motors. The equation for the determination of the stray load loss due to the belt leakage is

$$W_b = mI^2 k_m R_{2B}\left[\frac{K_{2m-1}^2 + K_{2m+1}^2}{K_1}\right] \tag{2.8}$$

where k_m is the skin-effect ratio for rotor bars at the Phase belt frequency which is 2mf at synchronous speed;

$K_{2m\pm1}$ pitch times distribution factor of the stator winding for the $(2m \pm 1)$ field;

K_1 pitch times distribution factor of the stator winding for the fundamental field.

2.2.6 Losses Due to Skew Leakage Flux

If the rotor slots are skewed relatively to the stator core axis, there is a phase displacement of the fundamental mmf waves of the stator and rotor at the two ends of the core. This will cause a loss termed "the losses due to the leakage flux". This loss can be determined by the equation:

$$W_k = \frac{\pi^2}{12}\left(\frac{\sigma I'}{sI_0}\right)^2 \tag{2.9}$$

where I' is the vector difference between the load current I and the magnetizing component of this current, I_0;

σ is the ratio of the skew to one stator slot pitch.

2.2.7 Total Stray Load Losses

The total stray load loss of a poly-phase induction squirrel-cage type motor is the sum:

$$W_{SLL} = W_C + W_E + W_{SL1} + W_{SL2} + W_Z + W_B + W_K \tag{2.10}$$

2.2.8 Method of calculating Stray Load Losses from [4]

Another approach to calculating the SLL in poly-phase induction motors is described in [4]. According to this method, the SLL can be found as a sum of independent high order harmonics P_ν of an order $\nu = 2km \pm 1$ where k=0,1,2,..,ets. We will omit here some details of deriving all of the formulas and will show just the final expressions. The losses that are created in the rotor by the field harmonic of the order ν can be found by one of the formulas below depending on crosspath or rotor bar insulation resistance. If the crosspath resistance is high:

$$P_{2\nu} = s_2 E_{1\nu}^2 \left[\frac{r_{l\nu}}{Z_{l\nu}^2} \left(\frac{\sin\frac{\alpha_1 L}{2}}{\frac{\alpha_\nu L}{2}} \right)^2 + \frac{l^3}{r_{q\nu}} \frac{1}{*(\alpha_\nu L)^2} \right] \tag{2.11}$$

where s_2 is the rotor slots number;

$Z_{l\nu} = r_{l\nu} + jx_{l\nu}$ is bar impedance per unit length;

$Z_{q\nu} = r_{q\nu} + jx_{q\nu}$ is the cross impedance per unit length between two adjacent bars;

$E_{1\nu}$ is the emf induced by ν-order harmonic;

α_ν is the skew angle for the ν-order harmonic;

L is the lamination pack length.

In the case of low crosspatch resistance the loss in the rotor by the field harmonic of the order ν can be found by the formula

$$P_{2\nu} = s_2 E_{1\nu}^2 \left[\mathrm{Re}\left(\frac{L}{Z_{l\nu}} \right) - \frac{r_{q\nu}{}^*}{l^2} (\alpha_\nu L)^2 \mathrm{Re}\left(\frac{1}{Z_{l\nu}^2} \right) \right] \tag{2.12}$$

In a case of complete insulation $(r_q \to \infty)$ the losses can be found by the expression:

$$P_{2\nu} = s_2 \left(\frac{E_{1\nu}^2}{Z_{l\nu}^2} \right) r_{l\nu} L \left(\frac{\sin \frac{\alpha_\nu L}{2}}{\frac{\alpha_\nu L}{2}} \right)^2 \tag{2.13}$$

2.2.9 Method of Calculation of Stray Load Losses from [5]

Heller and Hamada [5] have described the following method of calculating the SLL. The additional loss on the rotor surface, induced by the stator slots can be found by the equation:

$$P_{2\nu} = \frac{k_0}{2} (Z_1 n_s)^{1.5} (B_{01} t_{d1})^2 \pi D_1 L \left(\frac{t_{d1} - o_1}{t_{d1}} \right) \tag{2.14}$$

where k_0 is the factor that depends on the rotor material;

B_{01} is an average value of flux density in a stator tooth pitch;

Z_1 is the number of stator slots;

t_{d1} is the stator tooth pitch;

n_s is the synchronous speed;

D_1 is the stator internal diameter;

L is the stator core pack length;

o_1 is the stator slot opening

The additional loss on the stator surface induced by the rotor slots can be found from the expression:

$$P_{01} = \frac{k_0}{2}(Z_2 n_s)^{1.5}(B_{02} t_{d2})^2 \pi d L \left(\frac{t_{d1} - o_1}{t_{d1}}\right) \tag{2.15}$$

where B_{02} is an average value of flux density in a rotor tooth pitch;

Z_2 is the number of rotor slots;

t_{d2} is the rotor tooth pitch;

d is the rotor external diameter;

o_2 is the stator slot opening.

The pulsation loss which is induced in the stator teeth by flux pulsation with the frequency $f_z = z_2 f$ is recommended to be determined by the equation:

$$P_{p1} = \sigma\left(\frac{f_z B_p}{100}\right) \tag{2.16}$$

where B_p is the amplitude of flux density pulsation in the air-gap;

σ is the specific loss factor in the stator teeth.

The formula for the calculation of the loss in the squirrel-cage rotor induced by the stator slots when the saturation is taken into account is:

$$P_{20} = 6.25 B_p^2 (k_{c1}\delta)^2 \left(\frac{a_1}{2a_0}\right)^2 \left(\frac{Z_1}{Z_2}\right)^2 \frac{R_2 Z_2 k_f}{(1+\tau)^2} 10^3 \tag{2.17}$$

where δ is the air-gap length;

k_c is the Carter factor for the stator;

$a_0 = \frac{1}{k_c \delta}$;

$$k_f = h_{cu}\sqrt{\frac{f'}{f}};$$

$$f' = f\frac{Z_1}{p};$$

$$\tau = \left(\frac{\pi Z_1}{Z_2}\right)^2 \frac{1}{\sin^2 \frac{\pi Z_1}{Z_2}} - 1;$$

a_1 is a pole pitch.

In the case of the skewed rotor the rotor losses can be found from the equation:

$$P_{20S} = \frac{P_{20}}{2}\left\{\left[\frac{\sin\frac{b\pi}{t_{d1}Z_1}(Z_1+p)}{\frac{b\pi}{t_{d1}Z_1}(Z_1+p)}\right]^2 + \left[\frac{\sin\frac{b\pi}{t_{d1}Z_1}(Z_1-p)}{\frac{b\pi}{t_{d1}Z_1}(Z_1-p)}\right]^2\right\} \tag{2.18}$$

where P_{20} is the losses in the rotor without skew (2.17);

t_{d1} is the tooth pitch;

b is the length of skew arc.

2.3 Effects of Stray Load Losses

Many studies have investigated the different aspects of the influence of SLL on the motor characteristics. In [1], a brief survey about the connections between SLL and motor parameters was given. According to [1] the SLL can affect motor parameters in the following ways.

2.3.1 Heating

SLL can produce heat in the different parts of the motor. At first, it can be related to the outer surface of the rotor teeth and surface of the rotor bars from the side of an air-gap. SLL also heats the wires of the stator winding and the surface of the stator teeth from the side of the air-gap. Besides this, the losses are induced in the massive parts in areas which are close to the end parts of the motor, such as ventilation shields, shafts, bells etc. For some motors, these local temperature rises can reach remarkable values. The main harm caused by this local heating might be the significant reduction of the motor life by the thermal affect on the bearings and stator insulation.

2.3.2 Torque Pulsations and Torque Losses

SLL has a negative effect on the torque characteristic of the motor. It is well known that the steps in (mmf) distribution around the air-gap cause the tooth-frequency harmonics. These harmonics produce asynchronous torques. The shape of this higher frequency harmonic curves is similar to the shape of the fundamental harmonic (with the order $\nu = 1$). The direction of rotation of these harmonics alternate and can be positive or negative in relation to the fundamental. The point of synchronous speed for each of these harmonics is equal to n_s/ν, where n_s is the fundamental synchronous speed and ν is the order of the respective harmonic. Because of the influence of these high frequency asynchronous torques the resultant torque curve has peaks and troughs especially in the range between the starting point (slip equal one) and the maximum torque point (critical slip). Figure 2.1 is the graphical representation of the experimental torque-speed characteristic of the Baldor 30hp, 460V, 36A 60Hz, 1780rpm, $\eta = 92.4\%$ squirrel cage induction motor that was tested in the MSRF lab. At the speed range between 0 and 300rpm, we can clearly see the torque rippling caused by the asynchronous torques which have the same nature as SLL. These torque dips on the curve create minimum torque point that is less than the starting torque. When the value of the minimum torque is too low it can create problems with starting the motor. Some researchers have noticed the relationship between the asynchronous parasitic torques and the SLL. This may be one method of estimating SLL, through measurement of the asynchronous parasitic torques.

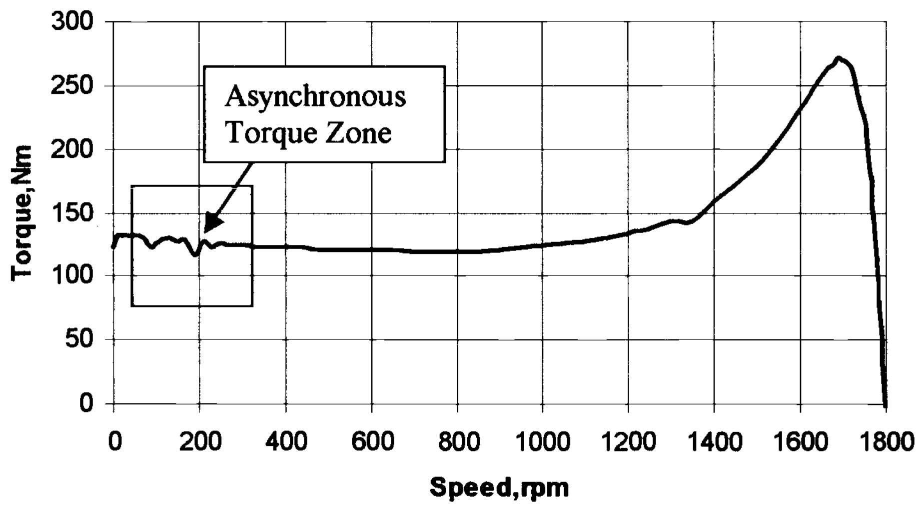

Figure 2.3 Torque-speed characteristic of the Baldor 30hp, 460V, 36 A 60Hz, 1780 rpm, $\eta = 92.4\%$ squirrel cage induction motor

2.3.3 Acceleration and Deceleration

In some cases SLL can increase the duration of start and stop of the motor that should be taken into account when designing high speed drives.

2.3.4 Efficiency

In the case when the efficiency is not determined by the input-output method, the real value of SLL in the motor can exceed the value that was determined by taking the percentage of the input power (or other similar way) and because of this, the efficiency value could be found along with the error.

3 EXPERIMENTAL METHODS OF EFFICIENCY AND STRAY LOAD LOSS DETERMINATION

3.1 Testing of the Induction Motor According to IEEE Standard 112-1996 Form A Method A

The test method according to IEEE Standard 112-1996 (Form A, Method A) is the simplest method of efficiency determination. Mostly, it is recommended for the fractional horsepower motors. Before performing the test, the value of the winding cold resistance should be determined together with the motor temperature. The test is supposed to be performed under the load conditions. The load might be created by the means of a mechanical brake or a dynamometer. The readings of the electric power, current, voltage frequency motor speed, torque, ambient temperature, and stator winding resistance should be recorded during the test. It is recommended to test the motor at least at six points of the load. These points should be uniformly distributed between 25 % and 150 % of the load, but not exceeding 150 %. The loading of the machine should start at the highest load value and then move progressively to the lowest point. A better way to find the winding temperature is by quick measurement of the motor winding resistance after the data is taken and the motor is stopped. The IEEE standard recommends finding the stator winding temperature by measuring the stator winding resistance. The stator winding temperature can be found by the formula

$$t_t = t_b + \left(\frac{R_t - R_b}{R_b}\right)(t_b + k) \tag{3.1}$$

where: t_t is the total temperature of winding, at which R_t was measured;

R_t is the resistance measured during the test;

R_b is the value of cold resistance previously measured at known temperature t_b;

t_b is the temperature of winding when cold resistance R_b was measured.

It should be mentioned that if the winding temperature is not known, the temperature of motor surface can be used. If the motor temperature cannot be measured precisely, the ambient temperature can be used as the motor winding temperature, but in this case, the motor needs to stay cool for a relatively long time.

k is usually equal to 234.5 for the copper windings.

After calculation of the winding temperature, the stator resistance value should be brought to the specified temperature. According to the Standard IEEE 112, the specified temperature should be chosen from the following parameters:

a) The measured temperature rise by the resistance from a rated load temperature test plus 25°C. In this case, it is necessary to perform a load test at 100% load, during which the temperature stability should be obtained. The temperature stability means that the change of the temperature of different parts of the motor during a specific time will be less than some previously determined value. In the MSRF practice, for instance, we consider the temperature stability when the temperature of the motor case that is measured at two points (in the middle of the motor case and at the bearings area) for both measurements will be less than 0.3° over 10 min. Then, the temperature rise from the test can be found as

$$t_{rise100\%} = t_{w1} - t_{amb} \tag{3.2}$$

where:

t_{w1} is the stator winding temperature that is measured at 100% load after getting temperature stability;

t_{amb} is the ambient temperature.

From this, the specified temperature can be found as:

$$t_s = t_{rise100\%} + 25°C \tag{3.3}$$

b) the measured temperature rise in a duplicate machine;

c) In the case, when the rated load temperature rise for some reason cannot be measured, the resistance of the winding should be corrected to the temperature shown in Table 3.1.

Table 3.1

Class of Insulation System	Specified Temperature in °C
A	75
B	95
F	115
H	130

During the test, the following motor parameters need to be recorded: the phase voltage V_{ph}, the phase current I_{ph}, the input power P_{in}, the power factor pf, the motor speed n, and the motor torque T. The sequence of the output parameters calculation after finishing the measurements is the following.

Observed slip:

$$s = n_s - n \tag{3.4}$$

where n_s is the synchronous motor speed.

Stator electrical loss:

$$P_{cu1} = 3I_1^2 R_{ph} \tag{3.5}$$

where R_{ph} is the stator phase resistance value that is measured after taking each load point. Then, the stator winding temperature for each load point can be found from (3.1). The value of the specific temperature should be determined from (3.2) and (3.3). After that, the value of the stator winding resistance corrected to the specified temperature should be found from the following equation:

$$R_s = \frac{R_t(t_s + k)}{(t_t + k)} \tag{3.6}$$

where t_s is the specified temperature for the resistance correction, in °C;

R_t is the test value of the winding resistance at temperature t_t ;

t_t is the winding temperature, when the resistance was measured;

k =234.5 for the copper wires.

After finding the corrected resistance value, the stator electrical loss (corrected to the specified temperature) can be found:

$$P_{cu1s} = 3I_1^2 R_s \tag{3.7}$$

Then, we can calculate the difference between the two values of stator electrical loss corrected to the specified temperature and the one that is not. This difference can be called "stator power correction" and might be found from:

$$\Delta P_{cu1} = P_{cu1s} - P_{cu1} \tag{3.8}$$

The corrected value of the input power is:

$$P_{1s} = P_{1m} + \Delta P_{cu1} \qquad 3.9)$$

where P_{1m} is the measured value of the electrical input power for every load point. Then, the slip value should be corrected to the specified temperature by the following equation:

$$s_s + \frac{s_t(t_s + k)}{t + k} \tag{3.10}$$

The corrected value of speed might be determined as:

$$n_{cor} = n_s(1 - s_s) \tag{3.11}$$

The value of the shaft (output) power can be determined from the expression:

$$P_{out} = \frac{T n_{cor} 2\pi}{60} \tag{3.12}$$

where T is the measured torque value, Nm.

And, finally, the efficiency value is equal to:

$$\eta = \frac{P_{out}}{P_{1s}} 100\% \tag{3.13}$$

3.2 Testing of the Induction Motor According to IEEE Standard 112-1996 Form B Method B (the Indirect Method of SLL Determination)

The test Method IEEE 112 B has some differences with the test method IEEE 112 A. During the test 112B, the rated load temperature test should be performed. The rated load temperature test is made by setting 100 % of the rated load and continuing the test until the temperature stability is reached. The other important feature of the Test 112 B method is that no load test and the loss segregation should be performed.

No Load Test:

The motor should be decoupled from the load and the test must be performed for the different voltage values. It is recommended to start with the highest voltage value (usually 120% of the rated voltage) and then to reduce the voltage until the current stops decreasing and starts going up. The readings of the voltage, current, input power and stator winding resistance should be taken during the test. Some motors may experience a change in the friction loss until the bearings will reach a stabilized operating condition. The stabilization is considered to have occurred whenever the power input does not vary more than 3% between two successive readings at the same voltage in 30 minutes intervals.

The loss segregation might be done in the following sequence. Usually, the no-load power P_0 can consider as the sum of stator electrical loss by the no-load current, core loss, and friction and windage loss. The no-load electrical loss equals:

$$P_{cu\_nl} = 3I_0^2 R_0 \tag{3.14}$$

where I_0 is the no load current;

R_0 is the stator winding resistance.

Thus the sum of the core loss and friction and windage loss can be found by:

$$P_c + P_{fw} = P_0 - P_{cu\_nl} \tag{3.15}$$

The core loss and the friction and windage loss can be separated graphically by plotting the sum of $P_c + P_{fw}$ versus voltage squared. The point of the intersection of the $P_c + P_{fw}$ curve with the ordinate axis will show the friction and windage loss value (Figure 3.1). By doing this, we assume that the core loss equals zero at zero voltage.

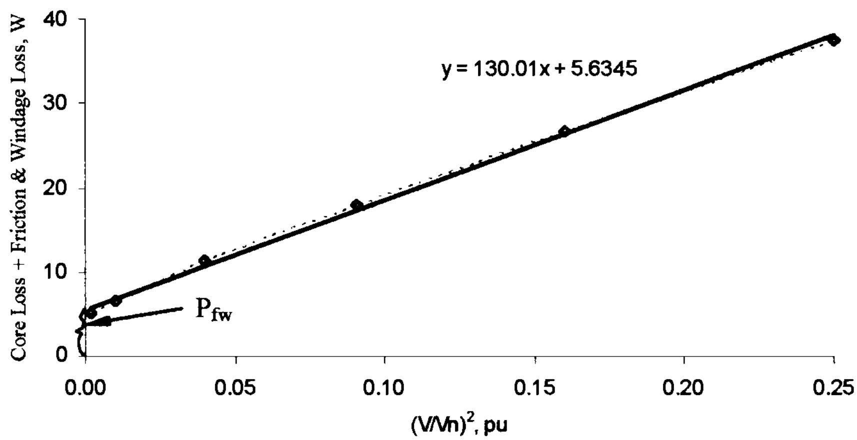

Figure 3.1 Segregation of the friction and windage losses

After that, the core loss for the rated voltage can be found:

$$P_c = (P_c + P_{fw})_{rated} - P_{fw} \tag{3.16}$$

The rest of the experimental part of the Method 112B is quite similar to Method 112A.

The sequence of the output parameters calculation is the following. The values of the voltage V, the current I, the input power P_{in}, the torque T and the speed n are obtained from the load test. The stator winding temperature can be found from (3.1), the slip can be determined from (3.4), the stator I^2R loss should be calculated by (3.5).

The power across the air gap can be determined by subtracting the stator I^2R loss and the core loss from the input power:

$$P_{gap} = P_{in} - P_{cu1} - P_c \tag{3.17}$$

The rotor loss can be found from the expression:

$$P_{cu2} = P_{gap} \frac{s}{n_s} \tag{3.18}$$

where n_s is the synchronous speed.

After all, the total conventional losses can be found as a sum:

$$\sum P_{conv} = P_{cu1} + P_c + P_{cu2} + P_{fw} \tag{3.19}$$

The output (shaft) power can be found from (3.12).

The apparent total loss is:

$$\sum P = P_{in} - P_{out} \tag{3.20}$$

The preliminary value of the stray load loss is equal to:

$$P_{SLL} = \sum P - \sum P_{conv} \tag{3.21}$$

After this point, the specified temperature and the value of winding resistance corrected to the specified temperature can be found from (3.3) and (3.6) respectively.

The corrected power across the air gap can be found from the formula:

$$P_{gaps} = P_{in} - P_{cu1s} - P_c \tag{3.22}$$

The values of the corrected slip and the corrected speed can be found from (3.10) and (3.11) respectively.

The rotor loss needs to be corrected to the specified temperature and will be equal to:

$$P_{cu2s} = \frac{P_{gaps} s}{n_s} \tag{3.23}$$

After that, the SLL correction needs to be done. This action might be performed in several steps. The first step is to plot the experimental results calculated from (3.21) versus motor torque squared, and then the dependency $P_{SLL} = f(T^2)$ should be represented as a formula:

$$P_{SLL} = AT^2 + B \tag{3.24}$$

where P_{SLL} is the SLL as plotted versus torque squared;

T is the torque:

A is the slope;

B is the ordinate of the interception with the zero torque line.

Now, it is possible to get rid of the offset error by putting the SLL line to the origin.

$$P_{SLLcorr} = AT^2 \tag{3.25}$$

On the Figure 3.2 we can see the process of smoothing and correcting the SLL for a Toshiba motor, nameplate details of which are: 5 hp, 460V, 60 Hz, 1730 rpm, 6.5A, $\eta = 85.5\%$.

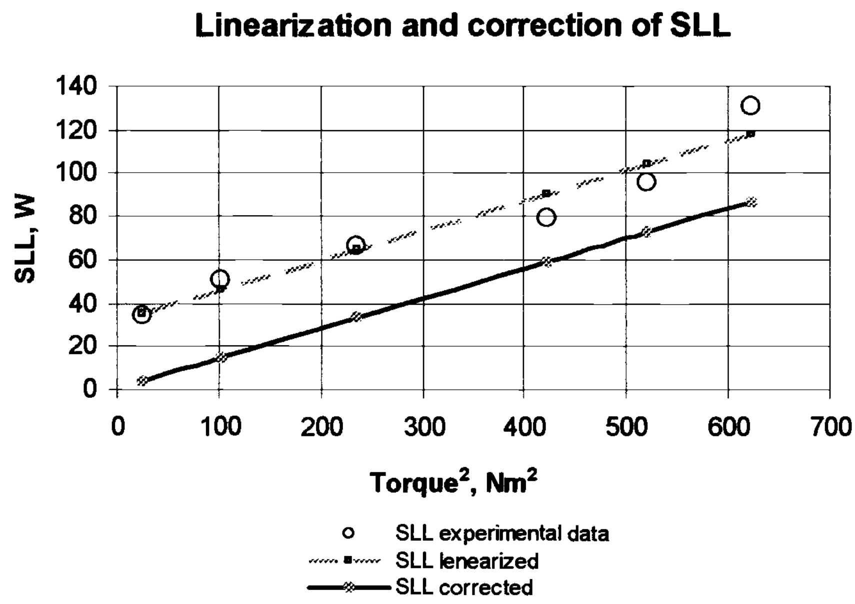

Figure 3.2 Linearization and correction of the SLL

The corrected total loss will be equal to:

$$\sum P_{corr} = P_{cu1s} + P_c + P_{cu2s} + P_{fw} + P_{SLLcorr} \tag{3.26}$$

The corrected output (shaft) power value is equal to:

$$P_{outc} = P_{in} - \sum P_{corr} \tag{3.27}$$

The efficiency value can be found from the formula:

$$\eta = \frac{P_{outc}}{P_{in}} 100\% \tag{3.28}$$

It should be mentioned that according to this method, the SLL value is a relatively small number that is obtained by the subtraction of nearly equal numbers much larger than SLL. Thus, any relatively small value of error in the measurment of the input and output power can become significant in the final result. According to the state of art with the instruments that exist nowadays, the precision of the electrical measurements is much higher than the precision of the mechanical parameters like torque and speed, so, a very important problem for the true determination of electrical motor efficiency is the constant development of the high precision torque and speed transducers and measuring devices.

3.3 Test Method IEEE 112-E (Direct Method of SLL Determination)

3.3.1 Reverse Rotation Test – Rotor Removed Test

This test method was incorporated into the American Standard test code for polyphase induction motors and generators in 1954. This test method is based on the following assumptions [1]:

a) The fundamental frequency component of the stray load loss occurs only in the stator;

b) Tooth-ripple and pulsation harmonics are the main sources of high-frequency components of SLL;

c) The stray losses can only be supplied by mechanical power;

d) The values of the high-frequency losses are the same for both full speed forward and reverse rotation;

e) High-frequency losses are independent of the supply, DC or AC under short circuit conditions.

Technically, this test includes two independent tests: reverse rotation test and rotor removed test.

Rotor Removed Test

The rotor removed test that was suggested by Ware [2], is used for the determination of the fundamental frequency component of SLL. This test should be performed with the motor in which the rotor is removed, but all the other parts (like bearings, bearing plates and shields) should be in place.

Before performing the test, the value of the stator winding current should be determined. According to [6], this value is equal to:

$$I_s = \sqrt{I^2 - I_0^2} \tag{3.29}$$

where I_s is the value of the stator winding current during the rotor removed test;

I_0 is the value of no-load current;

I is the operating value of stator line current for which the SLL needs to be determined. If it is necessary to find SLL at a load that is different from 100%, the value of the stator current I should be recalculated. The configuration for the rotor removed test is shown on Figure3.3.

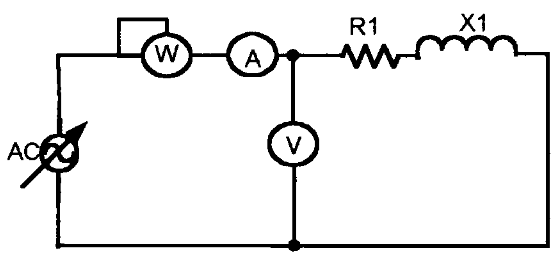

Figure 3.3 Configuration for the rotor removed test

The test should be performed by the following method: AC voltage is applied to the stator terminals, and (starting from zero) it should be increased until the preliminary value of stator current I_s is reached. Then, the readings of the voltage, current, input power and stator winding resistance should be recorded. The stator winding current loss during the rotor removed test will be equal to:

$$P_{cuRR} = 3I_s^2 R_1 \tag{3.30}$$

where R_1 is the measured value of the stator winding resistance.

The fundamental frequency component of the stray load loss can be found from the expression

$$P_{SLLf} = P_{RR} - P_{cuRR} \tag{3.31}$$

The Reverse Rotation Test

This test is sometimes called the “Morgan test” after its’ author. The main purpose of this test is to find the high frequency component of the SLL by testing the motor under a 200 % slip condition. Technically, that means that the motor field should rotate in one direction and the rotor should be driven by a special machine with a synchronous speed in the opposite direction. During the test, 3-phase voltage should be applied to the motor. The motor current value could be obtained by adjusting the voltage level, and (3.29) is then used to calculate it.

The test can be performed in two stages. During the first stage, the tested motor should be driven with a synchronous speed without energizing, using the load machine in the direction which is opposite its’ normal operation. The value of the speed and torque should be measured and controlled. During the second stage, the motor should be driven in the same direction, but the stator winding needs to be energized with the voltage level that provides the current from (3.29). The reading of the voltage, current, input power, torque, speed and stator winding resistance should be taken at each point.

The mechanical power required to drive the rotor without voltage being applied at the stator winding terminals is given by:

$$P_m = T\varpi_r \tag{3.32}$$

where T is the torque value, which is measured during the test;

$\varpi_r = \dfrac{2\pi n_s}{60}$ is the angular speed of the rotor;

n_s is the rotor speed that in ideal case should be equal to the synchronous speed.

The high frequency component of the SLL is equal to:

$$P_{SLLhf} = (P_{men} - P_m) - (P_{rev} - P_{RR} - P_{cu1\mathrm{Rev}}) \tag{3.33}$$

where P_{men} is the mechanical power that is required to drive rotor with voltage being applied to the stator;

P_m is the mechanical power that is required to drive the rotor without voltage being applied to the stator;

P_{rev} is the electrical input power to stator winding during the reverse rotation test;

P_{RR} is the electrical input power to the stator winding during the rotor removed test;

P_{cu1Rev} is the current loss in the stator winding during the reverse rotation test.

The SLL can be found as a sum of fundamental frequency and high frequency stray load losses.

$$P_{SLL} = P_{SLLf} + P_{SLLhf} \tag{3.34}$$

After that, the SLL curve needs to be smoothed by using a regression analysis. For smoothing the decimal logarithm of the functions $(P_{men} - P_m)$, P_{rev} and P_{RR} should be found. Then, each of them needs to be plotted versus the decimal logarithm of the current, for example, $\log(P_{men} - P_m) = f(\log(I))$ (see Figure 3.4). Then, the curve fitting by using a linear regression is done.

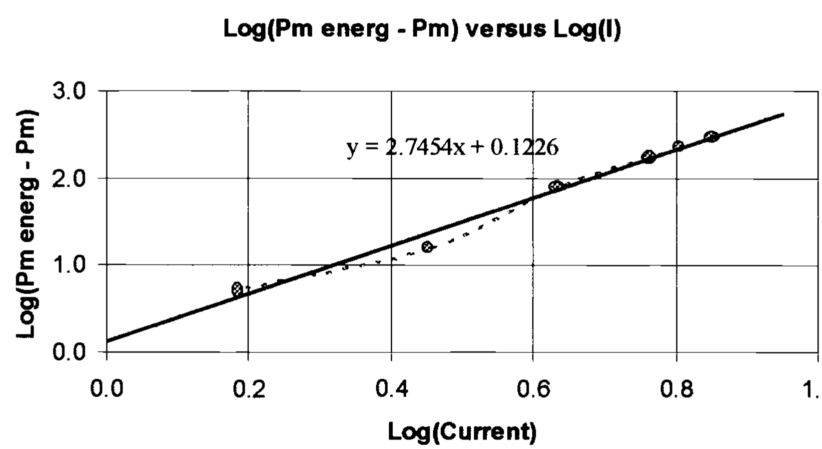

Figure 3.4. Smoothing the components of SLL

For each of those logarithmic curves, we can find the slope N (for example, for the Figure 3.4 N=2.475), and the ordinate of the intersection A (equal to 0.1226). The same procedure has to be done for all of the functions mentioned above. After that, these functions can be expressed as: $(P_{men} - P_m) = A_1(I)^{N_1}$, $P_{RR} = A_2(I)^{N_2}$ and $P_{rev} = A_3(I)^{N_3}$. Finally, we can find the stray load loss for any load current from the equation [6]:

$$P_{SLL} = A_1(I)^{N_1} + 2A_2(I)^{N_2} - A_3(I)^{N_3} - 3I^2(2R_{1RR} - R_{1rev}) \tag{3.35}$$

where R_{1RR} is the stator phase winding resistance during rotor removed test at the test temperature;

R_{1rev} is the stator phase winding resistance during the reverse rotation test at the test temperature.

3.3.2 Efficiency Determination by Method IEEE 112-E

According to this method, the output torque may not be measured. All of the others measurements should be performed similarly to the IEEE 112-B method (including no-load test and loss segregation). All of the parameters need to be corrected to the specified temperature, thus the input power P_{in} and the conventional losses P_{cu1s}, P_c, P_{cu2s}, P_{fw} have to be determined similarly to the IEEE 112-B method. The SLL should be determined as shown in the 3.3.1 section of this chapter. The output (shaft) power value equals:

$$P_{outs} = P_{in} - \sum P_c \tag{3.36}$$

The efficiency value can be calculated from the formula:

$$\eta = \frac{P_{outs}}{P_{in}} 100\% \tag{3.37}$$

3.3.3 Efficiency Determination by Method IEEE 112-E1

The overall method is similar to the 112-E method. The only significant difference is that (according to this method) the SLL at the rated load depends on the motor output power and may be chosen from the Table 3.2 [6].

Table 3.2

Assumed Values for SLL

Machine Rating		Stray-Load Losses Percent of Rated Output
1-125 hp	1-90 kW	1.8 %
126-500 hp	91-375 kW	1.5 %
501-2499 hp	376-1850 kW	1.2 %
2500 hp and greater	1851 kW and greater	0.9 %

3.3.4 Calorimetric Method of the Efficiency, Total Losses and SLL Determination

The highest precision approach for the evaluation of the overall efficiency of the electric motor, the total loss and hence, the value of the stray load losses is undoubtedly a calorimetric method. On the other hand, this method is technically complex, time consuming, and does not fit well in industrial environment. The main principle of this method is the direct measurement of the total heat (losses) produced in the machine. For this purpose, the motor should be placed inside a special, thermally insulated enclosure, while the motor is under load. The power losses of the motor convert into heat, which is then transferred to the air inside the enclosure by conduction, convection and radiation. Then the heat energy needs to be extracted from the enclosure by using special heat exchanging device with the circulating a coolant substance that can be either liquid or gas. Usually, water or air can be used for a calorimeter method as a coolant. In steady state, the heat extracted from the box is equal to the motor total loss. The heat that is removed from the box should be evaluated by measuring the coolant temperature at the entry to the calorimeter, coolant temperature at the exit from the calorimeter, and the volume rate of cooling flow. The total sum of the motor losses can be found from the equation [9]:

$$\sum P = Qc_p\Delta\vartheta_t \tag{3.38}$$

where $\sum P$ is the sum of the losses dissipated in the motor;

Q is the volume rate of flow of cooling medium;

c_p is the specific heat capacity of cooling medium;

$\Delta\vartheta_t$ is the difference in temperature of the cooling medium at the entry to the calorimeter and at the exit.

As mentioned above, the input electrical power of the motor can be determined with the good precision by using special laboratory electrical equipment, for example power analyzers. Knowledge of the input power and the sum of the losses enables finding an efficiency using (3.36) and (3.37). For the precision evaluation of each motor loss component and the SLL, particularly the additional no load test, should be done.

The calorimetric method has one important advantage in comparison to all the other methods of efficiency determination: it enables avoidance of the least precise measurement of the evaluation (torque measurement) as in method IEEE 112-B, or statistical evaluation of SLL as in IEEE 112 E1. On the other hand, it requires bulky and complex test equipment and expends a large amount of testing time to obtain temperature stability.

3.3.5 DC Excitation Method

This method is similar to "reverse-rotation – rotor removed test method" [10]. According to this method, the following three separate tests should be performed: a rotor removed test, a direct current excitation test and a regular AC blocked rotor test. The rotor removed test that is performed to determine the fundamental frequency component of SLL is described above. The DC excitation and blocked rotor tests are performed to find the high frequency component of the SLL. The AC blocked rotor test is well known, so only the DC excitation rotation test will be described here. During this test, the tested motor should be driven at a synchronous speed with the use of a loading machine, and DC excitation should be applied to two of three phases of the stator winding. The input mechanical power (torque and speed) needs to be recorded. The direct current value should correspond to the peak value of the alternating load current from (3.29).

The input mechanical power of the motor during the DC excitation test is equal to:

$$P_{Mch} = P_{cu1} + P_{cu2} + P_{SLLhf} \tag{3.39}$$

where P_{cu1} and P_{cu2} are the electrical losses in the stator and in the rotor, respectively;

P_{SLLhf} is the high frequency component of the SLL.

After the blocked rotor AC test, the P_{SLLhf} can be determined as:

$$P_{SLLhf} = P_{Mch} - P_{BR} \tag{3.40}$$

where P_{BR} is the value of blocked rotor test power .

During the blocked rotor test the current should correspond to the current condition of DC excitation test. Further, the total SLL can be determined similarly to how it is described above in Section 3.3.1

4. EXPERIMENTAL EVALUATION OF SLL AND EFFICIENCY AT DIFFERENT SUPPLY FREQUENCIES FOR 5 HP, 10HP AND 30 HP INDUCTION MOTORS

4.1 Statement of the problem

Due to the need to improve the process control and efficiency there is a significant increase in the use of induction motors controlled by adjustable speed drives (ASDs) in industry over the past few years. Unlike the supplies for motor testing laboratories, the ASDs do not usually provide a source of low harmonic distortion voltage for the motor, which further complicates the efficiency/loss issue. Also, accompanying a significant shift of motor manufacturing to factories overseas, there is a need to understand how testing at 50 Hz and 60 Hz can be related and how efficiencies are affected. At the same time, as follows from the information given in the Chapter 3, the IEEE Standard 112-1996 recommends to test electrical induction motors in a rated mode (nominal frequency and voltage). Thus, the IEEE 112 test usually does not provide us with information about the motor efficiency and stray load losses at supply frequencies, which are different from the rated value. However, this information is very important for the correct evaluation of the motor efficiency at different stator current frequency modes. Therefore, one of the projects of MSRF Laboratory at Oregon State University was directed to the investigation of the stray load losses and efficiency of the induction motors under frequencies that are different from the rated conditions over a wide range of loads.

4.2 The Description of the Experiment and Test Equipment

With the purpose to examine the influence of the voltage frequency on the motor terminals on the stray load losses and the efficiency of the motor on different load levels (from 25% to 120% of rated), a series of tests have been performed on a selections of low-voltage induction motors over a range of frequencies (46, 50, 55, 60 and 65 Hz). A group of three motors 5 hp, 10 hp and 30 hp was tested during the realization of the experiment. The name plate data of these motors are given in the Table 4.1 below.

Table 4.1.

Parameters	Motor #1	Motor #3	Motor #3
Motor Manufacturer	Toshiba Corporation	Toshiba Corporation	Baldor Elec. Corporation
Model No	B0054DGF2AA	B0104DGF2U3	40G48W136
Power, hp/kW	5 / 3.73	10 / 7.46	30 / 22.38
Poles	4	4	4
Insulation Class	B	B	B
Nema Design	B	B	B
Nema Nom. Eff, %	85.5		92.4
Code	J	G	G
S.F.	1.15	1.15	1.15
Volts	230/460	230/460	230/460
Hz	60	60	60
Amp	13.0/6.5	26.8/13.4	72/36
RPM	1730	1740	1780
Max Ambient, °C	40	40	40
Time Rating	CONT	CONT	CONT
Frame	184T	215T	286T

Figure 4.1 shows a schematic of the test laboratory for this project. For the motors of 5 hp (3.73 kW), and 10 hp (7.46 kW), a 15 hp test platform (Figure 4.2) with a DC separate excitation machine as a dynamometer and a 3-phase rheostat as a load was used. For the 30 hp (22.4 kW) motor, a 300 hp test rig was used. During the test, the load for this motor was created by 300 hp squirrel-cage induction machine fed from the four-quadrant PWM inverter and controlled from the computer with special software. When the load machine (dynamometer) works as a generator, the electrical energy after filtering flows back to the network.

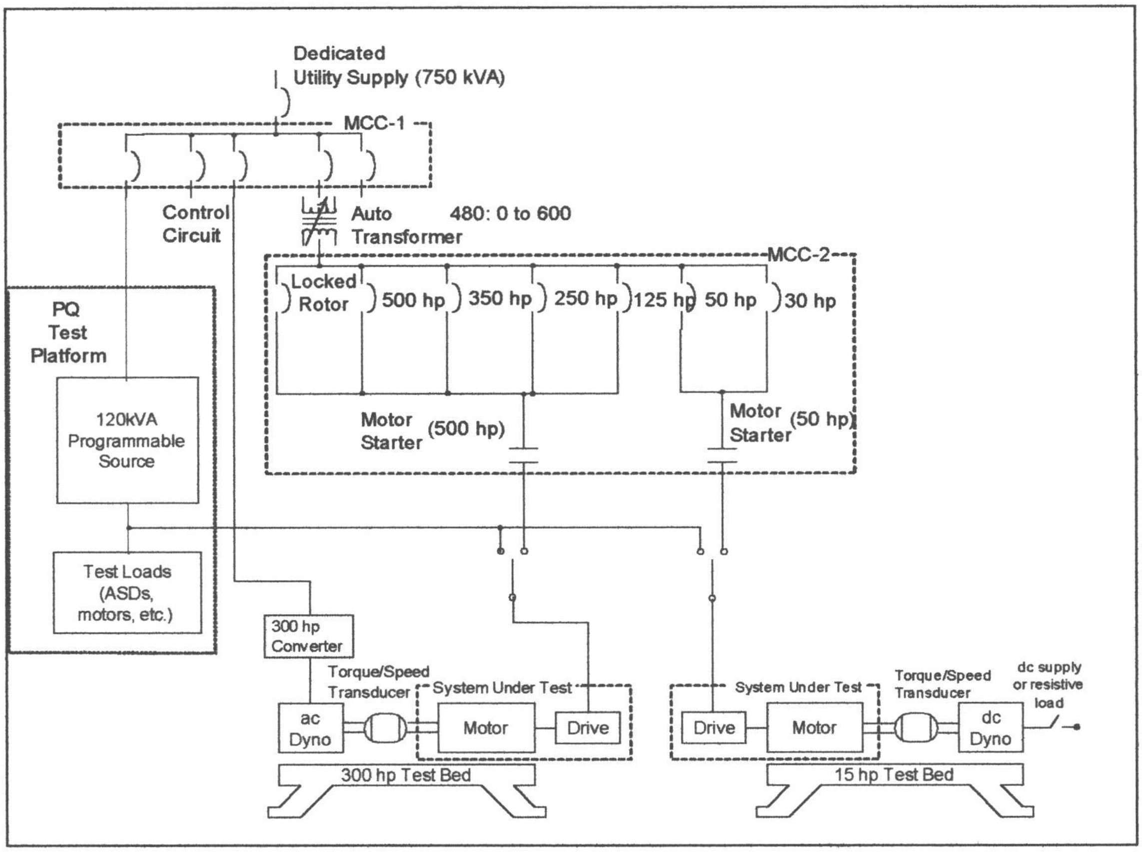

Fig. 4.1. Schematic of test laboratory, the Motor Systems Resource Facility (MSRF).

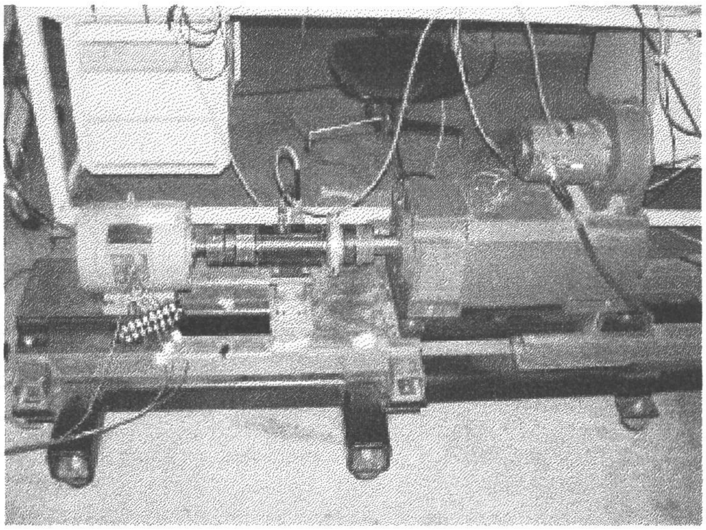

Figure 4.2. 15 hp test rig with the 5hp tested motor.

The tested motors were supplied electrically from the Behlman Programmable Source, (Figure 4.3) enabling creation of a voltage periodical signal of either one, two, or three phases of almost any shape within the range of parameters that is given in Table 4.2

Table 4.2

Manufacturer	Behlman Electronics
Output Phase Voltage	0-305 V
kVA	0-120
Frequency	50, 60, 400; 45-500 Adj
Amp/Phase	0-144

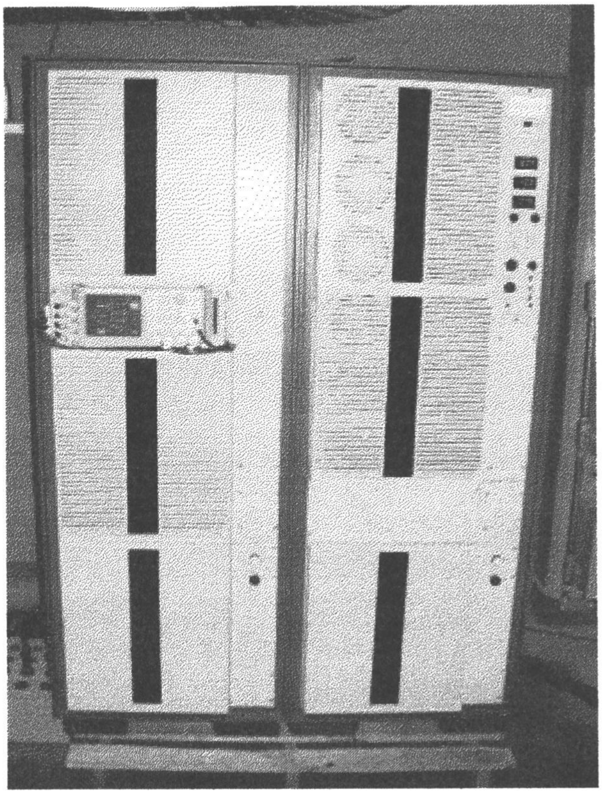

Figure 4.3 “Behlman Electronics” Programmable Source

During the tests, the input electrical parameters were measured by a Voltech PM 3300 Universal Power Analyzer (Figure 4.4) configured for a "Three Phase – Three Wire" method. The voltage was measured using direct connections to the analyzer. For the phase current measurements, the Voltech current transformers with the ratio of 100:1 were used. In addition to the quantities needed to specify the motor performance (voltage, current, power and power factor), the power analyzer also provided monitoring of the frequency and total harmonic distortion (THD) of the voltage and current supplied by a programmable source.

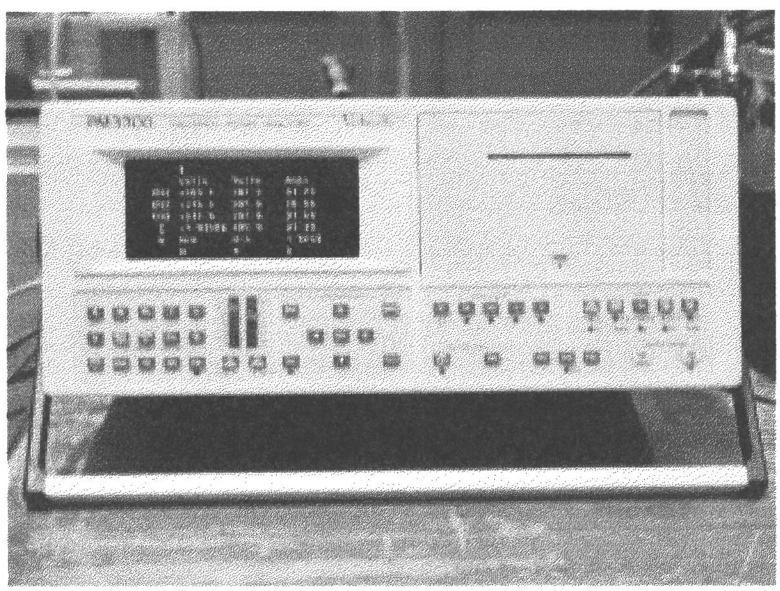

Figure 4.4 Voltech PM 3300 Universal Power Analyzer

For the motor shaft torque and speed measurements, Lebow strain gage transducers with the digital indicator (model 7540) were used. The torque transducers were calibrated "end-to-end" by precisely known masses and torque arms prior to the tests.

The measurement of the motor stator winding line-to line resistance was made at completion of each test load point after stopping and disconnecting the motor from the supply by using the NGI digital Micro Ohmmeter D 3700 (Figure 4.5). In order to reduce the cooling that affects the precision of the measurements, this procedure should be performed as quickly as possible.

Figure 4.5 NGI digital Micro Ohmmeter D 3700

During the execution of the test according to the 112 B test method, the motor should be kept under permanent load (torque), until the temperature stability (equilibrium) is reached. Achieving the equilibrium was assumed every time when the difference between the values of two consecutive motor temperature measurements that were performed every 10 minutes was les than 0.3 °C. The thermocouples were installed in the shaft bearing area, at the top of the case and in the air about one foot from the motor. The temperature measurements were performed using the Fluke 80-TK Thermocouple modules, connected to the Fluke 45 multimeters.

4.3 The Voltage Determination Test

As we can see from the Table 4.1, all of the motors tested in this study are rated at 460V/60Hz so that in order to operate at other frequencies, the voltage needs to be adjusted. A commonly applied "rule of thumb" is the constant Volts/Hz ratio. However, if this is employed directly, it tends to somewhat change the full-load operating point. Because of this, a special method to choose voltage values for the different frequencies was found. According to this method, each motor was completely tested at 60 Hz at 100% load point. The experimental values of the motor torque T_r and relative slip s_r were determined for this load value. Then, for each of the frequency values (46, 50, 55, 60 and 65 Hz) the voltage value that allows the same motor torque and the same relative slip at a stable operating temperature that were obtained for the 60 Hz, 100% load was found. The same procedure was done for the each of the three tested motors. These voltage values were chosen as rated for the proper frequencies. The rated output power for each of the frequencies equals to

$$P_{out} = T_r \varpi_s (1 - s_r) = T_r \frac{2\pi f}{p}(1 - s_r) \tag{4.1}$$

Where f is the supply frequency value;

p is the number of pole pairs.

Table 4.3.

Frequency, Hz		46	50	55	60	65
Volt for const V/Hz, V		352.7	383.3	421.7	460.0	498.3
Volt for const Slip-Torque, V	5hp	402.6	415.0	440.5	460.0	477.0
	10 hp	402.6	408.3	428.0	460.0	490.0
	30 hp	420.0	425.2	453.9	461.4	469.5
Speed at 100% Load, rpm	5hp	1323	1438	1584	1726	1869
	10 hp	1323	1438	1581	1725	1872
	30 hp	1362	1481	1629	1777	1925
Rated Torque at 100% Load,	5hp	20.56	20.56	20.56	20.56	20.56
	10 hp	40.9	40.9	40.9	40.9	40.9
	30 hp	119.9	120.0	120.05	119.95	120.15
Rated Output Power , kW /hp	5hp	2.85/3.82	3.1/4.15	3.41/4.57	3.72/4.98	4.02/5.39
	10hp	5.67/7.60	6.16/8.26	6.77/9.08	7.39/9.90	8.00/10.73
	30hp	17.10/22.92	18.61/24.95	20.48/27.45	22.32/29.92	24.22/32.4

4.4 The No-Load Test

After the series of voltage determination tests and prior to the load tests, a series of no-load tests was performed. As was mentioned in Chapter 3, according to the method IEEE 112B, the no-load test results are necessary for the loss segregation calculations. The no-load tests were performed for all of the three tested motors for each of the investigated frequencies. The motor was kept running until the change of the input power taken during 30 minutes was less than 3 % for every voltage point. The no-load test results are given in the Table 4.4. From this table we can observe the influence of no-load voltage and frequency of the motor on the saturation of the core, and respectively on the no-load current value.

Table 4.4

Frequency, Hz		46	50	55	60	65
No- load Voltage, V	5hp	402.6	415.0	440.5	460.0	477.0
	10 hp	402.6	408.3	428.0	460.0	490.0
	30 hp	420.0	425.2	453.9	461.4	469.5
Core loss, W	5hp	171.2	146.3	147.4	143.2	141.9
	10 hp	235.6	204.4	185.5	223.5	247.0
	30 hp	473.8	385.2	390.3	361.2	362.9
Friction and Windage loss, W	5hp	3.0	3.7	4.3	5.1	5.7
	10 hp	14.1	16.8	19.4	26.4	30.4
	30 hp	43.7	48.3	68.2	78.8	71.9
No-load Current, A	5hp	4.0	3.39	3.06	2.73	2.49
	10 hp	5.57	4.59	4.11	3.87	3.76
	30 hp	22.09	17.6	16.26	13.73	12.37

We can see that the friction and windage losses are increasing with the speed, which is obvious. Also, the saturation of the motor is decreasing with the growth of frequency. Because of this, there is a tendency for the no-load current to decrease for all three motors. The core loss does not have such a clear dependency because we have a mixed effect of the increasing frequency and decreasing saturation. Therefore, there is no obvious core-loss tendency relationship. The full-load current also does not clearly show tendency to increase, which can be explain by the growth of output power with the frequency and the simultaneous decreasing no-load (magnetizing) component of the current.

4.5 The Internal Magnetizing Electromotive Force Determination

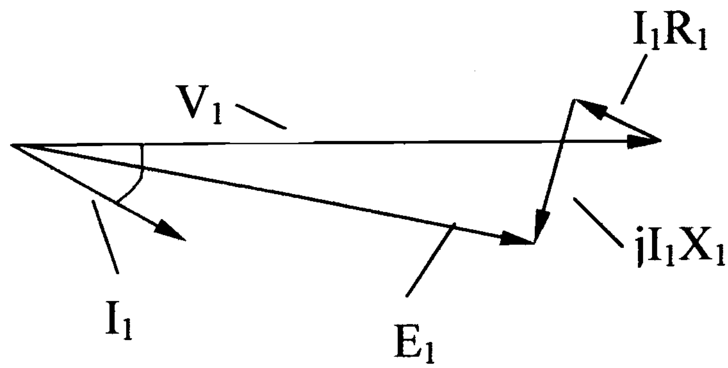

Figure 4.6 The phasor diagram for the calculation EMF

The other way to determine the saturation inside the motor core then the estimation of no-load current is to find the internal magnetizing electro-motive force (emf) E_1 for each value of frequency f and then to find the E_1/f ratio. The constant value of this ratio indicates that the saturation is the same. Usually, there is a problem to find the exact value of emf E_1 because the stator leakage reactance X_1 is not known. This value can be approximately determined by performing a blocked rotor test. However, in our investigation the special rotor removed test for the direct SLL determination was done, and thus R_1 and X_1 for each value of frequency were determined. The determination of E_1, when R_1 and X_1 are known is quiet straightforward, and can be done using the phasor diagram (Figure 4.6), based on the equivalent circuit of the induction motor. The voltage V_1 and current I_1 values can be found from the load test. The phase shift angle φ between the voltage and the current equals to $\arccos(pf)$, where pf is the measured value of power factor. Thus, from the phasor diagram, the emf equals to:

$$E_1 = V_1 - I_1 Z_1 = V_1 - I_1(R_1 + jX_1) \qquad (4.2)$$

The results of these calculations for the 5 hp, 10 hp and 30 hp motors are given in the Table 4.5.

Table 4.5

Frequency, Hz		46	50	55	60	65
Volt for const V/Hz, V		352.7	383.3	421.7	460	498.3
Stator Phase Winding Resist., Ω	5hp	2.142	2.142	2.142	2.142	2.142
	10 hp	1.152	1.152	1.152	1.152	1.152
	30 hp	0.144	0.144	0.144	0.144	0.144
Stator Phase Leakage Reactance, Ω	5hp	3.427	3.726	4.100	4.470	4.840
	10 hp	2.751	2.986	3.287	3.576	3.888
	30 hp	0.906	0.985	1.084	1.182	1.281
Electro-motive force, V	5hp	360.92	374.20	397.86	415.92	430.93
	10 hp	354.80	358.99	375.18	404.08	430.65
	30 hp	376.21	383.21	410.68	416.12	422.96
E_1/f	5hp	7.85	7.48	7.23	6.93	6.63
	10hp	7.71	7.18	6.82	6.73	6.63
	30hp	8.17	7.66	7.47	6.94	6.51

As we can see from Table 4.5, the motors are most saturated at 46 Hz. The most saturated motor at this point is 30 hp, the least saturated is 10 hp. This fact can be explained by the differences in the motor design for all three machines.

4.6 The IEEE 112B Load Test and the Reverse-Rotation/Rotor-Removed Test

After the series of no-load tests, the series of load test was performed. For each value of the frequencies, the motor was tested under the 25, 50, 75,100, 110 and 120 % load levels of the rated value. The general procedure of the test is described in the Section 3.2. During each of these six load tests, motor operating temperature stability must be ensured: the stator winding temperature must be determined (e.g. by precise resistance measurement) and the rotor slip is accurately established. This enables accurate segregation of the stator and rotor conduction (I^2R) losses. Finally, the title "stray load loss" is allocated to the difference between input and output power less than all of the loss components that are readily identified in the above categories. Albeit a little time consuming in laboratory hours, the process is fairly amenable to automation, and is well established and understood by testing laboratories. A representative data chart for an IEEE 112 B test is given in the appendix.

In contrast, IEEE Standard 112E provides the "direct measurement" of stray load loss. As described in the Section 3.3, this process involves driving the motor in the direction opposite to that expected from the sequence of its supply and measuring the shaft power both with and without the stator excitation. In addition, the motor must have its rotor removed, but otherwise be complete and reassembled, and the input power at normal stator terminal conditions must be measured. Throughout these "direct measurements", the stator resistance must be measured to enable the determination of the stator I^2R losses. Thus, the technique is not truly direct.

4.7 The IEEE 112B Test Results

From the Table 4.6, we can observe the percent contribution of the each loss component to the total loss at the different frequencies for all three motors. It should be mentioned that during the load test for a 30 hp motor that was performed on the largest 300 hp test rig, the dynamometer torque oscillations were observed, especially in a range of frequencies from 50 up to 60 Hz. These torque and at some points speed oscillations could definitely affect the measurements of accuracy, especially for the stray load loss determination.

From the analysis of the data contained in Table 4.6, it is obvious that the core loss to the total loss ratio is different for all of these motors, and it depends on the motor design. For the 5 hp and 30 hp motors the stable tendency of the core loss part to decrease with the frequency because of the saturation is observed.

Table 4.6

Frequency, Hz		46	50	55	60	65
Core loss to the Total loss Ratio,%	5hp	29.76	25.53	25.01	22.65	21.29
	10 hp	23.99	18.99	15.89	17.80	18.81
	30 hp	34.12	31.49	28.17	24.19	22.84
Frict & Wind Loss to the Total loss Ratio,%	5hp	0.53	0.65	0.73	0.81	0.85
	10 hp	1.44	1.56	1.66	2.10	2.32
	30 hp	3.15	3.95	4.92	5.28	4.52
Stator Current Loss to the Total loss Ratio,%	5hp	45.58	43.97	42.68	41.23	40.90
	10 hp	46.09	44.99	44.94	42.61	41.68
	30 hp	40.50	43.71	38.38	37.17	38.13
Rotor Current Loss to the Total loss Ratio,%	5hp	21.65	24.05	24.56	25.99	26.74
	10hp	24.78	25.92	27.41	26.18	25.97
	30hp	16.48	19.13	19.9	20.63	22.48
Stray-Load Loss to the Total loss Ratio,%	5hp	2.48	5.80	7.02	9.32	10.22
	10hp	3.70	8.54	10.09	11.31	11.22
	30hp	5.75	1.71	8.63	12.72	12.02

It is interesting that the share of the friction and windage loss in the overall loss is different for the motors, and it, probably, depends on the motor design and the types of the bearings. As was expected, the ratio of friction and windage loss to the overall loss increases with the frequency (rotor speed).

The stator current loss to the total loss ratio is slightly decreasing with the frequency. This may be explained by the reduction of the magnetizing current with the saturation.

The rotor current loss to the total loss ratio has a stable tendency to increase for all of the motors. This might be expected because under the same slip level (as it was explained before) the increasing of the stator frequency leads to the increase of the rotor frequency and, respectively, to the growth of the rotor emf and current.

The SLL in the total loss share does also have an established tendency to increase with the frequency, but after definite point (as we can see for the 10 and 30hp motors) this growth starts to slow down.

It should be mentioned that according to the IEEE 112 B process the "raw" data have to be taken from the tests, and then linearization of the results with the purpose of compensating for the inevitable experimental inaccuracies should be performed. After that it is recommended also to remove the offset error. This recommendation is based on the concept that SLL is by definition zero at no load. The "raw" (not corrected) data for the tested motors is shown in the Figures 4.7, 4.8 and 4.9.

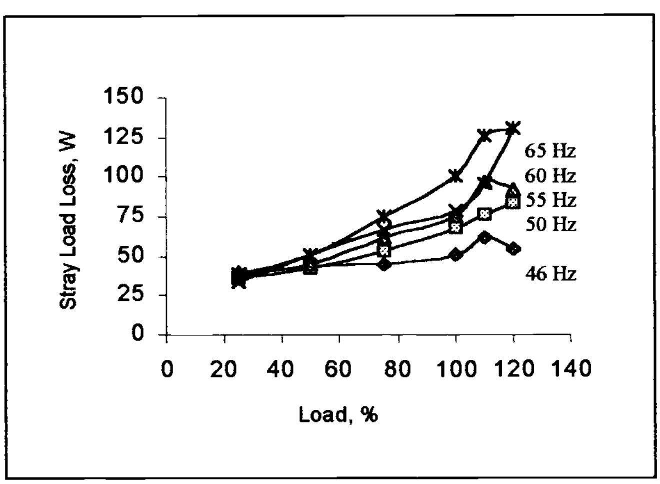

Fig. 4.7. Stray load loss for 5 hp motor before linearization and correction.

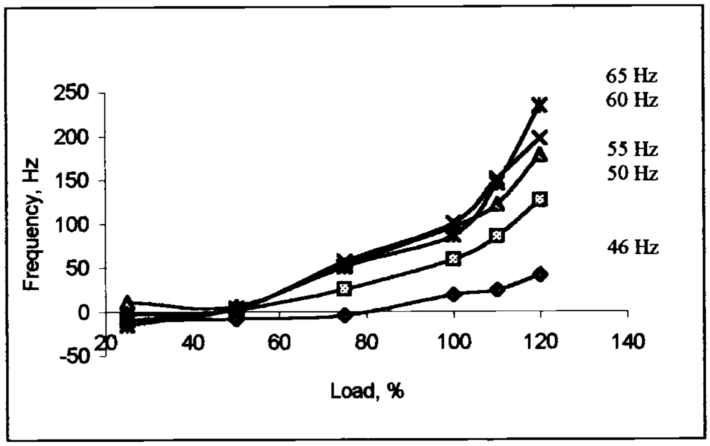

Fig. 4.8 Stray load loss for 10 hp motor before linearization and correction.

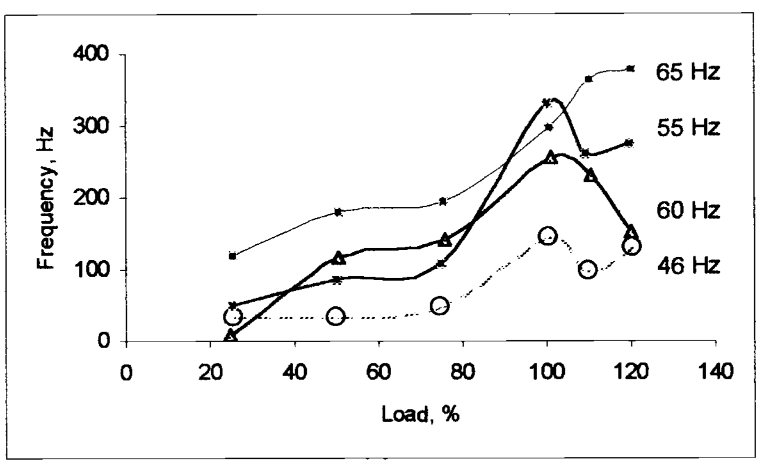

Fig. 4.9 Stray load loss for 30 hp motor before linearization and correction.

As we can see the disorderness of points for the 30 hp motor is much higher than for 5 hp and 10 hp motors. Because of this the results of stray load loss determination by the IEEE 112 B method will be excluded from the further discussion.

The SLL after the linearization and offset removal are presented in Fig. 4.10 and 4.11.

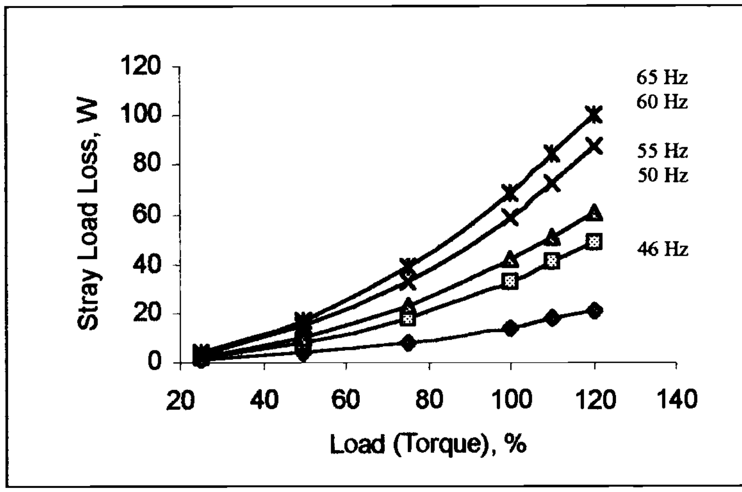

Fig. 4.10 Stray load loss for 5 hp motor versus load (torque) after linearization and correction

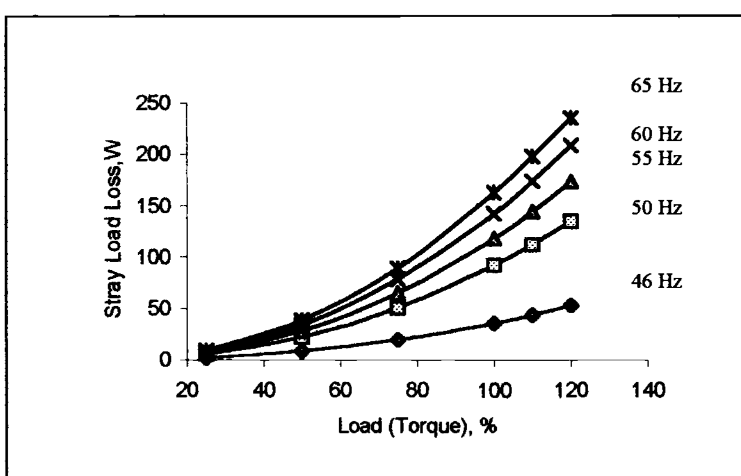

Fig. 4.11 Stray load loss for 10 hp motor versus load (torque) after linearization and correction

From Fig. 4.10 and Fig.4.11 it is evident that stray load loss is proportional to the square of the load and can be calculated from the expression:

$$P_{SLL} = a_f L^2 \tag{4.3}$$

where the coefficients, a_f for those two motors, are given in Table III for L being torque as a per unit of rated load.

Table 4.7

Hz	46	50	55	60	65
5 Hp	14.57	34.15	42.24	60.32	79.02
10Hp	36.85	93.58	119.76	144.56	164.09

Expressing the data of Fig. 4.10 and Fig. 4.11 in terms of frequency, rather than load, as shown in Figure 4.12 and Figure 4.13 indicates that the dependency between SLL and frequency for different load levels is very close to the linear..

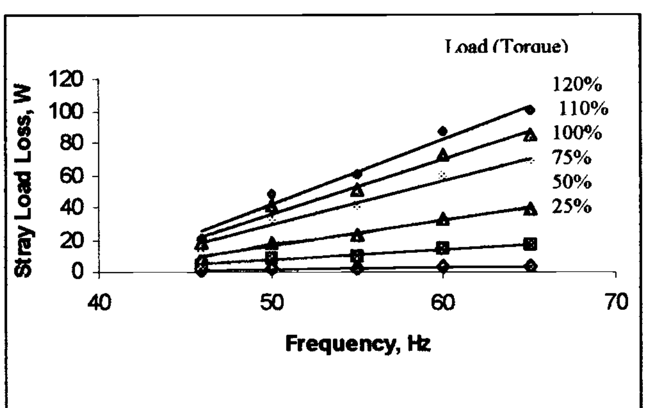

Fig. 4.12 Corrected stray load loss for 5 hp motor versus frequency.

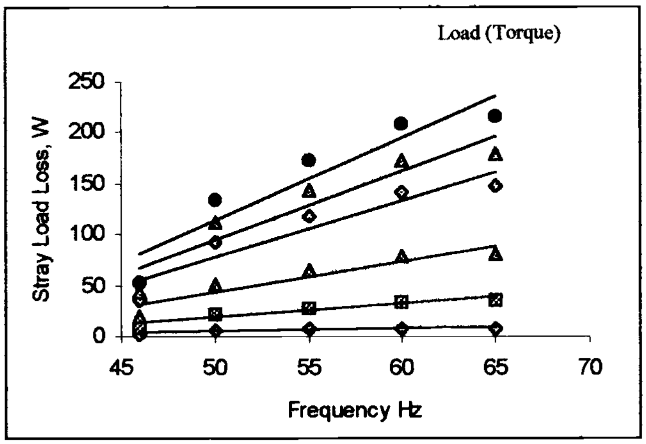

Fig. 4.13 Corrected stray load loss for 10 hp motor versus frequency.

The Table 4.7 shows the percentage of the measured SLL to the input power and to the output power ratio. This information is very interesting because according to the Method IEEE 112-E, the SLL can be determined as a constant percentage of the output power, and, according to the most of the European Standards, the SLL have to be determined as a fixed percentage of the input power.

Table 4.8

	Frequency, Hz	46	50	55	60	65
5 hp	SLL / P_{in}, %	0.41	0.90	1.03	1.35	1.44
	SLL / P_{out}, %	0.50	1.07	1.20	1.58	1.68
10hp	SLL / P_{in}, %	0.55	1.28	1.49	1.65	1.59
	SLL / P_{out}, %	0.64	1.50	1.75	1.93	1.85
30hp	SLL / P_{in}, %	0.43	0.10	0.54	0.79	0.74
	SLL / P_{out}, %	0.46	0.11	0.58	0.85	0.79

As we can see from the Table 4.8, the value of SLL / P_{in} and SLL / P_{out} for the different motors is different and dependent on the motor design. The value of 1.8 % for Stray-Load Losses Percent of Rated Output for 1-125 hp motors that is given by Method E1 of IEEE Standard 112 -1996 is slightly excessive and does not allow us to obtain the correct efficiency value. At the same time, the SLL / P_{in} ratio for all three motors exceeds the 0.5 % recommended by the most of the European Standards.

4.8 The IEEE 112E Test Results

The corresponding results for method IEEE 112E are shown in Figures 4.14 – 4.19 respectively. The comparison of the calculated values of line current, power factor and efficiencies are given in Table 4.9. For the comparison, the efficiency data is given for two test methods: IEEE 112 B and IEEE 112 E.

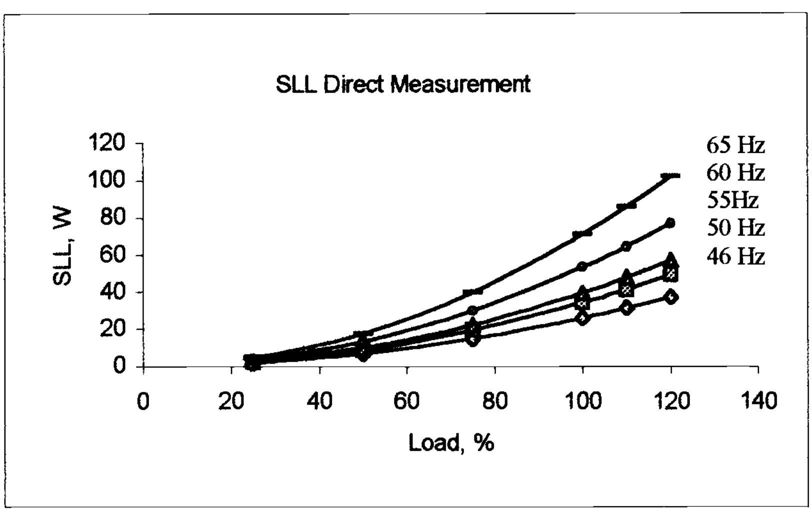

Figure 4.14 Stray load loss for a 5 hp motor versus the load obtained by direct measurements (method 112E).

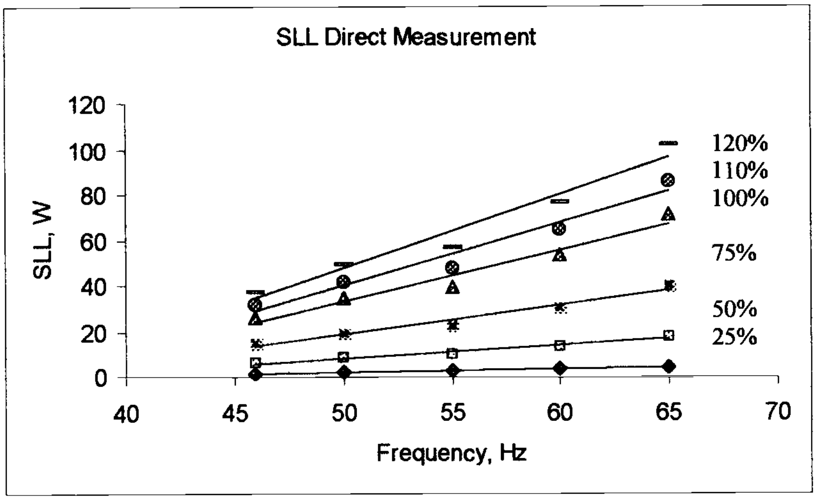

Figure 4.15 Corrected stray load loss for a 5 hp motor versus the frequency obtained by direct measurements (method 112E).

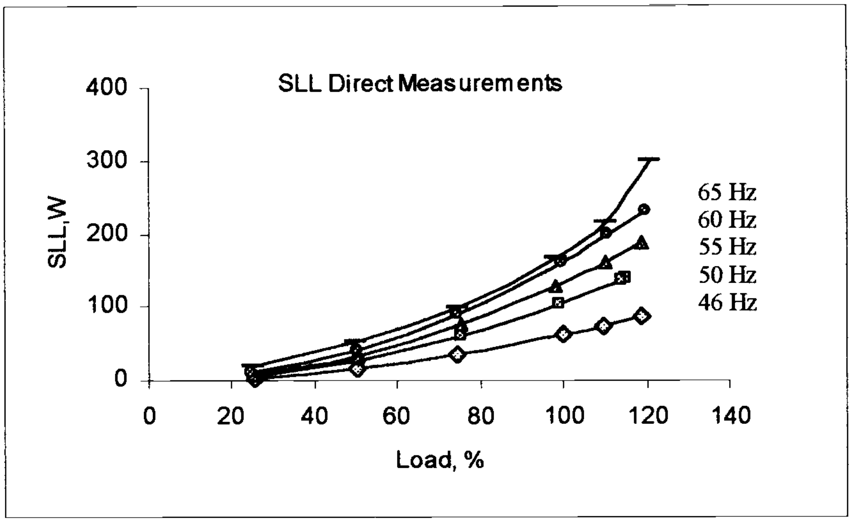

Figure 4.16 Corrected stray load loss for a 10 hp motor versus the load obtained by direct measurements (method 112E).

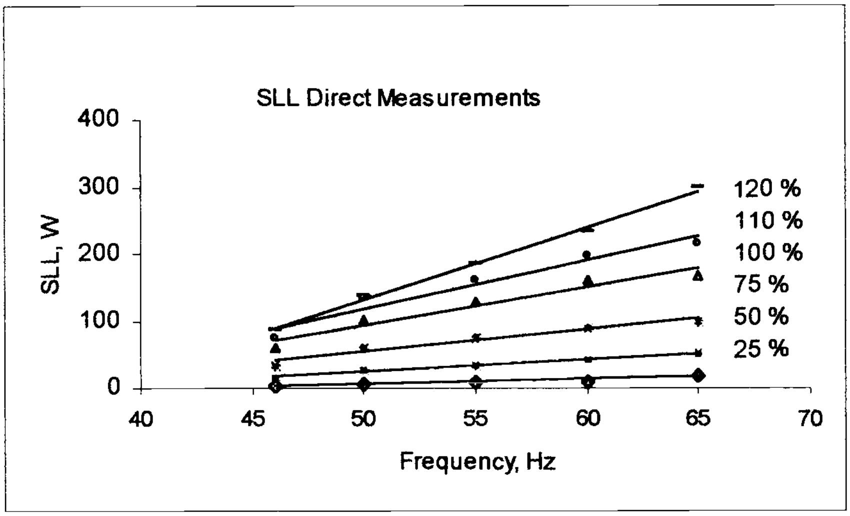

Figure 4.17 Corrected stray load loss for a 10 hp motor versus the frequency obtained by direct measurements (method 112E).

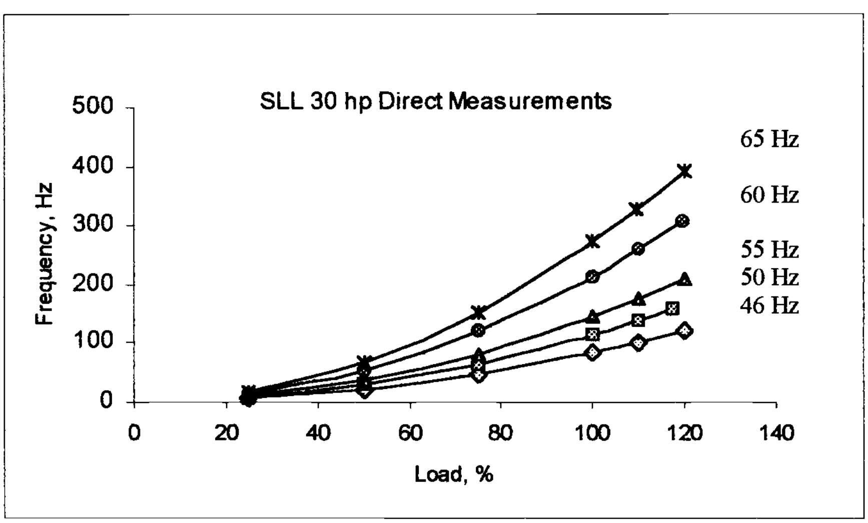

Figure 4.18 Corrected stray load loss for a 30 hp motor versus the load obtained by direct measurements (method 112E).

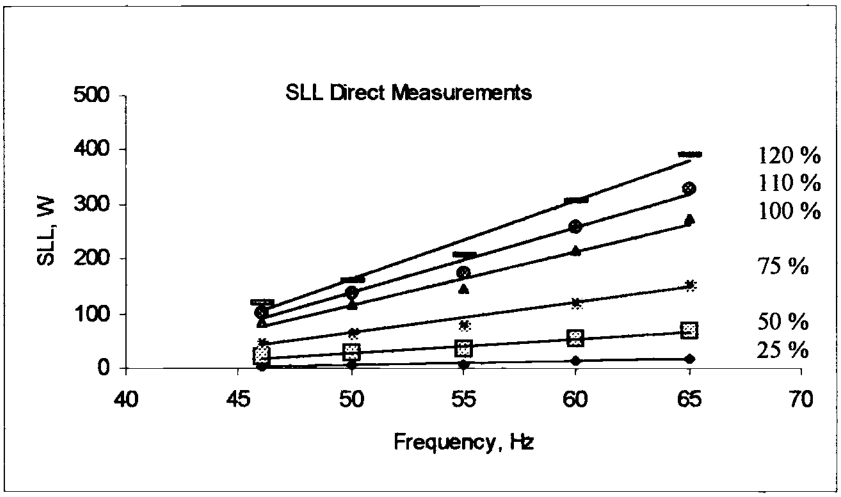

Figure 4.19 Corrected stray load loss for a 30 hp motor versus the frequency obtained by direct measurements (method 112E)

From Table 4.9, we can see that the current for all of three motors has the tendency to increase. The reason of this rising is that the output power of the motors is increasing with the frequency and hence speed as it is shown in Table 4.3. Also, we can observe an increase of the power factor with the frequency. This increase is caused by the reduction of the core saturation as it is shown in Table 4.5. The analysis of the efficiency values shows that the efficiency is increasing with the frequency for all of these motors. The efficiency values presented in the Table 4.9 show the good coincidence between the indirect and direct test methods. Mostly, the SLL obtained by the direct measurement method (112 E) is a little bit higher than the SLL obtained by the input-output method (112 B) that agrees to some literature sources [2].

Table 4.9

Frequency, Hz			46	50	55	60	65
Line Current, A		5 hp	6.32	6.24	6.28	6.37	6.53
		10 hp	11.40	11.81	12.25	12.41	12.56
		30 hp	35.72	35.10	35.05	35.87	37.39
Power Factor, pu		5 hp	0.79	0.82	0.84	0.86	0.88
		10 hp	0.83	0.86	0.87	0.87	0.87
		30 hp	0.71	0.78	0.80	0.84	0.85
Efficiency, %	Method 112 B	5 hp	83.37	84.48	85.37	85.52	85.89
		10 hp	85.24	85.03	85.21	85.40	85.82
		30 hp	92.53	93.93	93.72	93.76	93.86
	Method 112 E	5 hp	83.04	84.60	85.23	85.55	85.74
		10 hp	84.87	84.87	85.09	85.18	85.62
		30 hp	92.50	93.46	93.61	93.65	93.54

DISCUSSION AND CONCLUSIONS

The evaluation of the SLL in induction motors is an important part of the efficiency estimation process. Until recent times, a survey of the literature on the SLL in the induction machines has revealed a considerable disagreement with the definitions of this losses and their origin.

According to the state of the art with the instruments that exist today, the precision of the electrical instruments is much higher than the precision of the mechanical parameters like torque and speed. Thus, the further development of high accuracy torque and speed transducers and measuring devices is a very important problem for a precise determination of the electrical motor efficiency.

The experimental evaluation of SLL and efficiency for three-phase induction motors was performed involving the input-output or IEEE Standard 112-B method, and the SLL direct measurements method or 112-E method. Both methods were applied for the testing of 5 hp (3.73 kW), 10 hp (7.46 kW) and 30 hp (22.4kW) AC induction motors.

One of the questions, which it was necessary to solve before performing the main part of testing, is the determination of the voltage values in the case when the frequency differs from the rated value. For this purpose, a special technique that allowed keeping the relative slip value constant at the 100 % load for each frequency value was created. Thus, for each value of frequency, voltage values have been determined experimentally for every motor. Because of this technique (s=const), the level of saturation of the motors was different. This level was determined by the calculation of the internal magnetizing electromotive force to frequency ratio. The highest level of saturation was reached at 46 Hz.

From the analysis of the data obtained during the efficiency test, it could be observed that the core loss to the total loss ratio is different for all of these motors, and it depends on the motor design. For the 5 hp and 30 hp motors, the stable tendency of the core loss part to decrease with the frequency because of the saturation is observed. The ratio of the friction and windage loss to the overall loss increases with the frequency (rotor speed). The stator current loss to the total loss ratio is slightly decreasing with frequency. This may be explained by the reduction of the magnetizing current with the saturation. The rotor current loss to the total loss ratio has a stable tendency to increase for all of the motors. The SLL in the total loss share does also have an established tendency to increase with the frequency, but after definite point (as we can see for the 10 and 30hp motors) this growth starts to slow down.

During the load test for a 30 hp motor that was performed on the largest 300 hp test rig, the dynamometer torque oscillations were observed, especially, in a range of the frequencies from 50 up to 60 Hz. These torque and at some points speed oscillations have affected the measurements of accuracy, especially, for the stray load loss determination.

After performing the series of load tests, it was found that the stray load loss is proportional to the square of the load and the dependency between SLL and frequency for different load levels is very close to the linear.

The values of the stray load loss to the input power ratio and the stray load loss to the output power ratios for the different motors are different and dependent on the motor design. The value of 1.8 % for Stray-Load Losses Percent of Rated Output for 1-125 hp motors that is given by Method E1 of IEEE Standard 112 -1996 is slightly excessive and does not allow us to obtain the correct efficiency value. At the same time, the SLL / P_{in} ratio for all three motors exceeds the 0.5 % recommended by the most of the European Standards.

The current for all of three motors has a tendency to increase with the frequency. The reason of this rising is that the output power of the motors is increasing with the frequency as well. Also, an increase of the power factor with the frequency was observed. This increase is caused by the reduction of the core saturation. The analysis of the efficiency values shows that the efficiency is increasing with the frequency for all of these motors. The efficiency values obtained in this work show a good coincidence between the indirect and direct test methods. Mostly, the SLL obtained by the direct measurement method (112 E) is slightly higher than the SLL obtained by the input-output method (112 B) as it was mentioned by some literature sources. Generally, it was confirmed that the SLL in an induction machine is strongly dependent on the motor design.

The input-output (IEEE Standard 112 B) method seems to be more practical for the industrial applications because it does not require disassembly of the motor and removal of the rotor as needs to be done according to the SLL direct measurement method (IEEE Standard 112 E). Both techniques work well for the 5 hp and 10 hp motors. For the 30 hp motor, the accuracy of the experimental results for the 112 B method was distorted by the torque and speed oscillations that were observed at frequencies different from 60 Hz. In order to increase the accuracy of the stray load losses and efficiency determination by the input-output (IEEE Standard 112 B) method, it may be recommended to use a dc machine as a dynamometer for such tests.

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APPENDIX

APPENDIX

THE MOTOR SYSTEMS RESOURSE FACILITY (MSRF)
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Date: 3 Nov

IEEE Std 112-1991 **Form B**

Method B: Calculation Form for Input-Output Test of Induction Machine With Segregation of Losses and Smoothing of Stray- Load Loss

Manufacturer:	Toshiba
Model No:	BDD54DGF2AA
Serial No:	50909652
Type:	1K
Time rating:	cont
Design:	0
Frame:	184T
L. R. Code:	
Service Factor:	1.15

Hp:	5
Volts:	460
Freq:	60
FL RPM:	1730
FLA:	6.5
FL PF:	0
Nom. Eff:	85.5
Phases:	0
T Amb,°C	40
Ins. Class:	B

Item	Description (Motor.)/(Gener.)	1	2	3	4	5	6
1	Ambient Temperature, in °C	22.5	22.1	22.2	22.1	22.0	21.5
2	(t_t) Stator Winding Temp., in °C	91.14	87.34	73.45	58.23	46.72	39.88
3	Slip, in r/min	104.0	86.0	74.0	49.0	30.0	14.0
4	Speed, in r/min	1696.0	1714.0	1726.0	1751.0	1770.0	1786.0
5	Line-to-Line Voltage, in V	459.9	460.3	460.1	460.2	460.1	460.0
6	Line Current, in A	7.62	6.99	6.37	5.09	3.97	3.13
7	Stator Power, in kW	5.383	4.876	4.365	3.268	2.207	1.175
8	Core Loss, in W	143.1	143.3	143.2	143.3	143.2	143.1
9	Stator I^2R Loss, In W, at (t_t) °C	390.8	324.9	258.3	156.1	91.7	55.4
10	Power Across Air Gap, in W	4849.2	4407.8	3963.5	2968.6	1972.2	976.4
11	Rotor I^2*R Loss, in W	280.2	210.6	162.9	80.8	32.9	7.6
12	Friction and Windage Loss, in W	5.1	5.1	5.1	5.1	5.1	5.1
13	Total Conventional Loss, in W	819.2	683.9	569.6	385.4	272.9	211.3
14	Torque, in Nm	24.96	22.82	20.56	15.36	10.16	4.97
15	Shaft Power, in W	4433.2	4096.1	3716.3	2816.6	1883.3	929.6
16	Apparent Total Loss, in W	949.8	779.9	648.7	451.4	323.7	245.4
17	Stray-Load Loss, in W	130.7	96.0	79.2	66.1	50.9	34.1
t_s= 76.2	R_s= 4.286						
18	Stator I^2R Loss, in W, at (ts) C	372.9	313.6	260.6	166.3	101.3	62.8
19	Corr. Power Acr. Air Gap, in W	4867.1	4419.0	3961.2	2958.5	1962.5	969.1
20	Corrected Slip, in r/min	99.2	83.0	74.7	52.0	33.1	15.9
21	Corrected Speed, in r/min	1700.8	1717.0	1725.3	1748.0	1766.9	1784.1
22	Rotor I^2R Loss, in W, at (t_s) C	268.3	203.8	164.3	85.5	36.1	8.5
23	Corrected Stray-Load Loss, in W	86.8	72.6	58.9	32.9	14.4	3.4

24	Corrected Total Loss, in W	876.2	738.5	632.1	433.0	300.1	223.0
25	Corrected Shaft Po\ Σ	4506.8	4137.5	3732.9	2835.0	1906.9	952.0
26	Shaft Power, in hp	6.041	5.546	5.004	3.800	2.556	1.276
27	Efficiency, in %	83.72	84.85	85.52	86.75	86.40	81.02
28	Power Factor, in pu	0.887	0.876	0.860	0.806	0.698	0.472

Summary of Characteristics

Load, in % rated	1.208	1.109	1.001	0.760	0.511	0.255
Power Factor, in pu	0.887	0.876	0.860	0.806	0.698	0.472
Efficiency, in %	83.72	84.85	85.52	86.75	86.40	81.02
Speed, in r/min	1700.8	1717.0	1725.3	1748.0	1766.9	1784.1
Line Current, in A	7.62	6.99	6.37	5.09	3.97	3.13