High Accuracy Measurement of Total Losses in Fractional Horsepower Induction Motors

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***Abstract*—Large and small single-phase and three-phase induction motors are commonly used in industrial applications. The present work represents an attempt towards the design of a high accuracy system for the measurement of fractional horsepower (FHP) induction motor losses and efficiency. The calorimeter designed and built is capable of measuring heat losses of up to 1 kW with an overall accuracy better than 3%. During all tests, ambient temperature, humidity, motor speed and motor frame temperature were recorded using precise digital instruments. The inlet, outlet temperatures and resulting losses were recorded automatically using a high accuracy 12-bit data acquisition system. The preliminary results obtained demonstrate the suitability of the designed calorimeter for the accurate measurement of losses in FHP induction motors.**

***Index Terms*—Induction motor, fractional HP motor, calorimeter, calorimetry, motor losses, efficiency.**

I. INTRODUCTION

There are two major AC induction motor types that are usually used in fans and blowers: the single-phase motor and the polyphase motor. The polyphase motor that is the most commonly used is the three-phase induction motor. The three-phase motor is available in fractional and integral horsepowers.

FHP three phase motors are used across a wide range of activities and processes in the industry. Their applications include compacting, cutting, grinding, mixing, fans, pumps, materials conveying, air compressors and refrigeration. FHP motors are also used widely in the commercial sector for air conditioning, ventilation, refrigeration, water pumping, lifts and escalators.

FHP induction motors are slightly less efficient than the larger sizes induction motors. It is well known fact that the efficiency increases as the size of the motor increases. In recent years, motor manufacturers are in competition to produce motors with improved efficiency because of the high cost of energy. Most offer energy efficient or high efficient motors as their standard products. However, mechanical energy is more than often required at variable speeds. An induction motor supplied by an adjustable-speed drive can operate over a wide range of frequencies, typically from 0 to 50 Hz. This range of frequencies yields rotor speeds from 0 rpm to the rated value.

Adjustable-speed AC drives bring about additional harmonic losses and hot spot temperatures [1]. These additional losses are very difficult to be measured accurately using conventional watt-meters especially when the machine is loaded. Based on the principle of the calorimetric method suggested by the IEC [2, 3], electric machine losses can be evaluated directly by measuring the dissipated heat within the machine.

An early work on the application of the calorimetric method was presented by Turner et al [4] for the measurement of losses in a 5.5 kW squirrel cage induction motor. This calorimeter was of open type where air was employed as the cooling medium to take away the dissipated heat Turner's approach demands critical control of the air properties (flow rate, inlet temperature, specific heat, etc). For instance, an air conditioning system has been used to maintain the inlet air at 20^{o}C. Precautions have also been considered to correct the measurements according to the possible changes due to the air specific heat and density affected by variations of the barometric pressure and relative humidity. Other authors have used improved designs to compensate for the shortcomings of Turner's design [5, 6]. However, no attempt was made to apply the calorimetric method to the evaluation of losses in FHP motors.

In order to simplify and generalize the calorimetric loss measurement to FHP induction motors, an open type calorimeter is designed and constructed in the present work.

II. INDUCTION MOTORS EFFICIENCY

Efficiency is one of the most important elements that are mentioned when considering the performance of a motor. Motor efficiency is a measure of the effectiveness whereby a

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motor converts electrical energy to mechanical energy. When motors convert electrical energy into mechanical work some energy is inevitably lost during the conversion. Thus, efficiency for any motor can be determined by its losses. Motor losses fall into two categories; no load losses, which are fixed and remain constant, and load losses which increase with motor load. Losses in induction motors consist of the four components: iron, friction and windage, stator copper and rotor copper losses. These losses are rather significant and should not be ignored, because they have a direct impact on the efficiency. Breakdown of the motor losses is shown in Fig. 1.

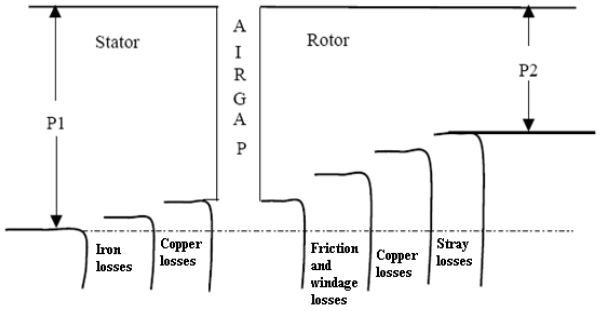


Fig. 1. Breakdown of total losses [7]

Efficiency is defined as the ratio of power output to power input. In terms of electrical power, motor efficiencies:

$$\eta = \frac{OutputPower}{InputPower} = \frac{Output}{Output + Losses} \quad (1)$$

Determination of efficiencies is based on measurements of input and output power. Efficiency is calculated as the ratio of the measured power to the corrected input power. From [7], efficiency is predominantly low when thermal energy is being changed into mechanical energy.

There is no single efficiency testing method that is held as the standard. There are testing methodologies from three major standard institutes that are widely used throughout the industry. These methods are:

1. IEEE 112 method B
2. IEC 34-2
3. JEC-37

There are some differences among these three methods, but the main difference is in the determination of stray load losses. IEEE 112 method B determines the stray load losses through an indirect process. The IEC standard assumes stray load losses to be fixed at 0.5 % of input, while JEC standard assumes there are no stray load losses. Therefore, the efficiency of a motor when tested under the different standards can vary by several percentage points. A simple calculation will show that an error of approximately 1% in measuring a motor efficiency is equivalent to hundreds of incorrectly evaluated kilo Watt Hours (kWhrs) of electric energy, as shown in TABLE I. This assertion holds true for FHP motors as well.

TABLE I. A single % point of efficiency is equivalent to significant KWhs.

Horsepower	Full-load Efficiency (%)		Equivalent Energy (KWh)
	Measured Efficiency	True Efficiency	
10	89.5	90.5	605
25	92.4	93.4	1,420
50	93.0	94.0	2,803
100	94.5	95.5	5,431
200	95.0	96.0	10,748

It is widely accepted that, among the three, IEEE 112 method B currently gives the most accurate efficiency values. However, the recently developed calorimetric methods have proved to be the 'Golden Standard' for efficiency measurement that could yield very high accuracy.

III. A NEW CALORIMETRIC METHOD

The designed calorimeter is used to measure directly the loss in a FHP induction motor operating under various load conditions. The objective is to measure directly the power loss by the motor under working condition. This is achieved by placing the FHP motor inside an enclosed chamber as shown in Fig. 2. To maintain a constant temperature in the chamber a cooling system is arranged to remove heat from the chamber. In steady-state, the power lost, P_{loss}, in a device is balanced exactly by the heat removed by the coolant. The heat removed is evaluated by taking measurements of the mass flow per second of coolant, the temperature of the coolant at entry to the calorimeter and its temperature at exit from the calorimeter. In steady state then:

$$P_{loss} = \dot{m} C_p (T_{out} - T_{in}) \quad (2)$$

where $\dot{m}$ = mass flow rate (kg/s), C_p = specific heat (J/kg °C), and, $T_{out} - T_{in}$ = temperature rise (°C).

The choice of coolant dictates the type of calorimeter to be designed. After careful consideration air was chosen as coolant for our design [8].

The designed calorimeter is capable of performing both motor and calibration tests at the same time. This results in a significant simplicity of the calorimeter operation,

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accompanied instrumentation and measurement system. The duration of each calorimetric test is about 3 hours. The designed calorimeter is found to be economical since the walls and insulation materials are relatively cheap. Also, there is no need for an air conditioning system to maintain the inlet air at a constant temperature while performing calorimetric tests. Therefore, this type of calorimeter is simpler and cheaper and more convenient for induction motor losses measurements with a high order of accuracy.



Fig. 2. The newly designed calorimeter

A. System Calibration

In order to test the operation of the constructed calorimeter, a series of calibration tests were performed. The results of the tests are used to determine air temperature rise inside and across each chamber, heater input power and the accuracy of the calorimeter. The accuracy of the constructed system at different input powers is shown in Fig. 3. These quantities are considered as the most important aspects which should be known before starting the calorimeter tests on the induction motor.

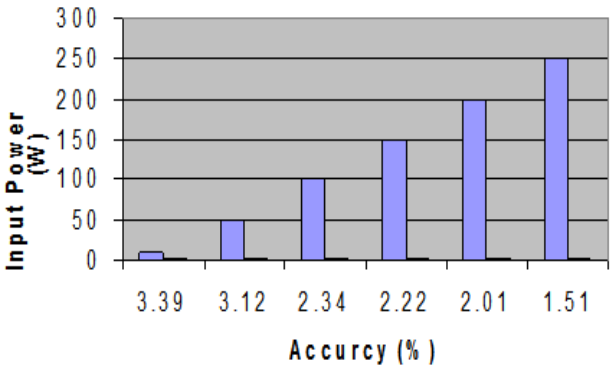


Fig. 3. System Accuracy at different input powers

The tests were performed at constant airflow rate and various input power levels ranging from 10 W to 250 W. Three DC standard laboratory power supplies were connected in series to achieve the required voltage at the required current. Voltages and currents were measured within ±0.8% and ±1% accuracy, respectively.

Based on the experimental results it was found that an airflow rate in the range 2 m^3/min is required through the calorimeter for loss measurements of 250 W. This value ensures sufficient air convection around the test induction motor to prevent it from overheating. The average air temperature rise across each chamber was determined to be 24°C for 250W losses.

Experimental results also proved that an average heat loss of 50 W dissipated in each chamber can cause an air temperature rise of 5 °C across that chamber. The tests were conducted with input power in the range 10-250W resulting in a temperature difference of about 1-24 °C between the inside and outside of the DUT (Device Under Test) chamber and of about 24°C-45°C between the inside and outside of the REF (Reference) chamber. During each test, the following parameters were measured and recorded:

- Ambient temperature (°C) and relative humidity (%)
- T_1, T_2, T_3 and power, voltages and currents

Variations of T_1, T_2, and T_3 with time were also logged as data samples and as plots. Later on, stored data were retrieved for analysis using EXCEL software. During all measurements and recordings a 300-point moving average filter was applied.

A typical temperature variation with time is shown in Fig. 4. Since the temperature rise involved in this operation is a first-order process. The temperature curve is used to determine the time constant, τ, of the calorimetry process. The time constant has been estimated as equal to about 15 minutes.

B. Measurement of FHP Induction Motor Losses

The calorimetric measurement facility described in the previous section is used to determine the total amount of heat losses generated by ½ hp three-phase induction motor under different load condition.

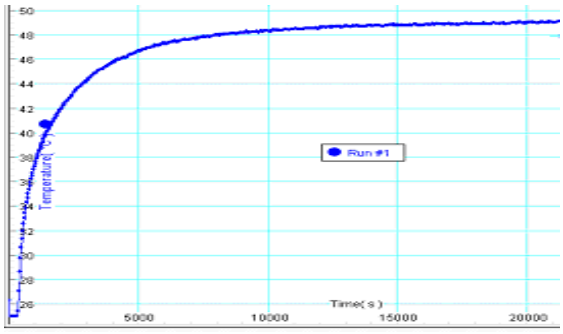


Fig. 4. Typical temperature variation in REF chamber during a calibration test

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The FHP motor to be tested is placed inside the DUT chamber, with the shaft protruding through the chamber's wall. The shaft is mechanically connected to the loading system. The motor under test and its loading system are shown in Fig. 5.

The motor was tested at different load levels. The results obtained at different load levels are summarized in TABLE II. It was established that FHP induction motors are highly inefficient, since most energy consumed is converted into losses (heat). Its efficiency, as calculated from the results obtained, reaches as low as 50%. At high load levels, the efficiency approaches 65%.

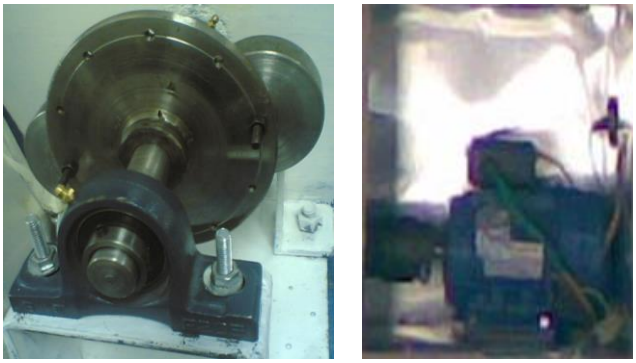


Fig. 5: The motor under test and its loading system

TABLE II. Measured motor losses at different load levels

Load levels	Losses(W)	Ambient Temperature(°C)
High load	343	26
Light load	326	27
No load	225	27

IV. CONCLUSION

The application of the calorimetric method for the measurement of FHP induction motor losses has been described in this paper. A calorimeter was constructed to measure losses of a ½ hp three-phase induction motor. The merits of this approach have been highlighted. The designed calorimeter is capable of measuring losses of other small devices up to nearly 1 kW, including harmonic losses, by simply extending the temperature sensors range. The performance and reliability of the calorimeter have been investigated by performing experimental tests. It has been experimentally established that FHP three-phase induction motors produce high losses, resulting in poor efficiency. It was also noticed, during testing, that the relationship between load and losses is not coherent in FHP induction motors as it is in larger motors. To conclude it can be said that the calorimetric method of measuring total losses of FHP induction motors proved to be a valid alternative to the conventional input-output method of heat loss measurement. This alternative method does not required very complicated processes, or expensive equipment. This is a very useful method, which can help motor designers to improve motor efficiency.

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