A NON-INTRUSIVE METHOD FOR MECHANICAL MEASUREMENTS

IN CONSTANT FREQUENCY ELECTRIC MOTORS

A Dissertation

by

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ABSTRACT

Electric motor-driven systems are basic components in most industrial processes. The four motor mechanical measurements of interest that dictate motor performance are shaft torque, shaft speed, mechanical power (motor load) and energy conversion efficiency. Torque and speed, along with the input electric power are needed to estimate load and efficiency. Mechanical performance monitoring is an ever-increasing trend, present in many industries. Such monitoring can identify equipment failures, predict system degradation, and monitor overload conditions. It also provides users with a deeper understanding of the operational demands of their machines, which is difficult to diagnose through standard vibration analysis. Nevertheless, it is extremely challenging to measure the in-situ motor shaft torque, and to a lesser extent shaft speed.

A comprehensive literature survey indicates that many estimation methods exist for motor mechanical measurements. However, almost all of these methods require at least one of the following: (1) load tests involving measurements of shaft speed and torque at a stable temperature, (2) no-load tests, i.e. with motor mechanically decoupled from driven load, (3) de-energized stator resistance measurements, i.e. with motor electrically disconnected. These three conditions require a level of access to the motor under test not generally acceptable or possible in an industrial environment, i.e. these are the "intrusive" requirements of the mechanical measurement estimation methods.

A non-intrusive approach to mechanical measurements is proposed, incorporating the equivalent circuit model of an operating induction motor. The estimation of the mechanical measurements is formulated as a non-linear, constrained optimization problem with the variables to be optimized being the parameters of the equivalent circuit model. The optimization problem is solved using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) method. The required inputs of the proposed method are the three-phase voltage and current phasors and the motor nameplate information. The resulting parameters of the equivalent circuit model and new voltage and current phasors are used to estimate the motor mechanical measurements.

Five (5) manufacturer's catalog data sheets, two (2) small motors, 1 HP and 3 HP, and two (2) larger motors, 100 HP and 200 HP, are used to test the proposed approach against direct mechanical measurements of torque and speed. The experimental results demonstrate that the proposed method achieves speed estimates within ±5 RPM of the sensor readings, which is comparable to existing non-intrusive methods. For torque, load and efficiency, the proposed method achieves accuracy within ±2-3% for high (>25%) loads, and up to ±5% errors for low (<25%) loads. The presented shaft torque accuracy is an improvement over existing, non-intrusive techniques and in the case of load and efficiency estimation is an improvement over existing, non-intrusive and even some intrusive techniques.

The novel contribution of this research is the estimation of mechanical measurements based only on motor electrical measurements and motor nameplate information. The need for a torque transducer, speed sensor and any motor field testing is eliminated. Further testing is needed to establish the accuracy of the method on a wider motor population.

To My Parents, My Parents-in-law, My Wife and My Son

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The Matlab code used in Section 3 were conducted in part by Professor Amir Atiya. All other work conducted for the dissertation was completed by the student independently.

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1. INTRODUCTION AND MOTIVATION

1.1 Overview

The motor drive system is the basic component of most industrial processes, such as chemical and power industries, minerals and mining, manufacturing, heating, air conditioning, and engine cooling. In the industrial field, motors are used to drive material handling and processing equipment such as pumps, fans, compressors, machine tools, conveyors, etc. There are four mechanical measurements of interest: shaft torque, shaft speed, motor mechanical power (load) and motor energy conversion efficiency. Although the input of induction motor is power, its output is mechanical power, so some terms and measurement indexes related to mechanical power should be known. Any mechanical load on the motor shaft will be shown as a torque indicator on the motor shaft. The torque is related to the output power of the motor and the rotor speed. And these four mechanical measurements are used to infer and improve energy efficiency, mechanical performance and mechanical condition (health).

1.2 Mechanical Power and Energy Conversion Efficiency

A study by the U.S. Department of Energy (DOE) cites that in 2016 electric motor-driven systems in all sectors consumed 1,449 billion kWh, or 40% of all electricity sold in the U.S, as shown in Table 1. Especially, within the industrial sector, about 62.5% of the total electrical energy use is for motor-driven equipment, which equates to about 17% of the total U.S. electrical energy use [1], as shown in Table 2.

More recent references [2] estimate the 2017 energy use by electric motors in the U.S. industrial sector closer to 1,100 billion kWh. The potential energy savings result from either (a) repairs/replacement/upgrade of electric motors, or (b) motor system improvements, such as electrical tune-ups, mechanical power transmission component upgrades, alignment and lubrication, driven load matching, driven load efficiency enhancements, driven load design enhancements, and motor control. In particular, electrical tune-ups, e.g. improving the power supply's quality metrics, could conservatively reduce energy use by electric motors from 1 to 5%, whereas mechanical drive train improvements and lubrication could contribute to this reduction by 3 to 7%. Correcting motor over-sizing problems could improve energy use another 5%, whereas motor replacements with premium efficiency motors could make an improvement of 2.5 to 4.5%. The potential total savings are reported at 28 to 42% of energy use [3]. These estimates indicate that simply conducting more effective and timely electric motor and driven load maintenance could impact energy consumption, through motor system efficiency improvements, by at least 3 to 5% of energy use.

Table 1 Electrical Energy Use by Electric Motors by Sector (million KWh/year 2016)

	U.S. Total Electrical Energy Use		Energy Use by Electric Motors	
Sector	Year 2006	Year 2016	Year 2006	Year 2016
Residential	1,351,520	1,411,058	297,000	310,084
Commercial	1,299,744	1,367,191	498,000	523,842
Industrial	1,011,298	976,715	632,000	610,388
Transportation	7,358	7,497	4,000	4,076
All Sectors	3,758,992	3,762,462	1,431,000	1,448,389

Table 2 Percentage of Sector Energy Use by Motor-Driven Systems (2016)

Sector	Total Electrical Energy Use for Sector, Million kWh/year1, 2016	Annual Motor-Driven System Energy Use, Million kWh/year	Percentage of Sector Use by Motor-Driven Equipment	Percentage of Total Motor-Driven Equipment Energy Use
Residential	1,411,058	310,084	22	21.5
Commercial	1,367,191	523,842	38.3	36.3
Industrial	976,715	610,388	62.5	42.2

Table 3 shows a single percentage point of degradation efficiency is worth significant dollar losses—even for motors as small as 10 horsepower (HP). All the data are based on purchase of a 1,800 rpm totally enclosed fan-cooled motor with 8,760 hours per year of operation, 75% load, and an electrical rate of $0.07/kWh.

Table 3 What is a point of motor efficiency degradation worth?

Horsepower	Full-load Motor Efficiency (%)		Annual Savings	
	Actual Efficiency	Assumed Efficiency	Annual Energy Wastes, kWh	Dollar Loss $/year
10	89.5	90.5	605	$41
25	92.4	93.4	1,420	$97
50	93	94	2,803	$191
100	94.5	95.5	5,431	$369
200	95	96	10,748	$731

In considering the life-cycle costs of electric motors one cannot but make an interesting observation: approximately 97% of an electric motor's life-cycle cost is attributed to energy use, whereas the rest is the initial purchase cost and the cost of a single repair. For comparison, a

$20,000 automobile's annual operating costs are 4% to 5% of its purchase price, whereas the equivalent number for a 60 HP motor is up to 1,600%. A motor can consume anywhere from 4 to 12 times its original cost in electricity per year [4]. One 200 HP motor, costs $20,000, operating at an assumed efficiency of 96% efficiency will result in $100,453 per year in energy costs; if the actual average efficiency is 90%, it results in $4,386 per year in excess energy costs or $109,650 over its 25 years life. Therefore, many replacement have payback times of 4~5 years. If it has the ability to estimate in-situ motor efficiency, plants can save a substantial amount of money by replacing existing inefficient motors with new highly efficient motors.

DOE estimates that industrial motor energy use could be reduced by 11 to 18% if facilities managers undertook all cost-effective applications of mature, proven efficiency technologies and practices. This translates to annual energy savings of 160 to 260 billion kWh, with a value of $11.9 to $17.7 billion, at industrial energy prices of ¢6.8 per kWh [2]. This would directly increase the bottom-line of industrial facilities. Realization of these savings would also reduce carbon equivalent emissions by up to 60 million metric tons per year [2].

Therefore, efficiency evaluation of electric motors is important in industry for overall energy savings and cost reduction. In recent years, there are many more research projects and literatures focused on the electric motors in order to reduce energy consumption and achieve environmental benefit.

1.3 Shaft Torque and Shaft Speed

Besides load and efficiency, torque and speed are also the main mechanical measurements for production machines.

$$\tau_{shaft} = \frac{P_{out}}{\omega_m}, \text{ where } \omega_m = \frac{2\pi \cdot Speed(RPM)}{60} rad / s \tag{1.1}$$

Torque and speed measurements [5] can identify equipment failures, predict system degradation, monitor overload conditions, ensures proper rotor/engine load balancing, provide accurate feedback for flight controls, determine health of vital rotating components. At present, torque monitoring is an increasingly important monitoring system, especially in industries such as cement, ships and electric power. When users are unable to diagnose problems through standard vibration analysis, it can satisfy users' need for deeper understanding of machine operation. In this way, users can make necessary corrections to ensure smoother operation and avoid unexpected failures of machine. Accurate monitoring of motor performance by continuous torque monitoring system can be used to identify progressive loss of efficiency. This in turn allows for the development of more concentrated maintenance areas, enabling the system to run optimally and efficiently.

Direct measurement of rotor speed requires installation of shaft speed decoders or optical tachometer. These additional instruments may reduce reliability and increase costs. Moreover, shaft torque is the most complex variable to measure in field operation because it requires intrusive tests and/or intrusive hardware which disrupt operation. Currently torque measurement techniques includes torque cells (sensors) appropriating for lab/shop environment and strain gauge telemetry which lacks robustness and reliability.

Therefore low-cost methods are needed to monitor motor mechanical performance and health conditions, particularly for industrial motors.

1.4 Problem Definition and Research Objectives

Hence, this research seeks to build one non-intrusive method to resolve the issues above mentioned. Non-intrusive methods make use of easily measured variables to infer mechanical measurements that are difficult to measure; when the driver is a three-phase electric motor it is easy to measure: voltages, currents, electric Power and also available are motor nameplate information. Although a lot of research literatures have been published on this research topic, estimating efficiency, torque and speed measurements from motor electrical signals while with comparable accuracies is still a very challenging problem.

From the previous sections, it can be inferred that it would be desirable to develop a new technology for the online non-intrusive estimation of industrial electric motor's mechanical measurements while eliminating some of the drawbacks of the existing methods. The key problems being studied in this research are as follows:

• Develop a method for estimation of efficiency, torque, speed and mechanical load based on the concept of equivalent circuit.

• Equivalent circuit parameters are to be estimated using a parameter estimation method based on non-linear optimization.

• Only electrical measurements with a tolerable accuracy (voltage, current, power) and motor nameplate information is used.

• The method must not require any mechanical sensing, motor tests and/or stator resistant measurements.

It is very difficult task that we are seeking some solutions to solve the above-mentioned key problems in efficiency evaluation and torque monitoring. In order to complete the difficult research task, on one hand, this dissertation setup the research schematic and research approach in following section.

1.5 Research Framework

The study of mechanical measurements estimation is a complex process that comprises of related literatures reviewing and some basic theory extended, main approaches and methods selection, experimental system setup, IT hardware and intelligent application sub-system software design and others. Additionally, the development of advanced technologies provides technical support. Therefore, the following proposed research framework, research paths and research approaches of this research can supply effective, efficient maintenance to enterprises through fusion a lot of information, and taking full advantage of limited resource based on above-mentioned conditions.

The research schematic in Figure. 1 shows a brief framework of this study on non-intrusive method for mechanical measurements in non-VFD electric machinery. Some main research tasks are completed in order to realize the objectives above-mentioned. The research planning is focus on the four topics: (1) Develop algorithm of determining parameters of equivalent circuit; (2) Develop sub-algorithm of estimating slip while eliminate speed measurements; (3) Design Constraints and Penalty Terms; (4) Generate total algorithm for efficiency and torque. And some experiments, such as efficiency estimation experiment, speed estimation experiment, hardware design experiment and calibration experiment, will be developed to test the above-mentioned innovations. Experiments for small size motor (1 HP & 3 HP) in laboratory and Experiments for larger motor (100 HP and 200 HP) at motor shop, as shown in Figure 2, are applied to the processes of this investigation to assure the higher persuasion of the results in this dissertation. By the technique paths and research approach and experiments to realize the goal of management for energy in induction motor.

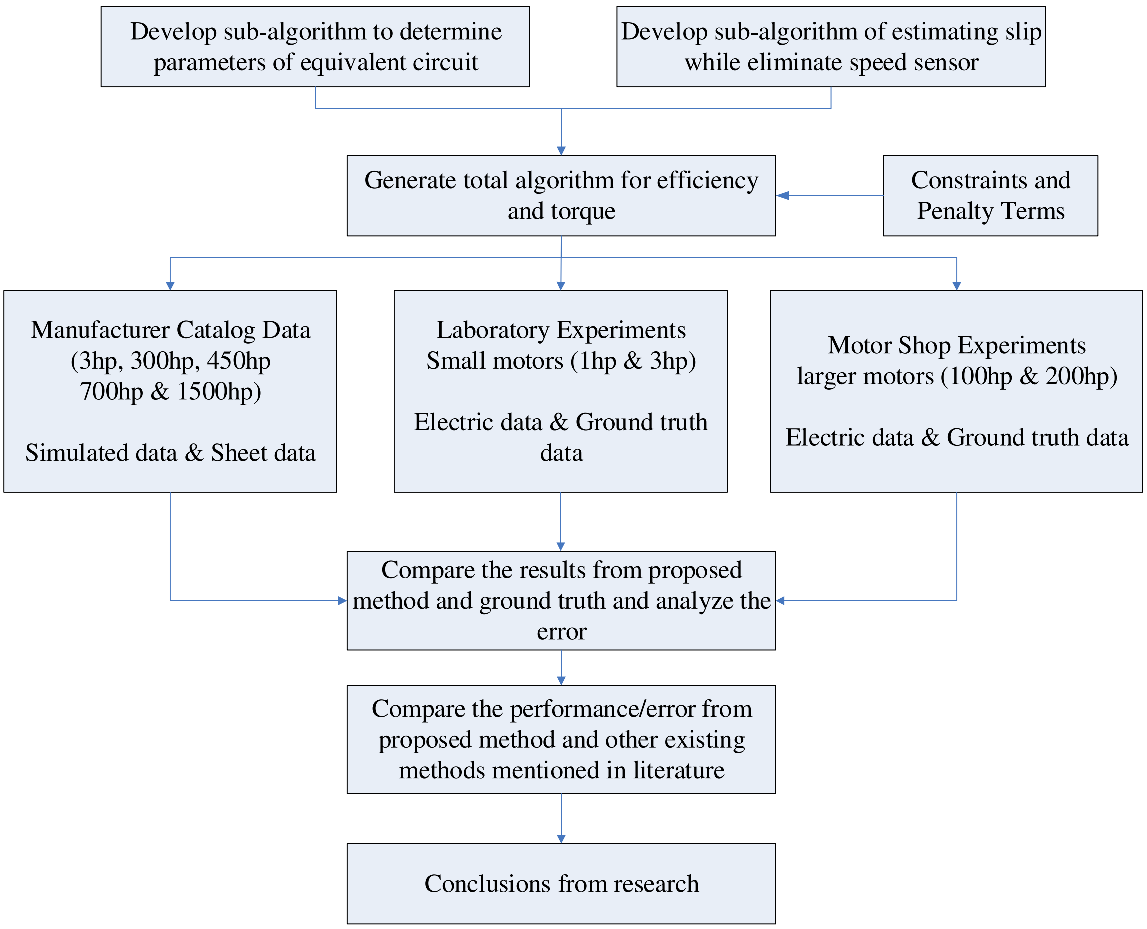


Figure 1 The research framework of the dissertation

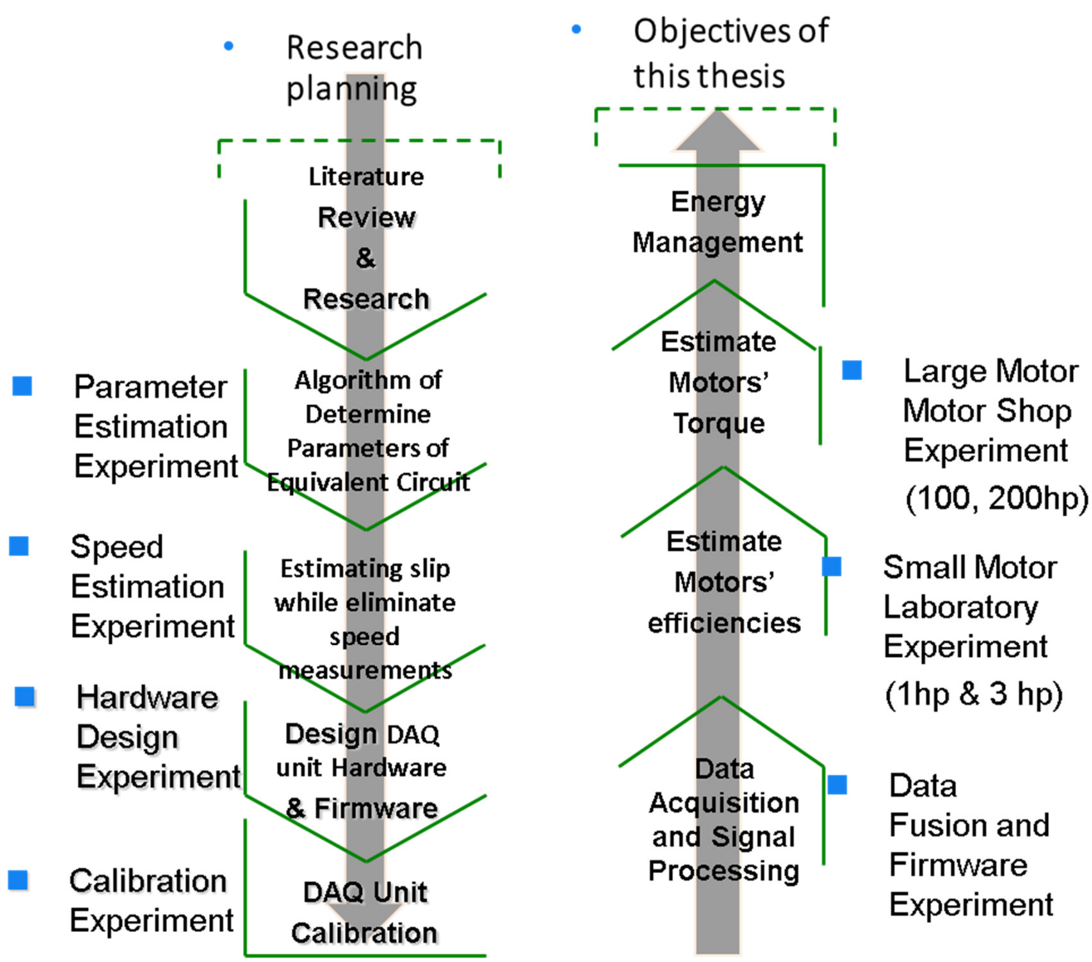


Figure 2 The research planning and objectives

1.6 Proposed Approach

As shown in Figure 3, the proposed algorithm for mechanical measurements in dissertations use the four steps: (1) data acquisition and signal processing to have symmetric components of electric quantities; (2) motor frication, windage and stray load loss estimation; (3) parameters of equivalent circuit and rotor speed estimation;(4) motors' efficiencies and torque estimation; (5) energy managing decision to support the realization of objectives of this dissertation.

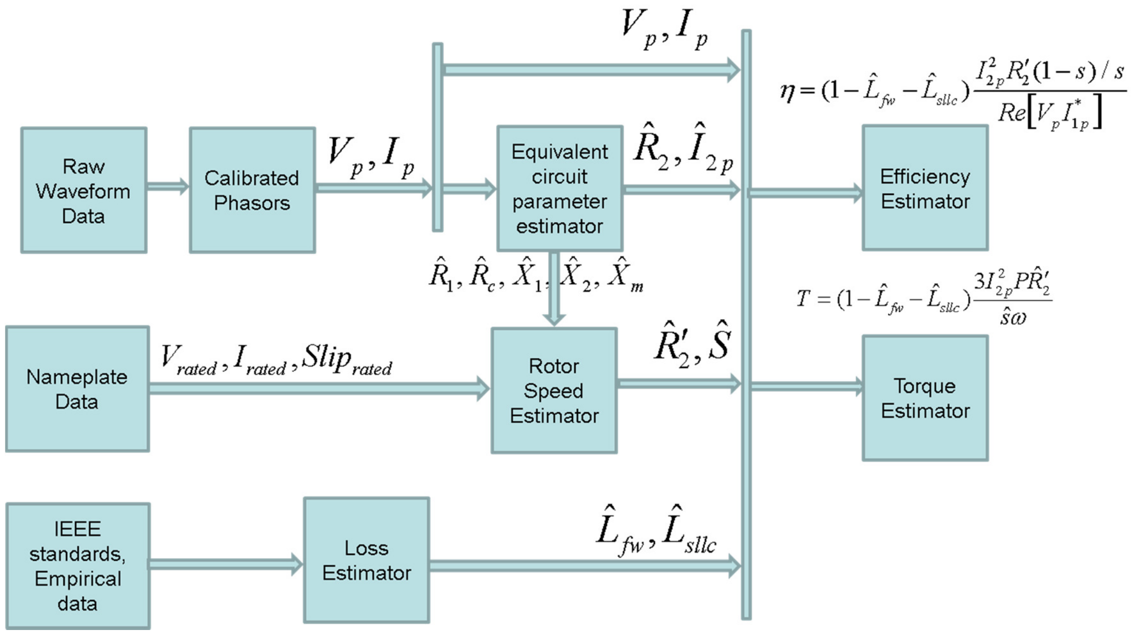


Figure 3 Proposed approach

1.7 Dissertation Contributions

According to the reaching objectives, the investigation implements the above-mentioned research schematic, so, the three characteristics of this research can be described as the following: It is a frontier research project on estimation of efficiency in electric motor driven system; it is a research project with higher application prospects in plant's motors and energy management; and it develops a novel integrated system which integrates four fields: artificial intelligent, IT, signal processing, electronics into energy and device management. Further, the research has the following attributes:

• A novel contribution of this research is expected to be the estimation of mechanical measurements, e.g. speed, torque, efficiency and load, based only on motor electrical measurements and motor nameplate information.

• A torque transducer and speed sensor are to be eliminated, because they are very costly and highly intrusive.

• A systematic error analysis on proposed non-intrusive method will be conducted and compared with the errors obtained from existing non-intrusive methods.

1.8 Dissertation Outline

It is expected that this research will provide a non-intrusive method for mechanical measurements in constant frequency electric motors by using equivalent circuit parameters estimation theory. The remaining parts of this thesis are organized as follows. Section 2 presents a comprehensive literature survey of previous work on motor-speed evaluation, shaft-torque estimation, and motor-efficiency estimation. In Section 3, presents a non-intrusive approach to mechanical measurements is proposed, incorporating the equivalent circuit model of an operating induction motor. The estimation of the mechanical measurements is formulated as a non-linear, constrained optimization problem with the variables to be optimized being the parameters of the equivalent circuit model. The optimization problem is solved using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) method. . In Section 4, Five (5) manufacturer's catalog data sheets, two (2) small motors, 1 HP and 3 HP, and two (2) larger motors, 100 HP and 200 HP, are used to test the proposed approach against direct mechanical measurements of torque and speed, the results of analysis from different test beds are presented. In Section 5, a summary and conclusions of this research, and the directions for future work are briefly described.

2. A SURVEY OF METHODS FOR MECHANICAL MEASUREMENTS

2.1 Overview

Over recent decades there have been various sensorless methods put forward for the estimating of motor mechanical measurements. They are often expected to be implemented in an integrated approach because of many common requirements and drawing on more methods. Most existed techniques require:

(1) No-load tests (motor mechanically decoupled), and

(2) Stator resistance measurements (motor electrically disconnected).

These two conditions require the degree of contact with the tested motor, which is unacceptable and impossible in the industrial environment. These two conditions are called "intrusive" requirements or conditions.

2.2 Speed Estimation Methods

Most methods of estimating motors' efficiency require direct measurement of the rotor speed. Direct measurement of rotor speed requires installation of shaft speed decoders or optical tachometer. These additional instruments may reduce reliability and increase costs.

Therefore, academics and researchers have a great interest in developing a high-performance induction motor driver that does not need a direct speed sensor to operate it, that is, to develop an induction motor driver that does not need a speed sensor. The information needed to estimate rotor speed is extracted from the stator voltage and current measured at the motor terminals. To this end, different speed estimation algorithms are used. In the past ten years, many sensorless rotor speed estimation schemes have been proposed.

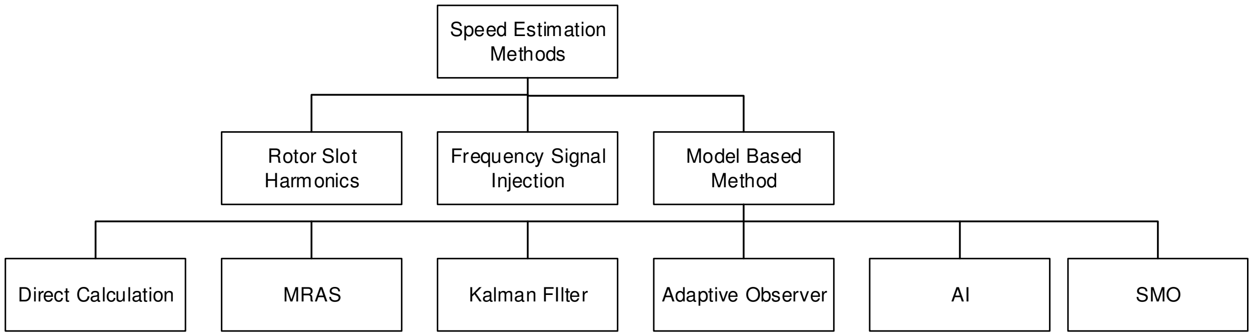


Figure 4 Speed estimation methods of sensorless systems

2.2.1 Rotor Slot Harmonics Method

The speed estimation method is based on the detection of the space harmonics generated by the rotor slot [6]. In the air gap magnetic force (MMF), the rotor slot produces spatial harmonics components, and the air gap magneto-dynamic force (MMF) regulates the frequency of the stator flux, which is proportional to the rotor velocity and the number of rotor slots. However, no-Load test may be required if eccentricity harmonic detects nothing. Therefore, rotor slot harmonics method is not always non-intrusive.

2.2.2 Frequency Signal Injection Method

In the method, speed estimation scheme is based on signal injection [7]. Typically, a high frequency voltage signal, superimposed on the fundamental voltage, is used to activate the anisotropy of the motor, and identify the rotor position or the direction of the magnetic flux direction from the current response [8]. However, this high intrusive method is not intended for constant frequency motor testing and it is impossible to add high frequency components to input voltages. [9]

2.2.3 Model Based Method

Speed identification and speed estimation can be obtained by using machine model and its terminals voltage and current [10]. These include different methods, such as the use of simple open loop speed calculators， model reference adaptive system (MRAS) and speed sensorless vector control based MRAS [11]; extended Kalman filter technique [12], adaptive and inherently sensorless observers [13]; artificial intelligence technology: artificial neural network, novel fuzzy adaptive model and neural network speed estimation [14]; adaptive sliding-mode observe (SMO) [15]. The model-based approach is characterized by its simplicity and good performance at high speed.

In industrial environments, however, the dynamic speed measuring of model-based methods for control purposes is sometimes unacceptable because of its low accuracy. Because rotor leakage inductance, stator leakage inductance, stator resistance and rotor time constant need to be pre-measured for modeling, and exhibit lower accuracy at low speeds mostly in parameter variations.

2.3 Torque Estimation Method

2.3.1 Airgap Torque Method

Shaft torque is the most complex variable to measure in field operation because it requires intrusive tests and/or intrusive hardware which disrupt operation. Currently torque measurement techniques includes torque cells (sensors) appropriating for lab/shop environment and strain gauge telemetry which lacks robustness and reliability.

To avoid torque sensors, shaft torque recently is measured indirectly through airgap torque. As shown in Figure 5, the shaft torque is the difference between the airgap torque and torque losses corresponding to mechanical loss and rotor stray-load loss produced by rotor current and is given by

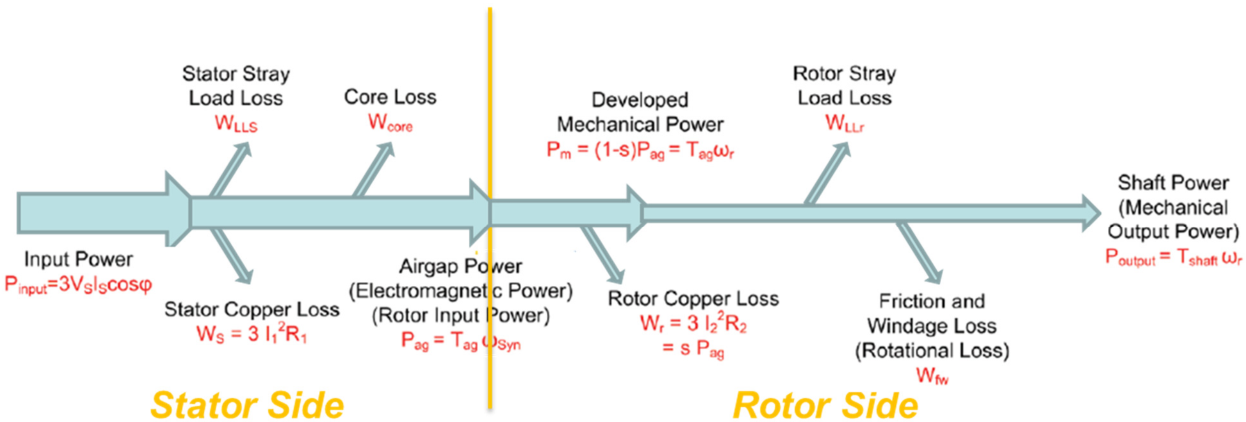


Figure 5 Power flow and loss definition of induction motors

$$P_{out} = T_{shaft} \cdot \omega_r = T_{ag} \cdot \omega_r - (W_{fw} + W_{sllc}) \tag{2.1}$$

$$T_{shaft} = T_{ag} - \frac{(W_{fw} + W_{sllc})}{\omega_r} \tag{2.2}$$

Where the losses W_{fw} and W_{sllc} are obtained from the no-load test and the air-gap torque T_{ag}, stationary reference frame, is calculated by using the motor instantaneous input line voltages v_{ca}, v_{ab}, phase currents i_a, i_b, i_c, number of poles P and stator resistance R_s as:

$$T_{ag} = \frac{\sqrt{3}P}{6}\left\{(i_a - i_b) \cdot \int \left[v_{ca} + R_s(2i_a + i_b)\right]dt + (2i_a + i_b) \cdot \int \left[v_{ab} - R_s(i_a - i_b)\right]dt\right\} \tag{2.3}$$

A significant advantage of this method is that it considers the losses associated with the unbalances in the voltages and currents, which has a relatively low level of intrusiveness and a high accuracy, as proven many times in the drive industry. The disadvantages lie in the requirement of measurement or estimation, and that friction and windage, as well as stray load losses and core losses have to be estimated as well, leading to expected inaccuracies. It is not a non-intrusive method neither.

2.4 Motor Efficiency Evaluation

2.4.1 Standardized Efficiency Measurements

The conventional definition of efficiency for all machines and electrical machinery in particular is by Equation (2.4):

$$\eta = \frac{P_{out}}{P_{in}} \tag{2.4}$$

where P_{in} is the electrical input power, and P_{out} is the mechanical (shaft) output power of the induction motor. The Institute of Electrical and Electronic Engineers (IEEE) specifies the procedures for measuring steady state operational efficiency in the standard IEEE 112a, intends to provide an accurate snapshot of the instantaneous efficiency which belongs to the class of input output efficiency testing methods. Rated, nameplate or nominal efficiency is the result of efficiency tests carried out, usually by the manufacturer's laboratory, according to the IEEE 112b standard on a statistically relevant sample of that particular model and rating. Standard 112b is much more involved and attempts to provide with two sets of information: Firstly, a load curve, specifying currents, power factors, efficiencies, operating temperatures and operating speeds for 25%, 50%, 75%, 100%, and typically 125% and 150% of mechanical loading at rated supply voltage conditions. Secondly, the IEEE 112b standard, being a loss segregation method, splits the occurring losses into different categories. From a systems point of view, standard IEEE 112a intends to describe the specific operating performance of a particular induction motor, while standard IEEE 112b attempts to describe the capabilities of a particular induction motor.

Plant operators and plant managers have good reasons for investigating the operating efficiencies of induction motors. But the standards IEEE 112a, and particularly IEEE 112b represent very intrusive procedures for test methods. Torque measurements and speed measurements are needed even in the simplest implementation of the standardized testing procedures, apart from also requiring more balanced voltage conditions than the ones commonly available at industrial sites. This high level of intrusiveness usually prohibits efficiency testing according to the IEEE specifications, leaving standardized testing to a laboratory environment option only. Many different efficiency estimation methods have been developed with field suitability as a goal.

These estimation techniques also share a lower level of intrusiveness in performing the required measurements, as well as a lesser accuracy in their predicted efficiencies. A thorough study on efficiency estimation techniques has been performed by J. R. Holmquist et al [16], which divides efficiency estimation techniques into the following classes:

2.4.2 Nameplate Method

It is based on the assumption that the machine will always operate at nominal efficiency. No doubly, it is non-intrusive. However, this method is the least intrusive, and the least accurate method which has anticipated error 10%. Because the machine will not always perform at the nominal efficiency, which dependent on field environment like load variations, source imbalances and harmonic components.

Volgelsang and Benning [17] made some improvement of the standard nameplate method. It is used in a dedicated commercial instrument: the "Motor Analyzer" while requires testing under no-load, normal-load, and unpowered and become intrusive.

2.4.3 Slip Method

The actual speed of the motor is less than its synchronous speed with the difference between the synchronous and actual speed referred to as slip. The percentage of load is presumed to be proportional to the ratio of the measured slip to the full-load slip as shown in Equation (2.5) and Figure 6.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{S_s - S_m}{S_s - S_{fl}} \times (Rated\ Load) \times \frac{1}{P_{in}} \tag{2.5}$$

Where, S_s is synchronous speed, S_{fl} is nameplate full-load speed and S_m is actual motor speed which is possible to measure by using a tachometer measure. Most of the motors are constructed such that the shaft is accessible to a tachometer or a strobe light, so it is convenient to apply the formula (2.7) derived from sliding method. However, the accuracy of the slip method is limited. The main drawback is that NEMA allows manufacturers to be too broad in the 20% tolerance of their report nameplate full loading speed. Also, it should be noted that the slip rate represents the percentage of the load, but the efficiency is not equal to the percentage of the load.

Speed estimation can be applied to avoid tachometer and make this method non-intrusive possible, while the anticipated error may increase from 7% to 8%.

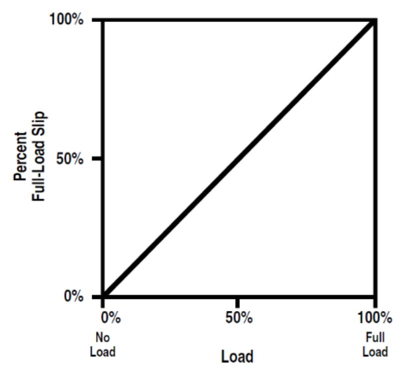


Figure 6 Percent Motor Slip as a Function of Motor Load

2.4.4 Current Method

Another simple method of obtaining an efficiency estimate is achieved by using current measurement manufacturer's data to estimate efficiency as shown in Equation (2.6) and (2.7).

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_m}{I_{fl}} \times (Rated\ Load) \times \frac{1}{P_{in}} \tag{2.6}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_m - I_{nl}}{I_{fl} - I_{nl}} \times (Rated\ Load) \times \frac{1}{P_{in}} \tag{2.7}$$

Where I_{fl} is the full load current in nameplate, I_{nl} is the no load current and I_m is the measured current which is possible to measure by using a clamp-on probe.

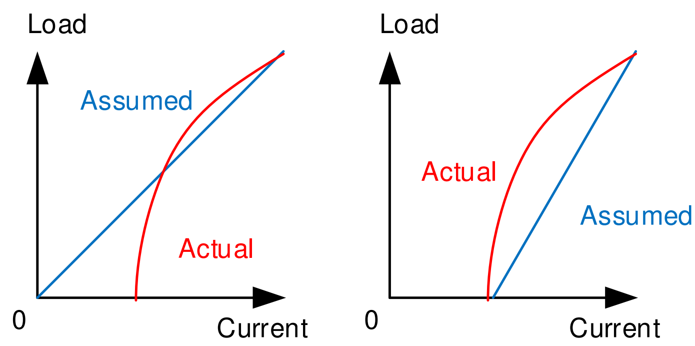


Figure 7 Assumed and actual load-versus-current curves with full-load and no-load current data points

The load evaluation is normally underestimated because the current-load curve is slightly nonlinear in reality while this method assuming that the percentage of load is proportional to the ratio of measured current to full-load current, as shown in Figure 7. The non-intrusive one has anticipated error at around 8%, while the intrusive one requiring no-load test has 6% anticipated error.

2.4.5 Equivalent Circuit Method

The efficiency of an induction motor can be calculated from its equivalent electric circuit. In particular, the circuit extracts all the impedances of the equivalent circuit by observing the voltages and currents. Determining all parameters of the equivalent circuit essentially fully defines the functionality of the motor and thereby the efficiency curve as well. Figure 8 shows the basic structure of the equivalent circuit. It consists of the

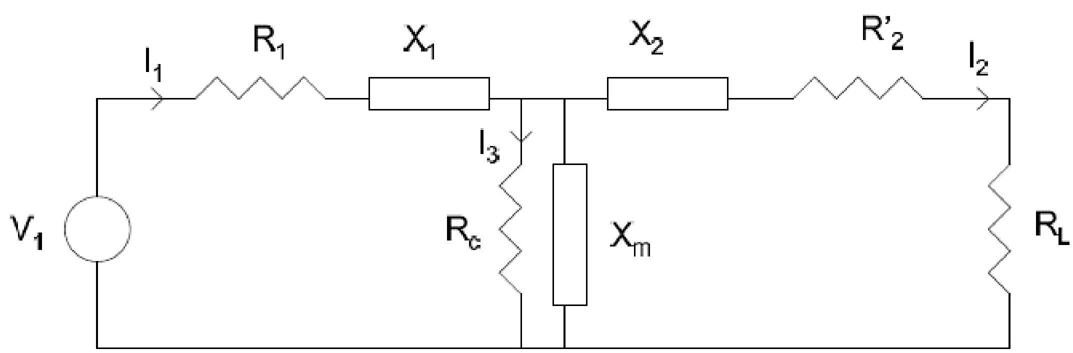


Figure 8 The equivalent circuit method

• R_1: stator winding resistance.

• X_1 : stator leakage inductance.

• R_c : core or iron losses.

• X_m : magnetizing inductance.

• R_2' : rotor winding resistance.

• X_2 : rotor leakage inductance.

• R_L : mechanical load.

Thus, the mechanical load output (per phase) for the positive component is given by

$$P_p = \frac{I_{2p}^2 R_2'(1-s)}{s} \tag{2.8}$$

where I_{2p} is the referred current in the rotor branch (see Figure 8) for the positive component circuit (i.e. the basic equivalent circuit). This means that we apply the positive component voltage V_p to the equivalent circuit, and compute the currents in the branches: I_{1p} and I_{2p} . These can be computed easily using simple electric circuit analysis. The efficiency is then given by

$$\eta = \frac{I_{2p}^2 R_2'(1-s)/s}{Re\left[V_p I_{1p}^*\right]} \tag{2.9}$$

Where $V_p = \frac{1}{3}\left(V_a + \alpha V_b + \alpha^2 V_c\right)$, $\alpha = e^{j2\pi/3}$, and $I_{1p} = \frac{1}{3}\left(I_{1a} + \alpha I_{1b} + \alpha^2 I_{1c}\right)$

It requires an off-line stator resistance measurement, and a no load measurement are performed to obtain the values of R_1 and R_2' , Additional nameplate information, particularly the design letter, is commonly used to obtain an X_1 / X_2 ratio. Power factor measurements at no load and at a load point are further values commonly used to segregate the inductive circuit components. These test methods are too intrusive, resulting in the operation of the motor needs more equipment and more cost. Therefore, although this method may be very accurate, sometimes it is not practical.

To make it less intrusive, speed estimation mentioned in 2.1 can be applied to get rid of speed sensor. In some cases, if motor's performance datasheet contains premeasured parameters, it can be used directly. The anticipated error will increasing from 5% of original method to 7%.

Ontario Hydro [18] and Rockwell Reliance [19] proposed another method based on equivalent circuit. The method uses the data from two different load conditions to calculate the parameters of the equivalent circuit of the standard asynchronous motor. It needs to measure the stator resistance and the temperature of the stator winding. Besides, the solution of the motor parameters requires the actual value of the stator leakage reactance, which is not available for in-service testing in operation.

The locked rotor method uses an equivalent circuit with two rotor loops [20]. The parameters of the circuit are obtained by locking rotor test. A no-load test must also be carried out.

The static frequency response method also has two rotor loops [21]. The parameters of the circuit are obtained by measuring the impedance of the motor in the frequency range from 0.01 Hz to 500 Hz, with its rotor stationary. The main advantage of this method is that there is no need for low voltage and no-load testing. However, in industrial environment and laboratory conditions, it is usually unacceptable or impossible.

2.4.6 Segregated Loss Method

An alternative method, the efficiency is usually determined by first determining losses and using input power. This method is called the loss segregation method in the standard. It is a common known method. If the loss of the stray load is determined properly, more accurate results can be obtained. However, this method is complex and requires skilled operators and much time consuming. It is not suitable for in service testing in operation, because no load, variable voltage, rotor removal and reverse rotation test are required.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - (W_{fw} + W_{core} + W_s + W_r + W_{sllc})}{P_{in}} \tag{2.10}$$

• Stator loss W_s : This is the loss in the stator windings. Referring to the equivalent circuit, this essentially equals $I_1^2 R_1$, where R_1 is the stator resistance.

• Rotor loss W_r : It is the loss due to the currents in the rotor bars. It equals $I_2^2 R_2'$.

• Core or iron loss W_{core} : It is the loss from eddy currents flowing in the different motor components. It is modeled as $I_3^2 R_c$ in the equivalent circuit.

• Friction and windage loss W_{fw} : This is the loss due to friction in the bearings, and due to wind resistance. It is not modeled by the equivalent circuit since this loss is experienced at the mechanical load side.

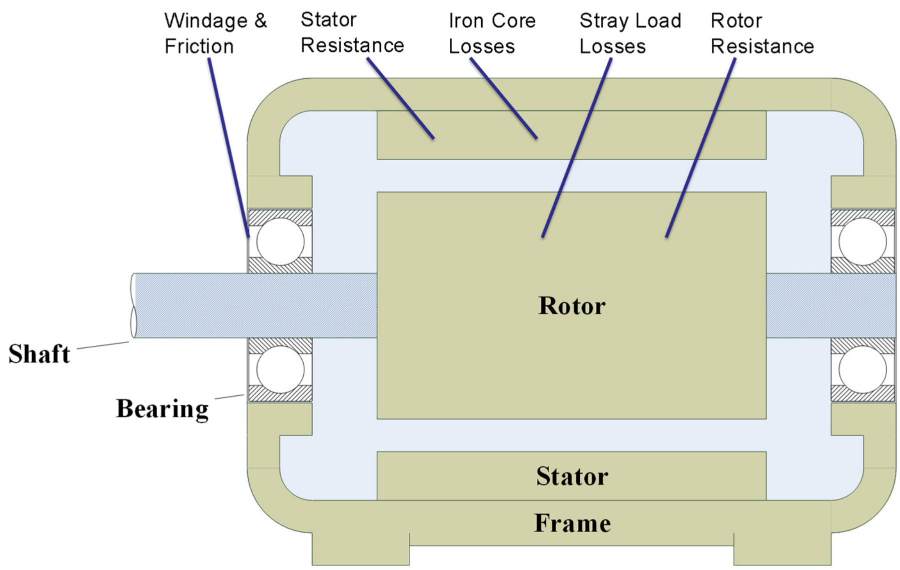


Figure 9 Segregated loss

• Stray losses W_{sllc} : These are the losses due to stray fields, as well as all other unaccounted losses bundled together. The stray-load loss is also estimated from Table 4

Table 4 Assumed values for stray-load loss

Machine Rating	Stray-load Loss in % of Rated Output
1-125 HP	1.80%
126–500 HP	1.50%
501-2499 HP	1.20%
> 2500 HP	0.90%

2.4.7 Shaft Torque Method

As the most straightforward of these approaches, this method measures directly the electrical input power and the mechanical output power, without the need to calculate the losses [6].

$$\eta = \frac{P_{out}}{P_{in}} = \frac{T_{shaft} \cdot \omega_r}{P_{in}} \tag{2.11}$$

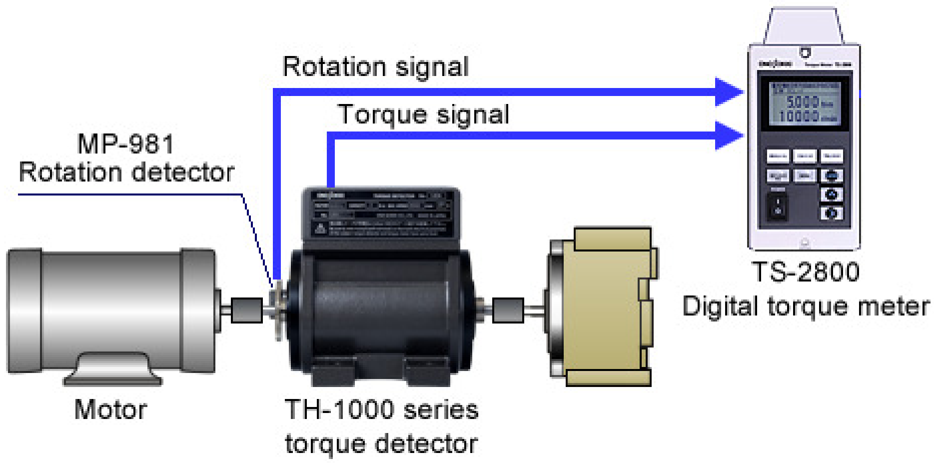


Figure 10 Shaft torque method

The torque is measured by a torque transducer, which has to be mounted solidly on the shaft of the induction motor between motor and load. It offers the most accurate field efficiency evaluation, but is also highly intrusive. Additionally, the high cost of the torque transducers makes this method unrealistic for most industrial applications. It is extremely uncommon that an induction motor will be operated with a calibrated torque transducer in an industrial application. Retrofitting a torque transducer in a plant means serious downtime, with large losses of productivity. Additionally, accuracies of torque transducers are relatively low, if they are not properly calibrated, for which laboratory setups may be necessary. Torque transducers are also known to be relatively weak mechanically, and frequent startup processes may damage them, or make re-calibrations necessary.

To make this method less intrusive, shaft torque can be measure by air-torque method and directly rotor speed measurement can be replaced with rotor slot harmonics method, which has been done in [3]. The alternative method has anticipated error at 4% while it is still not non-intrusive.

2.4.8 Dedicated Instrument Methods

This special dedicated instrument method requires universal portable instruments to measure Watt, VARS, resistance, volt, amps and speed. There are some universal instruments and devices in the market: MCE MAX from PdMA and Beck instrument Explorer. Their efficiency readings are carefully compared with the "true" efficiency and are measured by dynamometer and precision laboratory instruments according to each IEEE test standard. In particular, under the load of 25%-150%, the precision of the special device can be kept the accuracy within 2% under the unchallenged test conditions , and can be kept the accuracy within 3%, even under the adverse conditions of voltage deviation and imbalance of the old, damaged or rewound motors. These instruments require skilled electricians or highly trained personnel, and the safety connection of the electrical equipment in the industrial power system needs to be added to about one day of training and practice. The motor must be tested temporarily without electric resistance and temporarily unloaded at the same time. That is, testing without load under normal voltage. Decoupling in-situ is very inconvenient, but no load testing can be performed many times, such as tracking service or receiving inspection in the workshop.

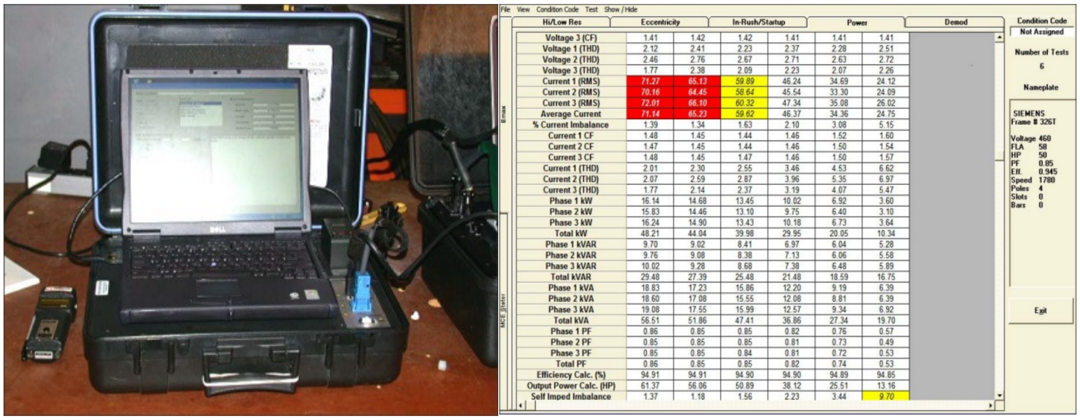


Figure 11 PdMA instrument and display Screen

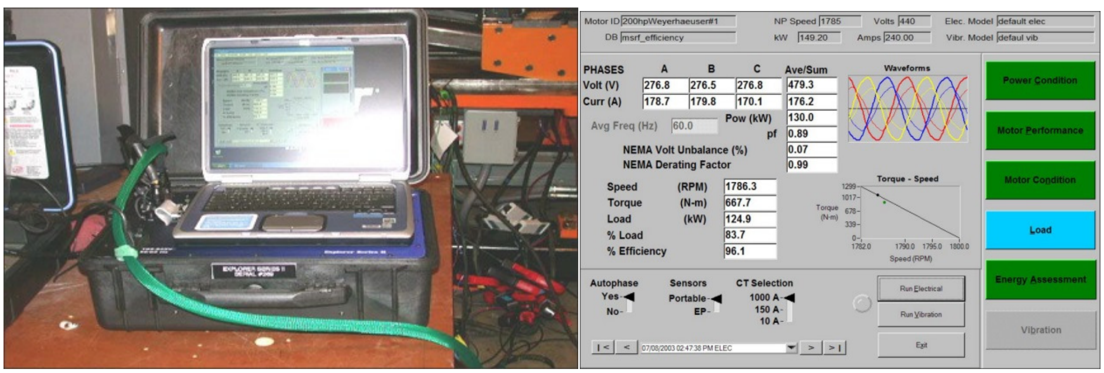


Figure 12 Baker instrument and display screen

2.5 CMA-ES for Evaluation Methods

As we all know, some efficiency estimators are proved to be very successful on unconstrained problems, but they can hardly be applied in constrained optimization. However, the covariance matrix adaptive evolutionary strategy (CMA-ES) proposed by Hansen, et al. 2003[22], has been used to solve many engineering optimization problems:

Hansen et al. [23] applies CMA-ES to the feedback control of combustion, and proves that their on-line optimization is effective in applying this method, especially in automation, even under highly unstable operating conditions, the application of this method can also enhance the online performance of the controller.

In the calibration of scientific instruments, Wilson et al. [24] has developed an additional reliable technique to align the pulse shaper by using CMA-ES to ensure that the output half of the Martinez stretcher can perfectly compensates for half of its input.

To solve the design problem in hydrogeology, Bayer and Finkel [25] use CMA-ES to reveal that the position of the well should be close to the source when the pump rate is minimized.

In combination CMA-ES with belief rules based fault diagnosis for wireless sensor networks, He et al. [26] applied the integrated method to a case study using a dataset of intelligent sensor laboratories to verify the effectiveness of the integrated method.

CMA-ES is used to evaluate the problem of chemical equilibrium (Faten, et al., 2012) [27]. The effect of CMAES on performance and stopping criteria at different iterations indicates that CMAIAES is the most effective algorithm.

A new method to optimize irrigation scheduling for crop water demand is proposed by Belaqziz et al. [28]. This method is based on covariance matrix adaptive evolutionary strategy (CMA-ES), which optimizes the potential factors of irrigation scheduling and reduces the water consumption by 25%.

Besides the above six application cases, CMA-ES has many other applications in different engineering problems. Such as, this study adopts the improvement proposed by Ros and Hansen [29], from the two time curve to the linear evolution of the internal time and space complexity. In addition, Jastrebski and Arnold [30] enabled the active CMA-ES option, which uses information about unsuccessful future candidate solutions to supplement its efficiency estimates. However, there are few literatures on CMA-ES application in motor efficiency evaluation.

2.6 Chapter Summary

In Table 5, a variety of motor efficiency evaluation methods are compared, and the rotor speed, current, voltage, input power, stator resistance, shaft torque measurement and machine nameplate data on machine or motor are presented. In [3 - 5] the main efficiency estimation method based on its physical characteristics, accuracy, intrusive degree and calculation method is proposed. Traditionally, the performance evaluation of induction motor includes the optimization method (CMAES) application and the effective process of the experimental platform, which can achieve good results. Generally speaking, the more intrusive the method is, the more accurate the efficiency estimation is. However, the intrusion method has become more expensive in the process of equipment installation and data acquisition, and this intrusion method makes the evaluation of motors in situ infeasible. In summary, estimating the efficiency of a motor in a non-intrusive way during its operation is a very hard problem. Among the evaluated methods, only the equivalent circuit method is one of the most concerned methods of this study， and the necessary technical characteristics are put forward in the following for real-time monitoring of the efficiency and operation conditions of induction motors.

Table 5 Comparison of motor efficiency-evaluation methods

	Test and Measurements/Estimations Required									
Efficiency Estimation Methods	No-Load	Full-Load	Unpower	Variable V/f	Rotor Speed	Shaft Torque	Nameplate Info	Stator Resistance	Intrusion	Anticipated Error
Nameplate Methods	No	No	No	No	No	No	Yes	No	No	10.00%
Slip Method 1	No	No	No	No	Measure	No	Yes	No	Yes	7.00%
Slip Method 2	No	No	No	No	Estimate	No	Yes	No	No	8.00%
Current Method 1	No	No	No	No	No	No	Yes	No	No	8.00%
Current Method 2	Yes	No	No	No	No	No	Yes	No	Yes	6.00%
Equivalent circuit method 1	Yes	No	Yes	Yes	Measure	No	Yes	Measure	Yes	5.00%
Equivalent circuit method 2	Yes	No	No	Yes	Estimate	No	Yes	Estimate	Yes	7.00%
Segregated loss method	Yes	Yes	Yes	Yes	No	No	Yes	Measure	Yes	3.00%
Shaft Torque Method 1	No	No	No	No	Measure	Measure	No	No	Yes	Accurate
Shaft Torque Method 2	Yes	No	No	No	Estimate	Estimate	No	Estimate	Yes	4.00%
Dedicated Instrument	Yes	No	Yes	No	No	No	Yes	Yes	Yes	3.00%

3. PROPOSED NONINTRUSIVE METHOD

3.1 Overview

Estimating the efficiency of a motor in a non-intrusive way during its operation is a very hard problem. The efficiency is simply the output mechanical power, which equals the mechanical torque times the speed, divided by the input electrical power. To obtain the mechanical power, we need to measure the torque and the speed continuously. But the torque and the speed are rather inaccessible variables, and only intrusive methods are available. See [4] for a detailed review of available motor efficiency estimation methods (almost all these methods are intrusive).

The other alternative is to rely on the input voltage and current measurements, and from these infer the internal parameters that would yield the efficiency. This, however, poses a very hard ill-conditioning problem. In this work we propose a method that is based on the equivalent circuit of the motor. The main idea is to utilize different conditions in the motor's voltage, current and load to obtain extra information about the internal parameters of the equivalent circuit. By solving a non-linear optimization problem, we find the best parameter values that yield the observed voltage and current measurements. Essentially, we rely on varying motor conditions, and this give us an additional glimpse on the unknown internal parameters. Each varying condition helps narrowing down onto their true values. The varying conditions rely mostly on:

- Varying motor speeds.
- Varying line voltages.

3.2 Equivalent Circuit Model of an Induction Motor

3.2.1 The Equivalent Circuit

The basis of the developed model is the equivalent circuit. In particular, our model will try to extract all the impedances of the equivalent circuit by observing the voltages and currents. Determining all parameters of the equivalent circuit essentially fully defines the functionality of the motor and thereby the efficiency curve as well. Figure 13 shows the basic structure of the equivalent circuit. It consists of the following parameters:

- R_1: Stator winding resistance.
- X_1: Stator leakage inductance.
- R_c: Core or iron losses.
- X_m: Magnetizing inductance.
- R_2': Rotor winding resistance.
- X_2: Rotor leakage inductance.
- R_L: Mechanical load.

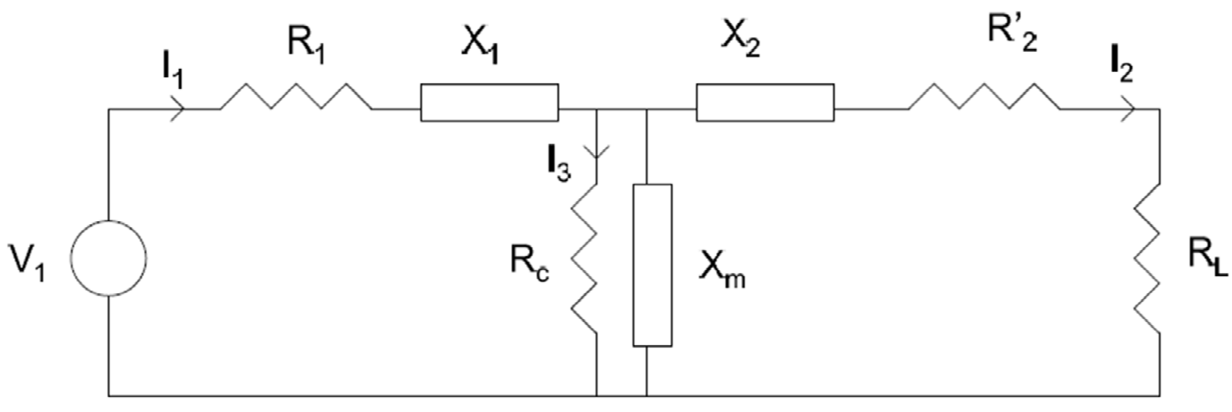


Figure 13 The motor equivalent circuit

All resistances except R_L represent the losses. For example, R_1 models the power dissipated in the stator windings, whereas R_c represents the core or eddy losses, and R_2' are the losses in the rotor windings. On the other hand, the power consumed in R_L is the useful mechanical power. This resistance is a function of the slip, as follows:

$$R_L = \frac{R_2'(1-s)}{s} \tag{3.1}$$

For simplicity, we also define the total resistance:

$$R_2 \equiv R_2' + R_L = \frac{R_2'}{s} \tag{3.2}$$

When handling unbalanced line voltages it is typical to consider the symmetric component model. It is based on transforming the three phase voltages to the following components.

The positive sequence component measures the symmetric component of the voltages. It gives more or less the average of the magnitudes of the three phase voltages. The negative component, on the other hand gives the degree of unbalance in the voltages. If the three phase voltages are perfectly balanced, then the negative sequence equals identically zero. It increases in value the more unbalanced (phase-wise or magnitude-wise) the three phases are. We will concentrate here on only the positive component. The positive component is given by

$$V_p = \frac{1}{3}\left(V_a + \alpha V_b + \alpha^2 V_c\right) \tag{3.3}$$

where $\alpha = e^{j2\pi/3}$, and V_a, V_b, V_c are the phase voltages. The negative component is also given by:

$$V_n = \frac{1}{3}\left(V_a + \alpha^2 V_b + \alpha V_c\right) \tag{3.4}$$

In all subsequent analysis we will use the positive component of the phase voltages, and this will be considered the voltage applied to the equivalent circuit. If we have a star connection, we have to first compute the positive component of the line voltages. From this, using some transformation, we can get the positive component with respect to the phase voltages. Section 3.5 explains this transformation.

3.2.2 Efficiency

The efficiency is typically measured as a function of the slip, leading to the celebrated efficiency-slip curve. It typically consists of an almost linear part for small slips followed by a flat part. The efficiency is also affected by other factors, such as:

- The degree of unbalance.
- The condition of the motor.

We will not consider these two factors for the time being. They will be tackled later. The goal here is to obtain the baseline efficiency curve. Following that we will factor in the effect of unbalance and motor health through empirical corrective factors.

The resistance represents the load and the power consumed in it represents the useful mechanical load. So, the efficiency could be formulated as the power consumed divided by the input electrical power.

For the time being we assume a balanced voltage case, so we can ignore the negative component. Thus, the mechanical load output (per phase) for the positive component is given by

$$P_p = \frac{I_{2p}^2 R_2'(1-s)}{s} \tag{3.5}$$

where I_{2p} is the referred current in the rotor branch, as shown in Figure 13, for the positive component circuit (i.e. the basic equivalent circuit). This means that we apply the positive component voltage V_p to the equivalent circuit, and compute the currents in the branches: I_{1p} and I_{2p}. These can be computed easily using simple electric circuit analysis. The efficiency is then given by

$$\eta = \frac{I_{2p}^2 R_2'(1-s)/s}{Re\left[V_p I_p^*\right]} \tag{3.6}$$

or it can be written as:

$$\eta = \frac{I_{2p}^2 R_2'/s}{I_{2p}^2 R_2'(1-s)/s + I_{1p}^2 R_1 + +I_{3p}^2 R_c} \tag{3.7}$$

In the latter equation the denominator represents all power consumed in all resistances. This should be equivalent to the input power. Both Equations (3.6) and (3.7) are equivalent (this was also checked in the simulations).

There are two loss components, however, that are not accounted for by this equation, namely the friction/windage loss and the stray loss. We have to subtract the loss fraction of these two components from the efficiency obtained in Equations (3.6) and (3.7). The detailed steps of how to account for these two loss types are described in Section 3.2.

The previous equation assumes that we can use the positive component as the main component to compute the efficiency. In reality, the efficiency depends on both the positive component and the negative component. However, we have found that the effect of the negative component on efficiency is negligible.

3.2.3 Torque

Let $\omega, \omega_m, \omega_s$ be respectively the electrical speed (e.g. $\omega = 2\pi 60$ for 60 Hertz case), the mechanical speed, and the synchronous mechanical speed. Then

$$\omega_s = \frac{\omega}{P} \tag{3.8}$$

where P is the number of pole pairs. Then, the torque equals the mechanical power divided by the mechanical speed:

$$T = \frac{3I_2^2 R_L}{\omega_m} \tag{3.9}$$

where I_2 is the RMS current in the rotor branch, and the multiplication by 3 is for the number of phases. But

$$R_L = R_2'(1-s)/s \tag{3.10}$$

and

$$s = 1 - \frac{\omega_m}{\omega_s} \tag{3.11}$$

Hence

$$\omega_m = \omega_s(1-s) \tag{3.12}$$

$$= \frac{\omega}{P}(1-s) \tag{3.13}$$

So the torque becomes:

$$T = \frac{3I_2^2 P R_2'(1-s)/s}{\omega(1-s)} \tag{3.14}$$

$$= \frac{3I_2^2 P R_2'}{s\omega} \quad (3.15)$$

However, this past formula neglects the friction/windage and stray losses that are not reflected in the equivalent circuit's load resistance. So, essentially the correct formula is:

$$T = (1 - L_{FW} - L_S)\frac{3I_2^2 P R_2'}{s\omega} \quad (3.16)$$

where L_{FW} and L_S represent the fraction of power lost as friction/windage and stray respectively (e.g. $L_{FW} = 0.02$ and $L_S = 0.015$).

3.3 The IEEE 112B Method for Efficiency Estimation

To evaluate the efficiency experimentally we employ the IEEE 112 Method B. This is for the purpose of validating the performance of our proposed approach.

Method B is based on segregating the losses, and measuring each loss separately with some experiment. There are five different loss types, which we describe below, along with the way the IEEE method measures these losses experimentally:

- Stator loss or I^2R loss: This is the loss in the stator windings. Referring to the equivalent circuit, this essentially equals $I_1^2 R_1$, where R_1 is the stator resistance.

  IEEE method: Measure the cold line to line DC resistance. From that obtain the phase stator resistance (by dividing by 2 if it is a star connection). Adjust the resistance by taking into account the temperature in which the motor is going to operate, for example at full load. This is done by running the motor continuously at full load, measuring the temperature, and applying the correction formula.

- Rotor loss: It is the loss due to the currents in the rotor bars. It equals $I_2^2 R_2'$.

  IEEE method: Measure the input power, and also measure the core loss as will be outlined next item. Then the rotor loss is given by

  $$Rotor\ loss = (Input\ power - stator\ I^2R\ loss - core\ loss) \times s$$

  where s is the slip, corrected according to a certain equation to take into account the temperature effect.

- Core or iron loss: It is the loss from eddy currents flowing in the different motor components. It is modeled as $I_3^2 R_c$ in the equivalent circuit.

  IEEE method: The core loss at each test voltage is obtained by subtracting the value of friction and windage loss (determined next item) from the input power minus stator I^2R stator loss. A plot of the core loss versus voltage can be constructed for use in determining the core loss at any desired voltage.

- Friction and windage loss: This is the loss due to friction in the bearings, and due to wind resistance. It is not modeled by the equivalent circuit since this loss is experienced at the mechanical load side. As such, it has to be added extra, on top of the losses modeled by the equivalent circuit that are given in Section 3.2.2.

  IEEE method: It is determined by performing a linear regression analysis using three or more points of the power versus voltage squared curve (we need experiments where we apply different voltages to the motor). First we subtract the stator I^2R loss from the total losses at each of the test voltage points and plot the resulting power curve versus voltage, extending the curve to zero voltage. The intercept with the zero voltage axis is the friction and windage loss.

- Stray losses: These are the losses due to stray fields, as well as all other unaccounted losses bundled together.

  IEEE method: The stray losses are computed experimentally by measuring all combined losses (input power minus output power), subtracting all other losses (stator, rotor, core, and friction), and repeating this a number of times for different loads. The resultant will be the stray loss. Then we fit a quadratic curve to these stray loss measurements (versus torque, i.e. $P_{stray} = A\ \mathrm{Torque}^2 + B$). That will give a general formula for the stray loss. Another alternative is to fit the stray loss against the current magnitude.

3.4 How to Obtain Symmetric Components of the Phase Voltages from Line Voltage Measurements

The most prevalent way motors are connected is a star connection rather than delta. In this situation only line voltages are available. From these line voltages, we have to obtain the symmetric component decomposition that should be based on the phase voltages. To see how this is possible, compute the positive component of the line voltages V_{pl} :

$$V_{pl} = \frac{1}{3}\left[V_{ab} + \alpha V_{bc} + \alpha^2 V_{ca}\right] \tag{3.17}$$

$$= \frac{1}{3}\left[(V_a - V_b) + \alpha(V_b - V_c) + \alpha^2(V_c - V_a)\right] \tag{3.18}$$

$$= \frac{1}{3}\left[V_a(1-\alpha^2) + V_b(\alpha - 1) + V_c(\alpha^2 - \alpha)\right] \tag{3.19}$$

$$= \frac{1}{3}\left[\sqrt{3}\angle 30^\circ\ V_a + \sqrt{3}\angle 30^\circ\ \alpha V_b + \sqrt{3}\angle 30^\circ\ \alpha^2 V_c\right] \tag{3.20}$$

$$= \sqrt{3}\angle 30^{\circ}\, V_{p\phi} \tag{3.21}$$

where V_{ab}, V_{bc}, V_{ca} denote the line voltages, V_a, V_b, V_c denote the phase voltages, and $V_{p\phi}$ denotes the positive component for the phase voltages. Thus:

$$V_{p\phi} = \frac{V_{pl}\angle -30^{\circ}}{\sqrt{3}} \tag{3.22}$$

If the negative component is needed, a similar derivation can be obtained as well, leading to

$$V_{n\phi} = \frac{V_{nl}\angle 30^{\circ}}{\sqrt{3}} \tag{3.23}$$

The line symmetric components for the currents are obviously equal to those of the phase, i.e.

$$I_{p\phi} = I_{pl} \tag{3.24}$$

$$I_{n\phi} = I_{nl} \tag{3.25}$$

3.5 The Proposed Efficiency Estimation Method

3.5.1 Problem Formulation

The proposed idea is based on multiple instances of measurements of the voltages and currents, hoping that each measurement will shed light on the values of the parameters. From all these measurements we formulate an objective function that we seek to solve using nonlinear optimization. We hope that we reach the true parameter values that are consistent with all the measurements.

Essentially, we measure the impedance of the motor during operation M times (let us say 20 times). During these M times, because of voltage fluctuations and speed changes, each measurement will add a piece of information or evidence. However, the difficulty is that the resistance R_2 would change in a way that we would not know. It will change according to load conditions and slip. This complicates the estimation process, but we have an approach to overcome this difficulty. All other circuit impedances are constant (as long as measurements are not too far apart to allow the motors condition to deteriorate or parameter values to drift). So, essentially the algorithm estimates R_2 as a function of all other parameters to eliminate the varying component. Then it estimates the constant impedances using least square from these M observations. The details are given below, but first let us compute and reformulate the input impedance of the equivalent circuit:

$$Z = R_1 + jX_1 + \frac{\left(R_2 + jX_2\right)\left(\frac{jR_cX_m}{R_c + jX_m}\right)}{R_2 + jX_2 + \frac{jR_cX_m}{R_c + jX_m}} \tag{3.26}$$

Simplifying, we get

$$Z = \frac{a_1 + b_1R_2 + j(a_2 + b_2R_2)}{a_3 + b_3R_2 + j(a_4 + b_4R_2)} \tag{3.27}$$

Where

$$a_1 = -R_1X_mX_2 - R_cX_1X_2 - R_cX_1X_m - R_cX_2X_m \tag{3.28}$$

$$b_1 = R_1R_c - X_1X_m \tag{3.29}$$

$$a_2 = R_1R_cX_2 + R_1R_cX_m - X_1X_2X_m \tag{3.30}$$

$$b_2 = R_1X_m + R_cX_1 + R_cX_m \tag{3.31}$$

$$a_3 = -X_2X_m \tag{3.32}$$

$$b_3 = R_c \tag{3.33}$$

$$a_4 = R_c X_2 + R_c X_m \tag{3.34}$$

$$b_4 = X_m \tag{3.35}$$

Next step we estimate R_2 as a function of all other parameters to eliminate the varying component. Then we estimate the constant impedances using least square from these M observations. Here are the details. Let

$$Z_1(m) = Z_{1R}(m) + jZ_{1I}(m) \tag{3.36}$$

denote the measured impedance at trial m ($m=1,\ldots,M$). This can simply be obtained using the measured voltage and current. Specifically, we consider the three line voltages, and the three line currents, obtain the positive components for the phase (rather than line) quantities, $V_{p\phi}$ and $I_{p\phi}$, and then compute the measured impedance as simply $Z_1 = V_{p\phi} / I_{p\phi}$.

Then we match the value of the measured impedance to the theoretically calculated in Equation (3.27):

$$Z \equiv \frac{a_1 + b_1 R_2 + j(a_2 + b_2 R_2)}{a_3 + b_3 R_2 + j(a_4 + b_4 R_2)} = Z_{1R}(m) + jZ_{1I}(m) \tag{3.37}$$

We get

$$\left(Z_{1R}(m) + jZ_{1I}(m)\right)(a_3 + b_3 R_2 + j(a_4 + b_4 R_2)) = a_1 + b_1 R_2 + j(a_2 + b_2 R_2) \tag{3.38}$$

We can equate the real parts of the equation, and the imaginary parts. But, for now we need only R_2. So we use only the real part of the equation to obtain R_2. We get

$$Z_{1R}(m)(a_3 + b_3 R_2) - Z_{1I}(m)(a_4 + b_4 R_2) = a_1 + b_1 R_2 \tag{3.39}$$

We can solve Equation (3.39), to get R_2:

$$R_2(m) = \frac{a_1 - Z_{1R}(m)a_3 + Z_{1I}(m)a_4}{-b_1 + Z_{1R}(m)b_3 - Z_{1I}(m)b_4} \tag{3.40}$$

In all previous equations we substitute for R_2 from Equation (3.40). The index m in $R_2(m)$ highlights the fact that the obtained R_2 is different for every measurement instant. We end up with equations that are function of the constant variables R_1, R_c, X_1, X_2, X_m, with the variable term R_2 eliminated. Now we equate the imaginary value of Equation (3.37) for each of the measurement instances m. We get M Equation

$$Z_{1I}(m) = \frac{(a_2 + b_2R_2(m))(a_3 + b_3R_2(m)) - (a_1 + b_1R_2(m))(a_4 + b_4R_2(m))}{(a_3 + b_3R_2(m))^2 + (a_4 + b_4R_2(m))^2} \tag{3.41}$$

where $R_2(m)$ is to be substituted from Equation (3.40). We have M equations in 5 unknowns. They can be solved using least square. This means we minimize the following error function w.r.t. the unknowns R_1, R_c, X_1, X_2, X_m:

$$E = \sum_{m=1}^{M} \Big[Z_{1I}(m) - \frac{(a_2 + b_2R_2(m))(a_3 + b_3R_2(m)) - (a_1 + b_1R_2(m))(a_4 + b_4R_2(m))}{(a_3 + b_3R_2(m))^2 + (a_4 + b_4R_2(m))^2} \Big]^2 \tag{3.42}$$

where $R_2(m)$ is given by Equation (3.40).

3.5.2 Elimination of Speed Measurement

As mentioned, we have determined all parameters, including R_2 using the impedance computations and the least square model. But we needed still need extra information to determine how R_2 decomposes into R_2' and R_L. The problem is that we need the value of the slip at each measurement, and this value is not available. We have initially tried to utilize the information in the negative sequence component, but it did not yield good results.

So we decided to use nameplate information. This will give the extra information needed to evaluate the remaining unknown quantities.

The nameplate data has information such as rated voltage, rated current, rated slip, rated torque (which is computed from the rated power or HP of the motor), and often rated power factor. We use the first three (i. e. rated voltage, rated current, rated slip) as a constraint to backtrack R_2'. To see that, compute the magnitude of the rated impedance (as rated voltage divided by rated current). Denote that by $\| W \|$. Equate that to the theoretical impedance magnitude Equation (3.40), measured at rated slip:

$$\| W \|^2 = \frac{\| a_1 + b_1 R_2 + j(a_2 + b_2 R_2) \|^2}{\| a_3 + b_3 R_2 + j(a_4 + b_4 R_2) \|^2} \tag{3.43}$$

$$= \frac{\left(a_1 + b_1 R_2\right)^2 + \left(a_2 + b_2 R_2\right)^2}{\left(a_3 + b_3 R_2\right)^2 + \left(a_4 + b_4 R_2\right)^2} \tag{3.44}$$

All constants $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ are already known because we evaluated the constant impedances R_1, R_c, X_1, X_2, X_m. So from Equation (3.44), we obtain the only unknown R_2. This amounts to a solution of a quadratic equation, giving:

$$R_2 = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{3.45}$$

where

$$A = b_1^2 + b_2^2 - \| W \|^2 \, (b_3^2 + b_4^2) \tag{3.46}$$

$$B = 2\left[a_1 b_1 + a_2 b_2 - \| W \|^2 \, (a_3 b_3 + a_4 b_4)\right] \tag{3.47}$$

$$C = a_1^2 + a_2^2 - \| W \|^2 \, (a_3^2 + a_4^2) \tag{3.48}$$

Once evaluating R_2, and since the rated slip s is given, we can evaluate the constituents R_2', R_L using Equations. (3.1), (3.2). We can obtain these quantities if rated power factor instead of rated slip is available. Note that some of the other nameplate information will also be exploited as "soft constraints". More will be said on that in Section 3.5.4.

3.5.3 Objective Function Formulation

As mentioned in the previous two subsection the main idea about the proposed method is to make use of the measured impedance values, and equate it to the impedance calculated from the equivalent circuit. We were able to eliminate the unknown and possibly time varying load resistance by simply equating the real part of the impedance equation. Subsequently, we use the imaginary component of the equation, and constructed a mean square error function of the fixed but unknown equivalent circuit parameters. We then seek to minimize this function given by Equation (3.42) to obtain the parameter values.

One can, however, pose the same principle in several different ways. For example, one can swap the roles of the imaginary and the real components. One can also reformulate the resulting equations by simple algebra. Each different formulation would probably yield a different result in the optimization. We made use of this possible diversity, by running the MSE optimization several times, each time corresponding to a different formulation of the equations. Subsequently, we combine the resulting solutions. This will lead to a more robust final solution. Rather than being at the mercy of one optimization run gone wrong, we are now more assured of reaching a good solution. There are six different combinations that lead to six different solutions (the variables flagtot and flagR2 are responsible for selecting which one of the six formulations is to use). We implemented several different ways of combining these six solutions. In the first one, called comb1, we combine each of the equivalent circuit parameter estimates, i.e. $R_1, R_2, X_1, X_2, X_m, R_c$, by taking the median of the six obtained values of each parameter. The other method (comb2) is based on following through each of the six solutions to obtain the efficiency curve for each. Subsequently, we take the median of the obtained efficiency curves, point by point. A third combination strategy (comb3) is to obtain the two combined efficiency curves for the two preceding combination methods, and we take the point by point average of these two curves. This latter method is the basis of the final method we used to obtain the efficiency curve. More specific details of the algorithms are given next section.

3.5.3.1 Another Level of Combination

Even though the optimization method used is quite superior, there are some instances where convergence to a good solution might not be achieved, yielding a suspect solution. We seek to prevent such bad runs by running it several times, each with different starting values for the parameters. Then we admit only the runs whose objective function (i.e. the error plus penalty term) is lower than a prescribed threshold. Those who get admitted are combined using the median, as mentioned above. Below are some detailed steps of the algorithm:

1. For i=1 to 10: Perform the six different optimization runs using the six different formulations.
2. From those 60 runs (6 combinations times 10 runs), take all runs with errtot $\leq$ threshold1 and err0 $\leq$ threshold2, where errtot is the total objective function (mean square error plus constraint penalty, discussed next subsection), and err0 is just the MSE.

3. If no run satisfies these error constraints, then just take the best K runs (best in errtot), provided that errtot $\leq$ threshold3 and err0 $\leq$ threshold4. Any run that violates these latter conditions is inadmissible.
4. Compute the median of the equivalent circuit parameters for the runs that are selected. Obtain the efficiency curve from these combined parameters. This is the comb1 method.
5. Compute the point by point median of the efficiency curves of the selected runs. This is the comb2 method.
6. Compute the point by point mean of the two efficiency curves obtained in comb1 and comb2. This is the comb3 method that we ultimately use.

3.5.4 Constraints and Penalty Terms

3.5.4.1 Constraints

The optimization will produce many valid solutions (local minima and the like). Multiple solutions will even yield the exact same impedances as the measured impedances. Naturally, from among these we should choose the most reasonable solution that reflects reasonable and natural behavior of the motor. We should rule out solutions that lead to inconsistent behavior. For example we could check that the torque curve is well-behaved. We should check that the estimated slips are in the expected range (e.g. [0, 0.05]). We use these checks as soft or hard constraints to rule out solutions. Here are the constraints that we used:

1. Constraints 1-7: All the seven impedances $R_1, X_1, R_c, X_m, X_2, R_2', R_L$ have to be positive.
2. Constraint 8: The estimated slip values of the measured points are preferably monotonically increasing with the measured input current, or monotonically decreasing

with the impedance magnitude. We define a measure of how monotonically decreasing it is, and penalize it if that measure exceeds a threshold.

3. Constraint 9: The estimated slips vary in the range 0 to 0.1.
4. Constraints 10 and 11: The resistive component of the positive sequence equivalent circuit (the real value of the input impedance of the circuit) is positive over the small slip range and over the rest of the slip range.
5. Constraint 12: The imaginary value of the input impedance of the positive sequence circuit is positive (the circuit is reactive *not* capacitive).
6. Constraint 13: The phase angle of the input impedance of the positive sequence circuit is monotonically decreasing with slip over the very small slip range (0-0.02)).
7. Constraints 14 and 15: The resistive component of the negative sequence equivalent circuit (the real value of the input impedance of the circuit) is positive over the small slip range and over the rest of the slip range. Note: Currently we are not using this constraint, are giving it zero weight. The reason is that the negative component turned out to be not very reliable, and we found from the experiments on the real motor that indeed it could have negative resistive part.
8. Constraint 16: The efficiency over the slip range of 55% to 150% of the rated slip has to be at least 50%.
9. Constraint 17: The efficiency over the slip range of 25% to 55% of the rated slip has to be at least 20%.
10. Constraint 18: The torque maximum (as a function of slip) occurs at slips 0 to 30%.

11. Constraint 19: The load resistance R_L is monotonically decreasing with the slip. We use also the measure of monotonicity that we used for Constraint 8, and compare it with a threshold.
12. Constraint 20: The estimated slip cannot be negative.
13. Constraint 21: The efficiency cannot be larger than $1 - s$.

Table 6 The weights of the different constraints

Constraint number	Weight
1	0.1
2	0.1
3	0.1
4	0.1
5	0.1
6	0.1
7	0.07
8	0.01
9	0.05
10	0.02
11	0.02
12	0.02
13	0.02
14	0
15	0
16	0.04
17	0.04
18	0.01
19	0.02
20	0.08
21	0.04

Note that some constraints are redundant, while some other ones are designed to lead to a well-behaved solution, the purpose being to rule out atypical estimates. Table 6 gives the exact weighting coefficients for the 21 constraints. In addition to these we incorporated some soft constraints, in the form of some penalty terms. This is described below.

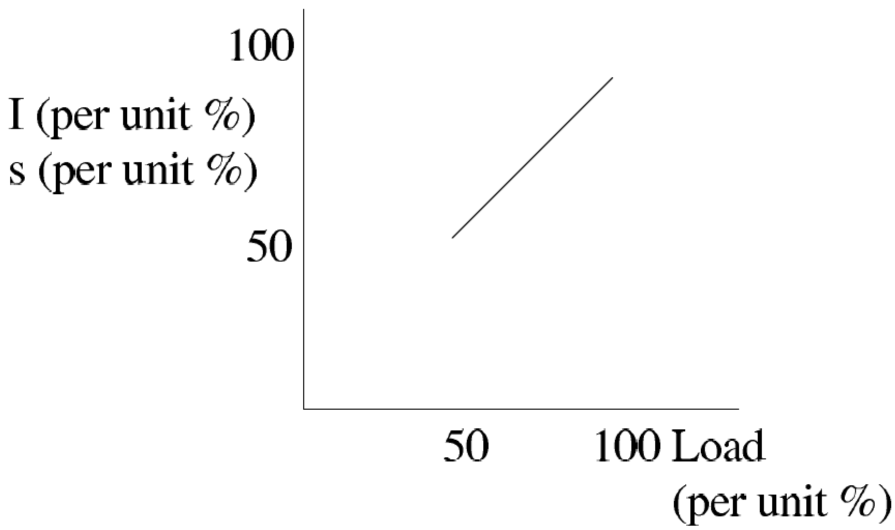


Figure 14 The per unit relationships

3.5.4.2 Penalty Terms of the Objective Function

We also add some additional penalty terms. Unlike the previous constraints, these are considered "soft constraints". The previous constraints were more like step functions. Here, the penalty terms penalize the degree of violation. The first set of penalty terms are based on the per unit analysis, described below.

By normalizing everything such that it is per unit, additional constraints can be formulated. The normalization is performed as follows:

$$I_{pu} = \frac{I}{I_{rated}} \tag{3.49}$$

$$s_{pu} = \frac{s}{s_{rated}} \tag{3.50}$$

$$T_{pu} = \frac{T}{T_{rated}} \tag{3.51}$$

The relationships among these three quantities are linear as shown in Figure 14. These can be used as additional constraints.

We used the following soft constraints:

1. Penalty Term 1: The torque at the rated slip should be near the rated torque.
2. Penalty Term 2: The slip at which the estimated torque equals the rated torque should be close to the rated slip.
3. Penalty Term 3: The slip at which the torque equals 75% of the rated torque should be close to 75% of the rated slip.
4. Penalty Term 4: The slip at which the torque equals 50% of the rated torque should be close to 50% of the rated slip.
5. Penalty Term 5: The input current at the rated slip should be near the rated current.
6. Penalty Term 6: The slip at which the current equals the rated current should be close to the rated slip.

In addition, we have the following penalty terms that punish situations which violate atypical values of the different quantities:

1. Penalty Term 7: The percentages of the different losses vary in certain typical ranges, given in Table 7. Any violation of these ranges will be softly penalized using a bump function that is close to zero in the specified range, and slowly picks up when we get out of the range. The figures in the tables is collected from various papers.

2. Penalty Term 8: The values of the parameters X_1 and X_2 obey some ratios given in Table 8 (which is a guideline for motor design by NEMA). So the constraint we used is that $0.3 \le X_1 / X_2 \le 1.1$.
3. Penalty Term 9: The ratios of the parameters X_1 and X_m are between 0.01 and 0.09. It was mentioned in the paper: B. Lu, W. Qiao, T. G. Habetler, and R. G. Harley "Solving Induction Motor Equivalent Circuit using Numerical Methods for an In-Service and Nonintrusive Motor Efficiency Estimation Method", that experimentally, the ratio X_1 / X_m is usually between 0.02 and 0.07. However, we put a very small weight on this constraint, because we could not verify from other publication the accuracy of this range.
4. Penalty Term 10: Typically the maximum of the efficiency curve is in the range of slip of 70 to 100% or the rated slip. This term adds this as a penalty.
5. Penalty Term 11: Typically, the magnitude of the current versus slip is linear for higher values of the slip. See Figure. 15 for an example of the current magnitude/slip relation for a real 7.5 HP motor. We perform a linear regression analysis on the range $0.3 s_{\text{rated}}$ to $1.2 s_{\text{rated}}$, and compute the normalized residues, i.e. errors from the fitted line. The size of the residuals is the penalty added.
6. Penalty Term 12: The full load power factor has to be in a certain range, depending on the HP of the motor. If $HP \le 10$ then $0.65 \le PF \le 0.94$. If $10 < HP \le 50$ then $0.75 \le PF \le 0.95$. If $HP > 50$ then $0.8 \le PF \le 0.96$. These ranges are confirmed by real motor data.

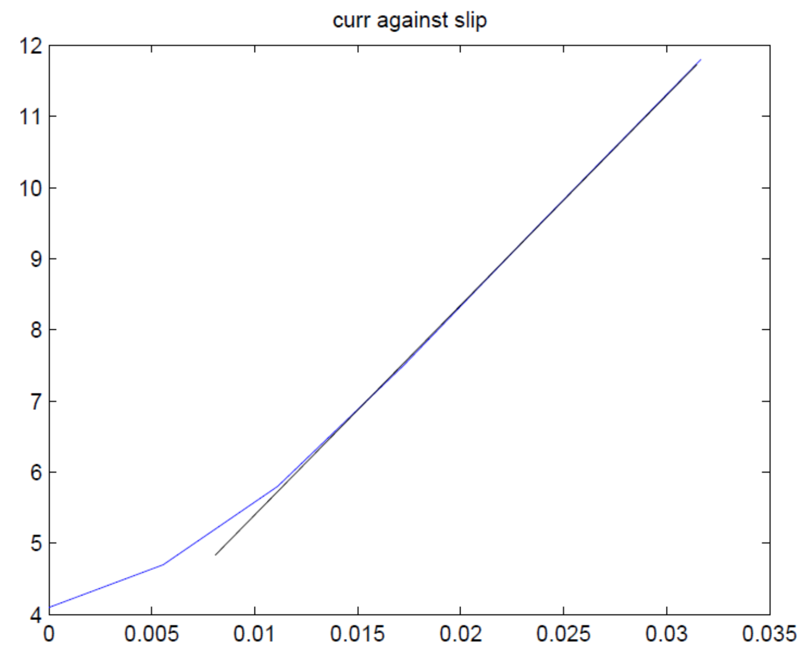


Figure 15 The magnitude of the current versus slip for a 7.5 HP motor. Shown also is a linear fit of the curve for the higher values of slip.

Table 7 Typical ranges of different loss types

Loss type	range
Stator loss	25 - 55 %
Rotor loss	15 - 40 %
Core loss	5 - 25 %
Friction/windage loss	3 - 22 %
Stray loss	5 - 25 %

Table 8 Ratios of the X1 and X2 inductances for different motor design types

Motor design type	X1/X2
A	1
B	0.67
C	0.43
D	1

Table 9 The Weights of the Different Penalty Terms

Penalty Term number	Weight
1	0.25
2	0.25
3	0.1
4	0.1
5	0.25
6	0.25
7	0.25
8	0.02
9	0.01
10	0.03
11	0.08
12	0.04

These soft constraints or penalty terms are to be added to the error term. See Table 9 for the weighting coefficients of the 12 described penalty terms.

Note also that the 21 binary constraints above are also added as penalty functions. The difference between these two types of constraints is that the first set of constraints are binary, inducing some step functions if any of them is violated. On the other hand, the penalty terms (described in this subsection) are gradual, and depend on the degree of violation.

3.5.5 Computation of the Friction/Windage and Stray Losses

As mentioned, the friction/windage and stray losses are not accounted for by the equivalent circuit, and have to be added extra. In our efficiency estimation method we have several options for calculating these losses. They are all coded in the function otherlosses.m. We can easily choose which option to use by setting up certain flags. These options are chosen from certain guidelines in the IEEE test, or certain key papers that analyzed such losses experimentally. The options are the following:

1. The total friction, windage, and stray loss is a fixed amount (for example 3.5%), independent on the operating conditions.
2. The friction/windage loss is a fixed percentage (we used 2%), independent of the load or any other operating condition.

   The stray load's nominal value at full load is given as in Table 10 below, obtained from the IEEE Standard 112-1991. To make it transition in a smoother way, we instead linearly interpolated between the given values in the table. For example in the middle of each of the intervals [125, 500] and [500, 2500], i.e. 312.5 and 1500 the value is 1.5% and 1.2% respectively. For any value in between, it is a linear interpolation of these quantities.

   However, these are the nominal values at full load. At any arbitrary load, given by current I or by torque T, the stray loss is then given by:

$$P_{\text{stray}} = P_{\text{stray-nom}}\left(\frac{I}{I_{FL}}\right)^2 \tag{3.60}$$

$$=P_{\text{stray-nom}}\left(\frac{T}{T_{FL}}\right)^2 \tag{3.61}$$

   where $P_{\text{stray-nom}}$ is the nominal value obtained using the linear interpolation described above, I_{FL} and T_{FL} represent respectively the full load current and the full load torque.

   We have both options (Equation 3.60 and Equation 3.61), but we prefer using the current because it can be measured. The torque would only be an estimate based on the model we have developed.

Table 10 Empirical Estimates of the Stray Loss from IEEE Standard 112-1991

Machine Rating	Stray Loss %
1-125 HP	1.8
126-500 HP	1.5
501-2499 HP	1.2
$\geq$ 2500HP	0.9

3. The friction/windage loss is a fixed percentage (we used 2%), independent of the load or any other operating condition.

   The stray load's nominal value at full load follows a newer IEEE standard, namely the following:

- If the rated output P_{out} is less than or equal 1 KW, then $P_{\text{stray-nom}} = 2.5\%$.
- For $1\ KW < P_{\text{out}} \leq 10,000\ \text{KW}$, then

$$P_{\text{stray-nom}} = 2.5 - 0.5 * log_{10}(P_{\text{out}}) \tag{3.62}$$

where P_{out} in the formula inside the brackets is given in KW.

- For $P_{\text{out}} > 10,000\text{KW}$, then $P_{\text{stray-nom}} = 0.5\%$.

Again, these give us the nominal values at full load. We have to apply Equations (3.62) or (3.53) to obtain the loss at any given operating condition.

3.5.6 On Handling Unbalance and Motor Condition

Voltage unbalance typically affects efficiency adversely, reducing efficiency by about 1 or 2 percentage points. Our method considered only a purely balanced case. To handle the unbalanced situation we use our previous efficiency curve estimate as a baseline curve. Subsequently, we correct that curve in a way that factors in the degree of unbalance.

Specifically, we use the following equation

$$\eta_{\text{unb}} = \frac{1}{\frac{1+E_x}{\eta_{\text{bal}}} - E_x} \tag{3.55}$$

where is the efficiency that incorporates the voltage unbalance compensation, is the efficiency with no unbalance as it is derived in the earlier sections. The   term represents the "excess losses", and is computed as a function of voltage unbalance empirically. It represents the excess losses that originate only from having an unbalanced supply. Table 11 gives a table of these excess losses as a function of unbalance level.

Table 11 The excess losses as a function of unbalance

Unbalance (%)	Excess Loss (%)
1	1.8
2	7.5
3	14.5
4	25
5	33
6	45
7	60

Concerning motor condition, it will definitely affect the efficiency. Deteriorating motor condition severely affects the efficiency. Work to account for this effect is currently in progress.

3.6 Optimization

This study has tested several optimizers, such as Matlab's optimizer, and the particle swarm optimization (PSO). None of them were very satisfactory. They frequently missed the global minimum, and were (especially PSO) quite slow. Finally this study found an excellent optimizer called the Covariance Matrix Adaptation Evolution Strategy, or CMAES in short. It is developed by Hansen and is publicly available at http://www.lri.fr/~hansen/cmaesintro.html. It is an evolutionary algorithm based on adaptively adjusting the search area. This algorithm was considerably more effective and lead to much better minima. Also, it is much faster. Rather than taking 7 or 8 hours, it takes about 20-30 minutes for single application to our problem. This also sped up the development effort. Instead of waiting half a day to see if some modification produces good results, we get the answer now very quickly. We also developed and coded another optimization algorithm based on a dynamic grid search. Even though promising, it needs some more development and testing. For now, it is better to stick to CMAES, and perhaps next version we could incorporate some aspects of the grid algorithm.

CMA-ES algorithm. Hansen et al. (2003) [44] proposed that the CMA-ES algorithm is a variant of the classical evolutionary strategy (ES), which uses the distribution model of the sample population to discover the correlation of variables and accelerate the evolution process.

In the n-dimensional sample space, the nonlinear optimization objective function $g : R_n \to R$, its dimension parameter n plays a vital role in the optimization of the actual parameters. In the process of minimizing the target function g, the dimension n importance is emphasized, the sampling space capacity increases with the n index, making the larger sample space sampling dimension the more difficult to deal with optimization. If the parameters of the objective function are dependent (interrelated) then the dimensionality parameter n is a very difficult problem, which is the larger the dimension is, the harder it is. When the parameters are independent, the search can be decomposed into n one-dimensional spaces, and search and merge optimization along the coordinate axes in the one-dimensional subspace. Therefore, it shows that the real difficult problem of real parameter optimization is the correlation between real parameters, which is the key to solving these problems by accelerate the evolution process of learning dependencies.

In learning dependency evolution, Ros and Hansen (2008) [29], Hansen and Ostermeier, (2001) [31] have successfully solved the learning dependent evolution problem in the real parameter search space by using covariance matrix adaptive (CMA). The CMA learns all pair-wise dependencies between all parameters by updating the covariance matrix of the sample distribution, and the updating mechanism is independent of the given coordinate system.

A simplified CMA-ES algorithm is proposed by Hansen (2006) [24], its parameters are functions as the overall dimension n of the sample and the general standard deviation (Hansen and Ostmemeer, 2001) [31]. This method is adaptable, so there is no need to fine tune any additional parameters.

4. EXPERIMENTS AND RESULTS

4.1 Overview

Five manufacturer catalog data sets, two experiments for small size motors (1 HP and 3 HP) in laboratory and two experiments for larger motors (100 HP and 200 HP) in motor shop are applied to the processes of this investigation to assure the higher persuasion of the results in this dissertation.

4.2 Fitness Function and Pseudocode of the Algorithm

According to the introduction of CMA-ES, the optimization method, this section simply revised CMA-ES and referred to Hansen et al. (2003) [25]. This modification is described in section 3.6. In addition, the framework of the algorithmic structure is presented next section in this dissertation.

So far, the CMA-ES optimization approach has proposed two methods for dealing with constrained scenarios: (1) penalty based methods (Hansen et al, 2009 [32]) and (2) model based methods (Arnold & Hausen, 2012 [34]; Kramer et al., 2009 [33]). In Hansen et al. (2009) [32], the constraint of the box is handled, the offspring's genome is allowed to violate the constraint, and the fitness of the box is calculated at the boundary of the feasible region, and the two function from the evaluation of the offspring's distance is punished by the adaptive weight. Kramer et al. (2009) [33] proposed a method to deal with the constraints of linear equality / inequality. In the process of evolution, a meta-model of the constraint function is established, and then the adaptive (rotation) covariance matrix is used by the agent model in the vicinity of the constrained boundary. Similarly, Arnold and Hausen (2012) [34] recently proposed an CMA-

ES improvement scheme, which is an online learning constraint model and uses it to reduce the change of the distribution model along the opposite direction of the constraint. The strategies obtained in this way can approach the boundary of the feasible domain and search them in tangent direction without violating constraints.

In this dissertation, the penalty function is introduced in the application CMA-ES scheme, in which the penalty is proportional to the size of the violation constraint. It is similar to the optimization algorithm proposed by the Birgin & Martnez (2012) [35], ALGENCAN, which makes the non-monotone penalty function.

Based on the contents of the preceding two sections 3.1 and 3.6 and the principle of CMA-ES penalty function mentioned above, the optimization objective function of this paper can be constructed as follows:

$f_i = fitness(x_i)$
For each solution $x_i = \{R_1(i), R_c(i), X_1(i), X_2(i), X_m(i)\}$

Step 1: Solve $R_2(m,i)$ for each obsevation;
Step 2: Caculate target function's error as following:

$$E = \sum_{m=1}^{M}\left[Z_{1l}(m,i) - \frac{(a_2 + b_2R_2(m,i))(a_3 + b_3R_2(m,i)) - (a_1 + b_1R_2(m,i))(a_4 + b_4R_2(m,i))}{(a_3 + b_3R_2(m,i))^2 + (a_4 + b_4R_2(m,i))^2}\right]^2$$

Step 3: Derive speed $s(m)$, torque $T(m)$, load P_{out}(m) and efficiency η(m) for each obsevation;
Step 4: Apply *constrains*;
Step 5: Appy *penalties*;
Step 6: $f_i = E + constrains + penalties$;

4.3 Manufacturer Catalog Data Sets test

Efficiency estimation is based on parallel equivalent circuit data and voltage and current data of different load cases (see Figure 18). The test methods used in the catalog data table of the manufacturers are tested for 5 types: 3 HP, 300 HP, 450 HP, 700 HP, and 1500 HP motors. The test results are displayed in the following Table 12, Table 13, Table 14, Table 15 and Table 16, respectively.

BALDOR-RELIANCE SALES ORDER	FRAME	HP	TYPE	PHASE	HERTZ	RPM
A50WG8653-R001	5012	800	P	3	60	1791

VOLTS	AMPS	DUTY	AMB°C	INSUL	S.F.	NEMA DESIGN
575	725	CONT	40	F	1.15	---

CODE LETTER	ENCL.	ROTOR WK² (lb-ft²)	STATOR RES.@25°C OHMS (BETWEEN LINES)	TYPICAL DATA
G	TEFC	228	0.00492	

PERFORMANCE

LOAD	HP	AMPERES	RPM	% POWER FACTOR	% EFFICIENCY
NO LOAD	0	212.8	1800	4.3	0.0
1/4	200	286.6	1798	55.8	93.8
2/4	400	410.5	1796	75.9	96.1
3/4	600	560.2	1794	83.0	96.6
4/4	800	724.9	1791	85.6	96.6
5/4	1000	902.1	1789	86.2	96.3
6/4	1200	1093.6	1786	85.6	96.0

SPEED TORQUE

	RPM	TORQUE % FULL LOAD	TORQUE LB-FT	AMPERES
LOCKED ROTOR	0	96	2257	4800.0
PULL UP	72	85	1989	4793.3
BREAKDOWN	1757	267	6265	2572.3
FULL LOAD	1791	100	2345	724.9

AMPERES SHOWN FOR 575 VOLT CONNECTION(S). IF OTHER VOLTAGE CONNECTIONS ARE AVAILABLE, THE AMPERES WILL VARY INVERSELY WITH THE VOLTAGE.

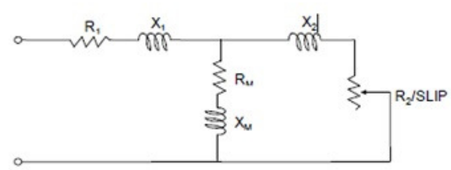
REVISION 0

BALDOR A MEMBER OF THE ABB GROUP | DR. BY CD CK. BY B.LeRoy APP. BY B.LeRoy DATE 2/11/2016 | A-C MOTOR PERFORMANCE | VGPM804E57 SH 1 OF 7 ISSUE DATE: 2/11/2016

B-R S.O.	A50WG8653-R001	HERTZ	60	AMB°C	40	CODE LETTER	G
FRAME	5012	RPM	1791	INSUL	F	ENCLOSURE	TEFC
HP	800	VOLTS	575	S.F.	1.15	STATOR RES.@25°C	0.00492
TYPE	P	AMPS	725	NEMA DESIGN	---	OHMS (BETWEEN LINES)	
PHASE	3	DUTY	CONT	ROTOR WK² (lb-ft²)	228	TYPICAL DATA	

EQUIVALENT CIRCUIT DATA
(Per Unit, Per Phase)

FULL LOAD				LOCKED ROTOR			
R_1	0.00563	X_1	0.07655	R_1	0.00469	X_1	0.06683
R_2	0.00420	X_2	0.12774	R_2	0.01573	X_2	0.05633
R_M	0.07145	X_M	2.77709	R_M	0.22816	X_M	2.54483
BASE OHMS	0.55400			BASE VOLTS	332		
SC Time Constant	0.078 Sec			$X'' = X_s$	0.12316		
OC Time Constant	1.835 Sec			X/R Ratio	18.23		



Parallel Equivalent			
FL R_M' pu	108.0102	LR R_M' pu	28.61245
FL X_M' pu	2.77893	LR X_M' pu	2.56529

R_1 = Stator dc resistance
R_2 = Rotor resistance
R_M = Core loss resistance
SC = Short circuit
OC = Open circuit
X_1 = Stator leakage reactance
X_2 = Rotor leakage reactance
X_M = Magnetizing reactance
FL = Full load
LR = Locked rotor

$X'' = X_s$ = Subtransient reactance

REVISION 0

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Figure 16 An example of manufacturer data

Table 12 Test result of manufacturer data 3 HP Motor

E01392-A-B005	Speed (RPM)	Load (HP)	Voltage (V)	Current (A)	Torque (FT-LB)	Efficiency (%)
Namplate	3519	3	460	3.6	4.48	88.5
	R1	**Rc**	**X1**	**X2**	**Xm**	**R2'**
True parameter values	0.2710	3681.8702	2.7946	4.6656	88.0256	0.1752
Estimated parameter values	0.4850	1212.3169	4.0000	3.5000	85.9745	0.1722
Relative Error	**79.0%**	**67.1%**	**43.1%**	**25.0%**	**2.3%**	**1.7%**
Load	**125%**	**100%**	**75%**	**50%**	**25%**	
True speed (RPM)	3495	3519	3541	3561	3580	
Estimated speed (RPM)	3500	3522	3543	3563	3581	
Absolute Error	**5**	**3**	**2**	**2**	**1**	
True torque (FT-LB)	5.6	4.5	3.4	2.2	1.1	
Estimated torque (FT-LB)	5.6	4.5	3.3	2.2	1.1	
Relative Error	**0.0%**	**0.3%**	**0.5%**	**1.1%**	**4.3%**	
True load (HP)	3.7	3.0	2.2	1.5	0.8	
Estimated load (HP)	3.7	3.0	2.2	1.5	0.7	
Relative Error	**0.1%**	**0.3%**	**0.5%**	**1.1%**	**4.3%**	
True efficiency (%)	87.7	88.5	88.8	87.7	81.3	
Estimated efficiency (%)	88.0	88.1	87.9	86.7	84.9	
Relative Error	**0.4%**	**0.5%**	**1.0%**	**1.2%**	**4.5%**	

3 HP motor in manufacturer's catalog data sheets was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±5 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±0.1-1.1% for high (>25%) loads, and up to ±4.5% errors for low (<25%) loads.

Table 13 Test result of manufacturer data 300 HP Motor

KMG30-302S-2340	Speed (RPM)	Load (HP)	Voltage (V)	Current (A)	Torque (FT-LB)	Efficiency (%)
Namplate	**3574**	**300**	**4000**	**38.4**	**441**	**95.2**
	R1	**Rc**	**X1**	**X2**	**Xm**	**R2'**
True parameter values	0.4947	8898.0588	6.9247	5.0867	221.7918	0.4382
Estimated parameter values	0.0100	1876.9781	4.0000	3.5000	196.7395	0.4670
Relative Error	**98.0%**	**78.9%**	**42.2%**	**31.2%**	**11.3%**	**6.6%**
Load	**150%**	**125%**	**100%**	**75%**	**50%**	**25%**
True speed (RPM)	3560	3567	3574	3581	3588	3594
Estimated speed (RPM)	3572	3574	3577	3581	3587	3594
Absolute Error	**12**	**7**	**3**	**0**	**1**	**0**
True torque (FT-LB)	662.9	551.5	441.0	330.1	219.1	109.6
Estimated torque (FT-LB)	675.9	559.3	444.1	329.7	215.2	104.7
Relative Error	**2.0%**	**1.4%**	**0.7%**	**0.1%**	**1.8%**	**4.5%**
True load (HP)	449.2	374.4	300.0	225.0	149.6	75.0
Estimated load (HP)	459.6	380.5	302.3	224.7	147.0	71.6
Relative Error	**2.3%**	**1.6%**	**0.8%**	**0.1%**	**1.8%**	**4.6%**
True efficiency (%)	94.5	94.9	95.2	95.1	94.4	91.0
Estimated efficiency (%)	96.7	96.4	95.9	95.0	92.7	86.9
Relative Error	**2.3%**	**1.6%**	**0.8%**	**0.1%**	**1.8%**	**4.6%**

300 HP motor in manufacturer's catalog data sheets was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±12 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±0.1-2.3% for high (>25%) loads, and up to ±4.6% errors for low (<25%) loads.

Table 14 Test result of manufacturer data 450 HP motor

KMG30-452S-2340	Speed (RPM)	Load (HP)	Voltage (V)	Current (A)	Torque (FT-LB)	Efficiency (%)
Namplate	**3575**	**450**	**4000**	**56.6**	**661**	**95.3**
	R1	**Rc**	**X1**	**X2**	**Xm**	**R2'**
True parameter values	0.2998	5853.8850	4.3730	3.7658	170.8821	0.2893
Estimated parameter values	0.1957	1205.7454	3.9942	3.5000	163.8387	0.3000
Relative Error	**34.7%**	**79.4%**	**8.7%**	**7.1%**	**4.1%**	**3.7%**
Load	**150%**	**125%**	**100%**	**75%**	**50%**	**25%**
True speed (RPM)	3561	3568	3575	3582	3588	3594
Estimated speed (RPM)	3565	3570	3576	3582	3588	3594
Absolute Error	**4**	**2**	**1**	**0**	**0**	**0**
True torque (FT-LB)	996.1	828.1	661.0	495.1	329.1	164.7
Estimated torque (FT-LB)	1007.7	833.3	661.2	490.4	322.0	156.3
Relative Error	**1.2%**	**0.6%**	**0.0%**	**1.0%**	**2.2%**	**5.1%**
True load (HP)	675.5	562.6	450.0	337.7	224.9	112.7
Estimated load (HP)	684.2	566.6	450.3	334.5	220.0	107.0
Relative Error	**1.3%**	**0.7%**	**0.1%**	**1.0%**	**2.2%**	**5.1%**
True efficiency (%)	94.7	95.1	95.3	95.3	94.5	91.3
Estimated efficiency (%)	95.9	95.8	95.4	94.4	92.5	86.7
Relative Error	**1.3%**	**0.7%**	**0.1%**	**1.0%**	**2.2%**	**5.1%**

450 HP motor in manufacturer's catalog data sheets was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±4 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±0.1-2.2% for high (>25%) loads, and up to ±5.1% errors for low (<25%) loads.

Table 15 Test result of manufacturer data 700 HP motor

KMG30-704L-2340	Speed (RPM)	Load (HP)	Voltage (V)	Current (A)	Torque (FT-LB)	Efficiency (%)
Namplate	1790	700	4000	92.5	2054	95.6
	R1	**Rc**	**X1**	**X2**	**Xm**	**R2'**
True parameter values	0.2218	3349.5924	2.3593	4.2020	80.8412	0.1526
Estimated parameter values	0.8070	1118.7179	3.2822	3.5000	78.0799	0.1485
Relative Error	**263.8%**	**66.6%**	**39.1%**	**16.7%**	**3.4%**	**2.7%**
Load	**150%**	**125%**	**100%**	**75%**	**50%**	**25%**
True speed (RPM)	1783	1786	1790	1792	1795	1798
Estimated speed (RPM)	1782	1786	1790	1792	1795	1798
Absolute Error	**1**	**0**	**0**	**0**	**0**	**0**
True torque (FT-LB)	3091.3	2572.2	2054.0	1538.2	1023.1	512.2
Estimated torque (FT-LB)	3008.2	2508.6	2011.4	1506.1	999.7	484.0
Relative Error	**2.7%**	**2.5%**	**2.1%**	**2.1%**	**2.3%**	**5.5%**
True load (HP)	1049.4	874.6	700.0	524.8	349.6	175.4
Estimated load (HP)	1020.6	852.8	685.5	513.9	341.7	165.7
Relative Error	**2.7%**	**2.5%**	**2.1%**	**2.1%**	**2.3%**	**5.5%**
True efficiency (%)	94.8	95.3	95.6	95.7	95.1	92.3
Estimated efficiency (%)	92.2	92.9	93.6	93.7	92.9	87.2
Relative Error	**2.7%**	**2.5%**	**2.1%**	**2.1%**	**2.3%**	**5.5%**

700 HP motor in manufacturer's catalog data sheets was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±1 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±2.3-2.7% for high (>25%) loads, and up to ±6.5% errors for low (<25%) loads.

Table 16 Test result of manufacturer data 1500 HP motor

KMO58-1502S-2340	Speed (RPM)	Load (HP)	Voltage (V)	Current (A)	Torque (FT-LB)	Efficiency (%)
Namplate	3573	1500	4000	191.3	2205	95.8
	R1	**Rc**	**X1**	**X2**	**Xm**	**R2'**
True parameter values	0.0987	1604.3543	1.7351	0.9583	48.6372	0.0922
Estimated parameter values	0.4091	450.4126	1.2470	1.6138	47.6556	0.0937
Relative Error	**314.6%**	**71.9%**	**28.1%**	**68.4%**	**2.0%**	**1.6%**
Load	**150%**	**125%**	**100%**	**75%**	**50%**	**25%**
True speed (RPM)	3556	3565	3573	3580	3587	3594
Estimated speed (RPM)	3553	3564	3573	3580	3587	3594
Absolute Error	**3**	**1**	**0**	**0**	**0**	**0**
True torque (FT-LB)	3324.8	2763.8	2205.0	1650.7	1097.8	548.5
Estimated torque (FT-LB)	3216.1	2679.5	2140.4	1598.4	1055.9	510.4
Relative Error	**3.3%**	**3.0%**	**2.9%**	**3.2%**	**3.8%**	**6.9%**
True load (HP)	2251.0	1875.9	1500.0	1125.2	749.7	375.3
Estimated load (HP)	2175.7	1818.3	1456.0	1089.6	721.2	349.3
Relative Error	**3.3%**	**3.1%**	**2.9%**	**3.2%**	**3.8%**	**6.9%**
True efficiency (%)	94.8	95.4	95.8	96.1	95.8	93.7
Estimated efficiency (%)	91.6	92.5	93.0	93.1	92.2	87.2
Relative Error	**3.3%**	**3.1%**	**2.9%**	**3.2%**	**3.8%**	**6.9%**

1500 HP motor in manufacturer's catalog data sheets was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±3 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±3.3-3.8% for high (>25%) loads, and up to ±6.9% errors for low (<25%) loads.

The experimental results of the above 5 types of motors show that the experimental method achieves speed estimation within the range of sensor readings (±1 to ±12 RPM). For torque, load and efficiency, the accuracy of this method is higher under the high (>25%) load, (such as 1500HP， ±3.3-3.8%), for low (<25%) load, the precision is low (such as 1500HP， ±6.9%), the detailed accuracy is expressed in the above tables.

4.4 Laboratory Experiments

4.4.1 Experimental Setup

In the estimation of motor efficiency, input power must be required as a known parameter. However, in industrial plants, only 500 HP motors are equipped with monitoring instruments, because the cost of the equipment is very high. Other small horsepower motors rarely assemble their monitoring instruments. Generally, these motors are equipped with potential transformers (PTS) and current transformers (CTS) based on protection purposes. The end voltage and current of the motor can be easily obtained from the motor control center, and the end voltage and current measurement will not bring additional costs in data collection. Therefore, the non- intrusive method proposed in this paper to estimate its efficiency is considered to be economically valuable for small power motors.

The high-precision electric power meter generally refers to its measuring tolerance of 1%, but there is no portable inexpensive instrument measuring the output power of the shaft of the coupling motor. The AD73360 instrument can be used to measure the voltage and current of all three phases of the three-phase power supply. The simultaneous structure of AD73360 is ideal for this application, in which simultaneous sampling is essential to keep the relative phase information between three voltages and three current phases. Figure 19 shows the block diagram of the three-phase metering system. And use DSP microprocessor to calculate the information provided by AD73360.

In the electrical data acquisition system shown in Figure 19, the voltage and phase currents of the motor are measured by potential sensor (PT) and current sensor (CT) respectively. AD73360 is a six input analog front end processor. It is particularly suitable for industrial power metering as a sampling synchronization for each channel. With this, 3 channel voltage signals and 3 channel current signals can be sampled. The sampling rate is set at 8 kHz. Serial port (Stand) allows simple interface between single or cascade devices and industrial standard DSP engines. Endpoint software is built around the simulation device VDK kernel. This is a multithreading kernel, which provides necessary support for Ethernet interface. This support is presented in the form of software and TCP/IP protocol stack. The data transmission algorithm is based on winsocket programming.

TS-700 is the latest type of torque converter. Although it is compact, it provides a variety of functions for torque signal processing and signal output. The torque and rotational speed measurement results can be read directly from the display and provide high precision (torque range of $\pm$ 0.2% FS) and repeatability. For output, 3 modes of output can be used: analog voltage, BCD, or RS-232C interfaces, which choose to expand the ability to connect to external devices, such as a pen recorder, sequencer, or CPU. In order to evaluate the universality of the proposed method, two induction motors (1 HP and 3 HP) were tested. All necessary physical configurations of these motors are also intentionally selected and equipped (see Figure 20).

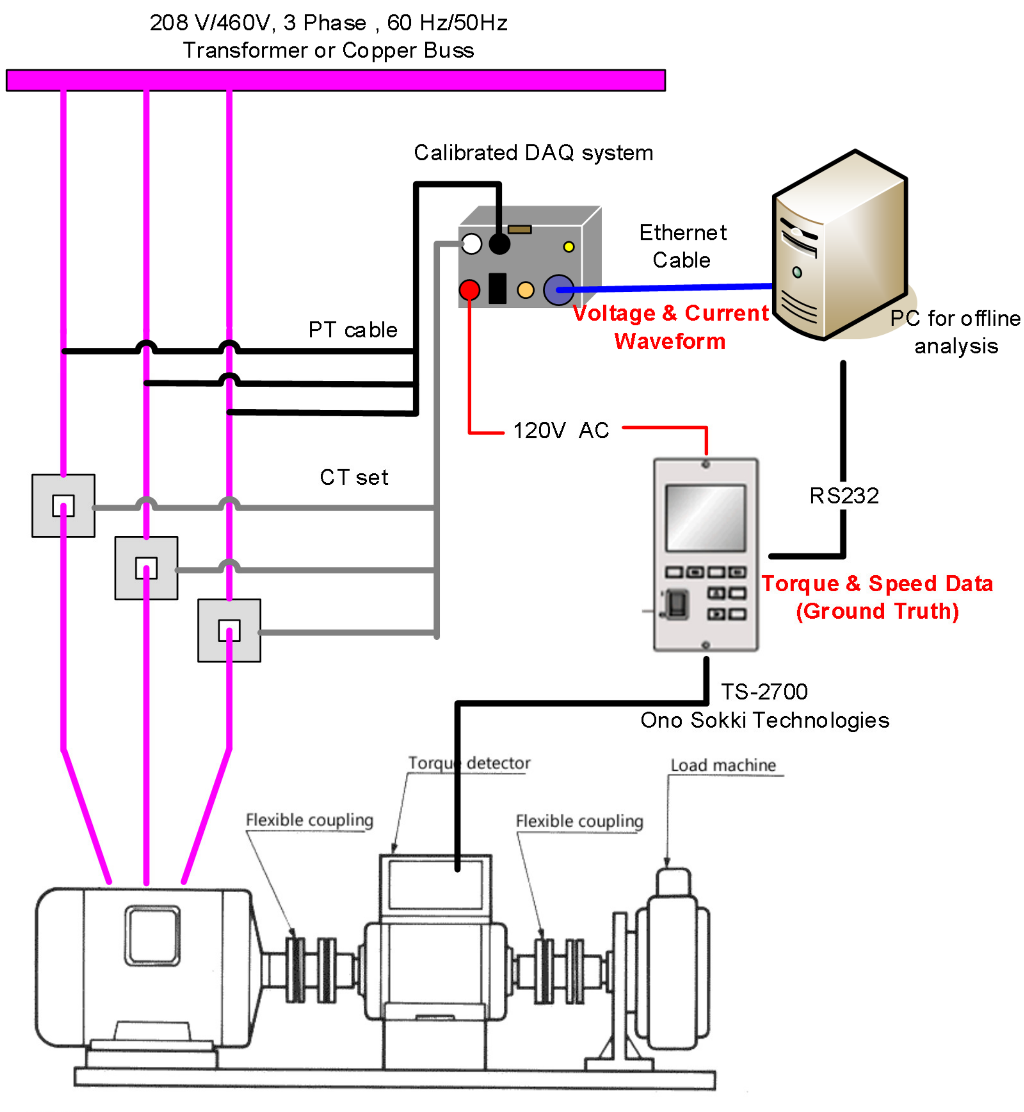

Figure 17 Experiment diagram of lab motor

This experiment setup selects two small motors, one is 1 HP, the other is 3 HP, with a torque convertor, a torque transducer & speed sensor, a DAQ system, terminal box & CTs as shown in Figure 20, to test the proposed approach in this dissertation.

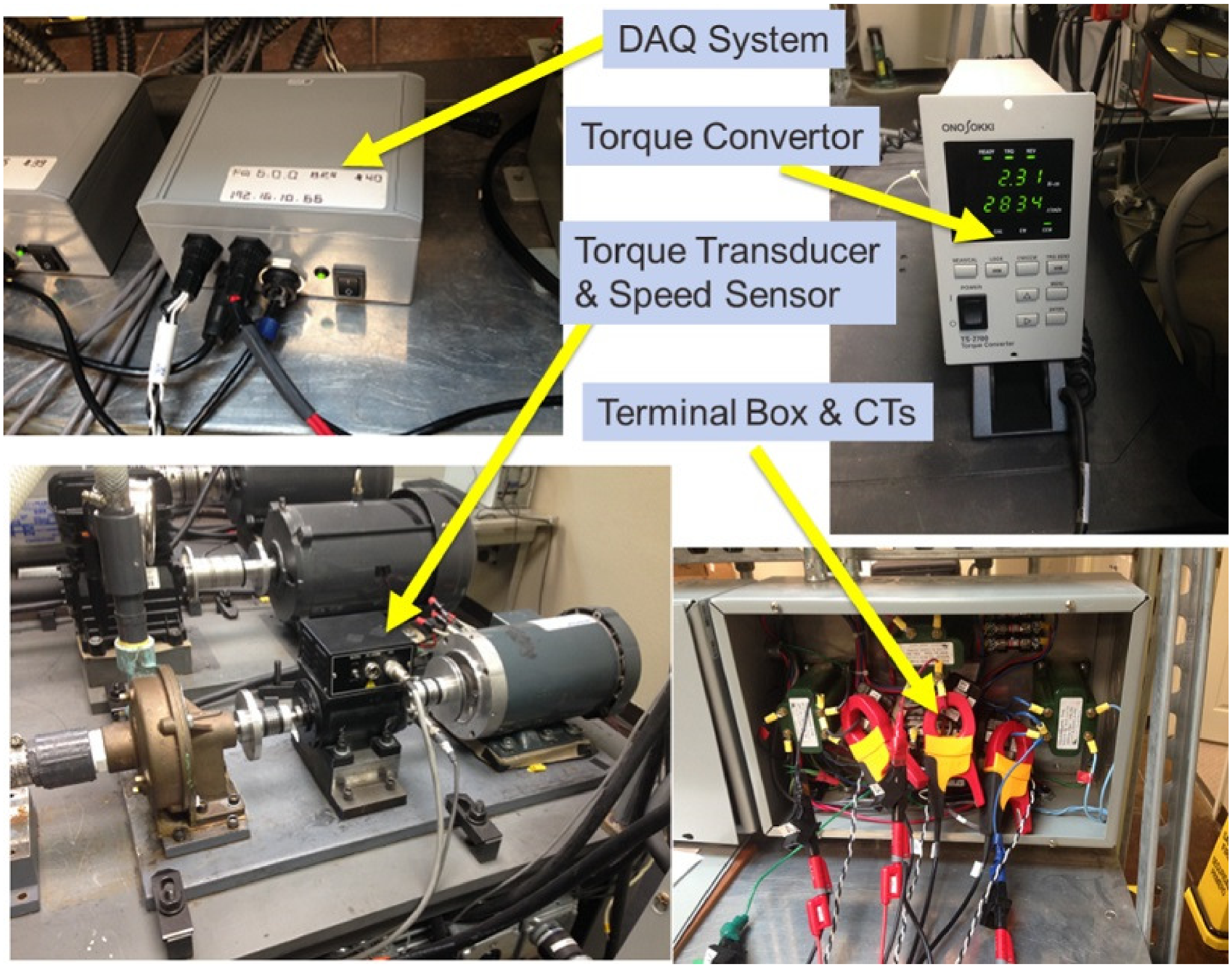

Figure 18 Experiment setup of lab motor

4.4.2 Experiment of 1 HP Motor

As shown in Figure 21, this motor is manufactured by Marathon, the horse power 1 HP, the current 3.5A, the speed 1725RPM, and the voltage 208V.

According to the formula and model described in 3.5 and 4.2 of this dissertation, the 1 HP motor in the laboratory room is selected as the object of the experiment. The speed, load, torque and efficiency of the motor are estimated and tested, and there are some results of experimental processes that shown as follows: Table 18, Table 19, Figure 20 to Figure 27.

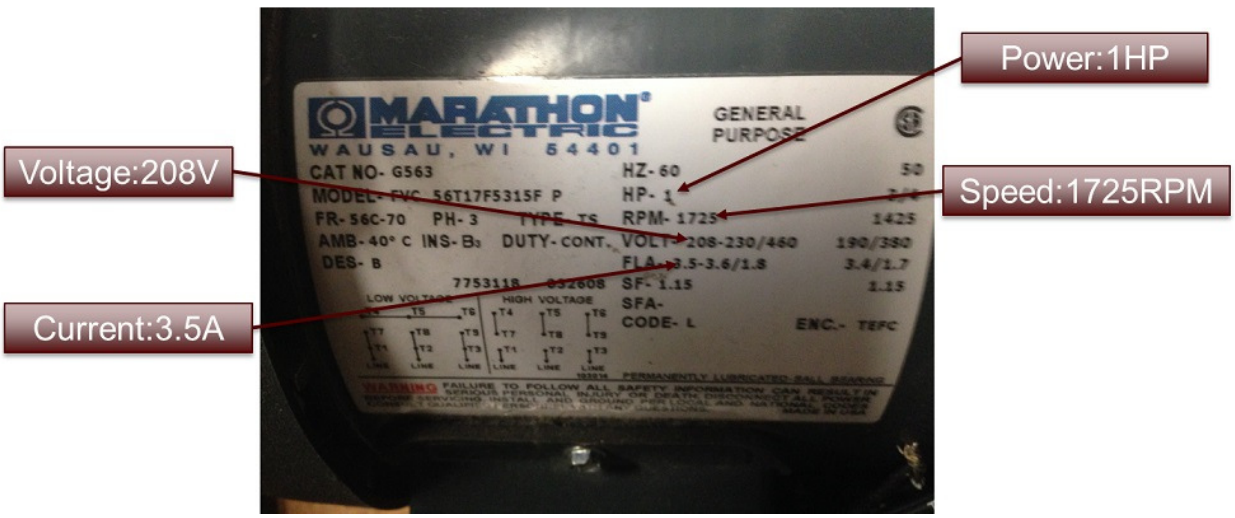

Figure 19 Nameplate of 1 HP motor

Table 17 Nameplate of 1 HP motor

	Speed	Load	Voltage	Current
Nameplate	1725 RPM	1 HP	208 V	3.5 A

Table 18 Estimated parameters of 1 HP motor

	R1	Rc	X1	X2	Xm	R2'
Estimated	0.3655	361.127	1.3403	1.7253	59.552	0.5709

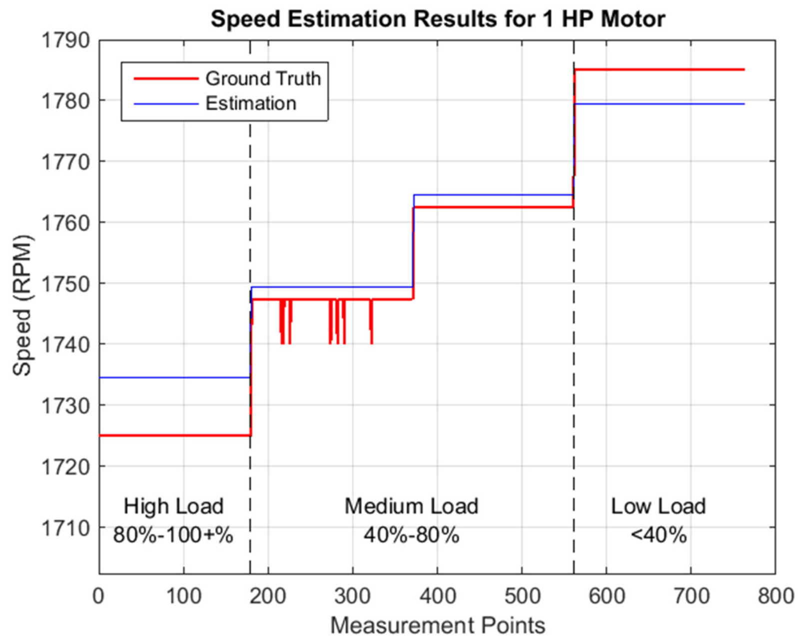

Figure 20 Speed estimation results for 1 HP motor

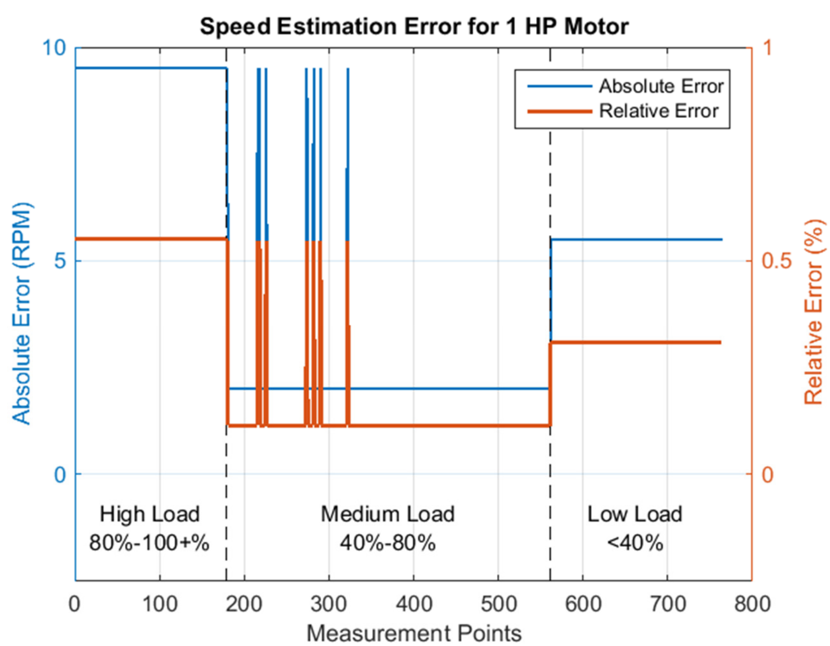

Figure 21 Speed estimation errors for 1 HP motor

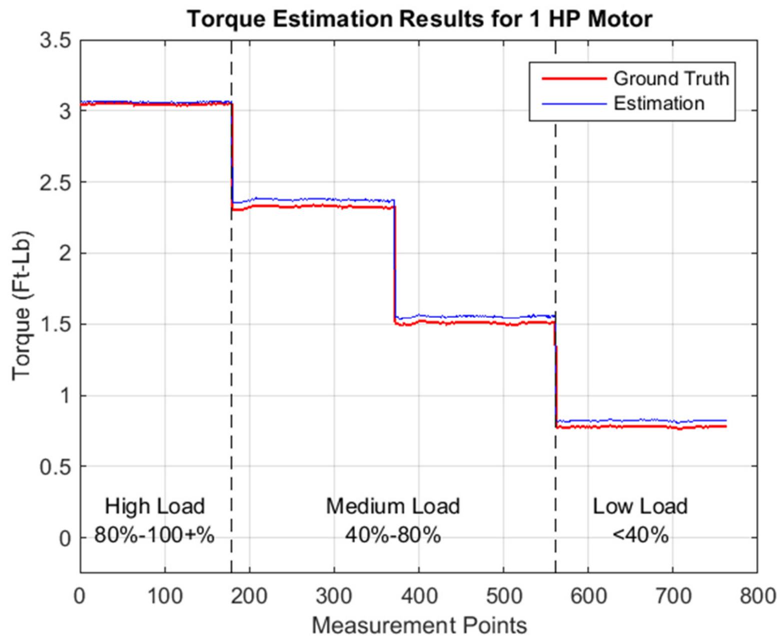

Figure 22 Torque estimation results for 1 HP motor

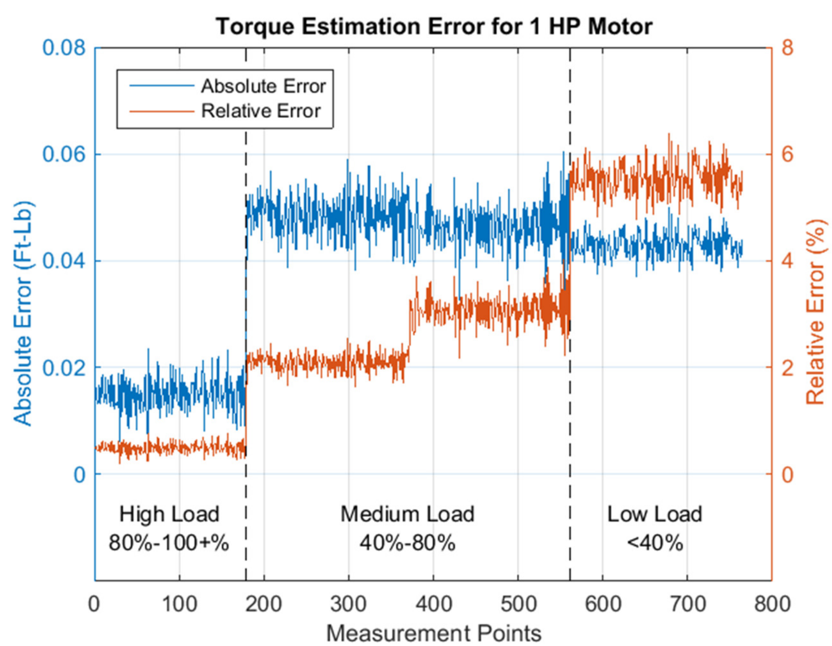

Figure 23 Torque estimation errors for 1 HP motor

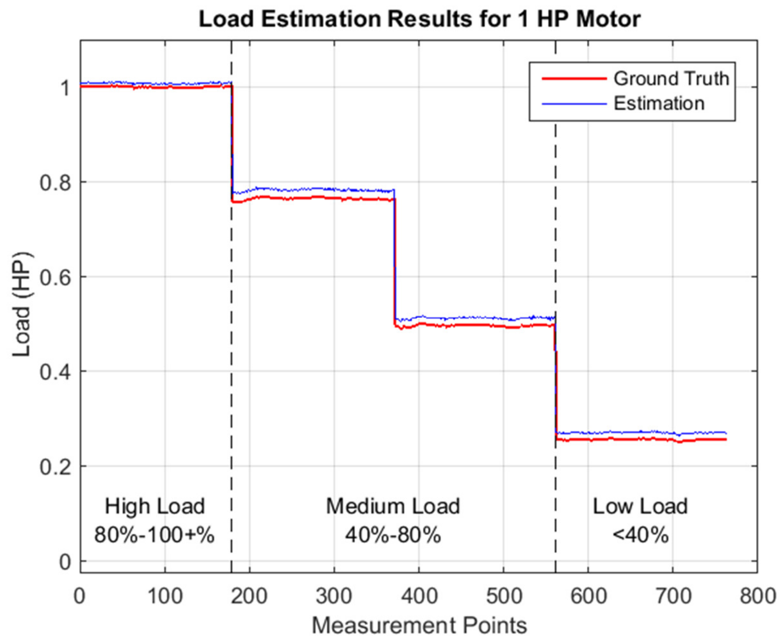

Figure 24 Load estimation results for 1 HP motor

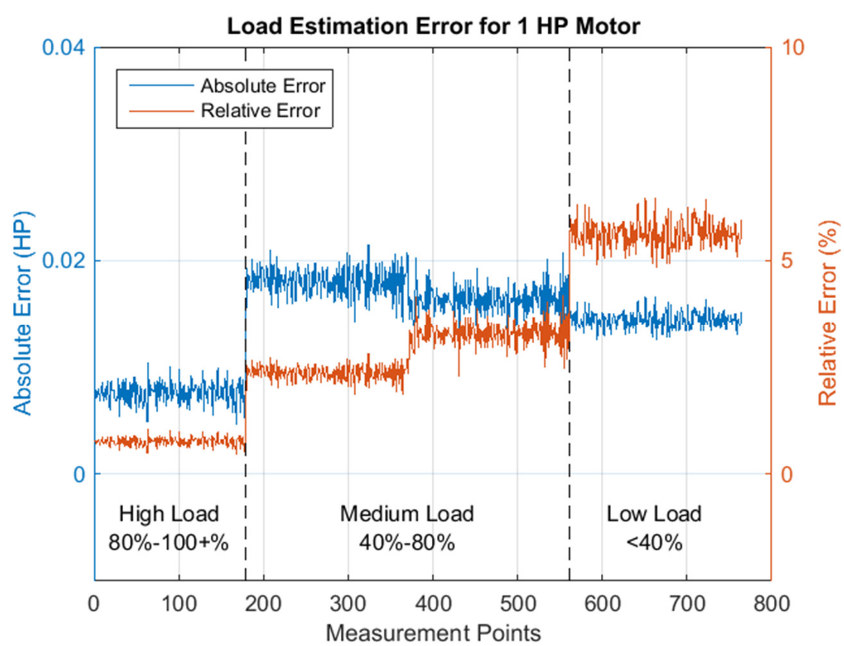

Figure 25 Load estimation errors for 1 HP motor

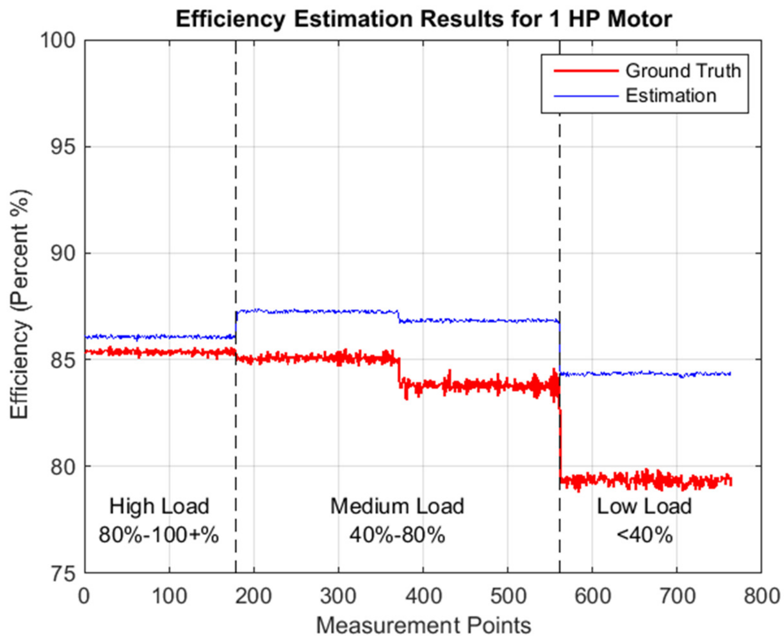

Figure 26 Efficiency estimation results for 1 HP motor

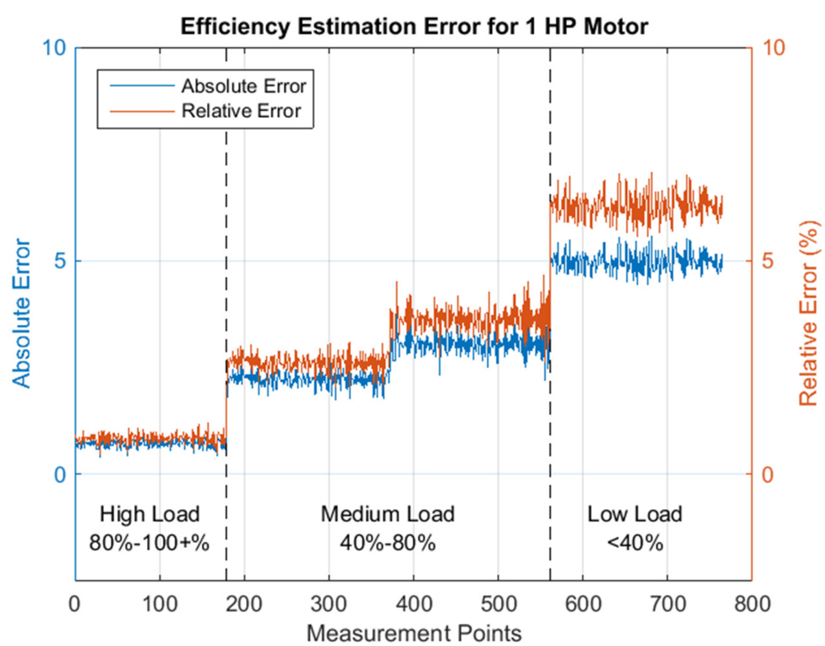

Figure 27 Efficiency estimation errors for 1 HP motor

Table 19 Summary of test results of 1 HP motor
(Average errors vs load)

Load	100.10%	76.50%	49.60%	25.80%
Speed	10 RPM	2 RPM	2 RPM	5 RPM
Torque	0.50%	2.10%	3.10%	5.50%
Load	0.80%	2.40%	3.30%	5.60%
Efficiency	0.80%	2.60%	3.60%	6.30%

1 HP motor in lab was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±10 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±0.5-3.6% for high (>25%) loads, and up to ±6.3% errors for low (<25%) loads.

4.4.3 Experiment of 3 HP motor

As shown in Figure 30, this motor is manufactured by Marathon, the horse power 3 HP, the current 8.4A, the speed 3450RPM, and the voltage 208V.

According to the formula and model described in 3.5 and 4.2 of this dissertation, the 3 HP motor in the laboratory room is selected as the object of the experiment. The speed, load, torque and efficiency of the motor are estimated and tested, and there are some results of experimental processes that shown as follows: Table 21, Table 22, Figure 29 to Figure 36.

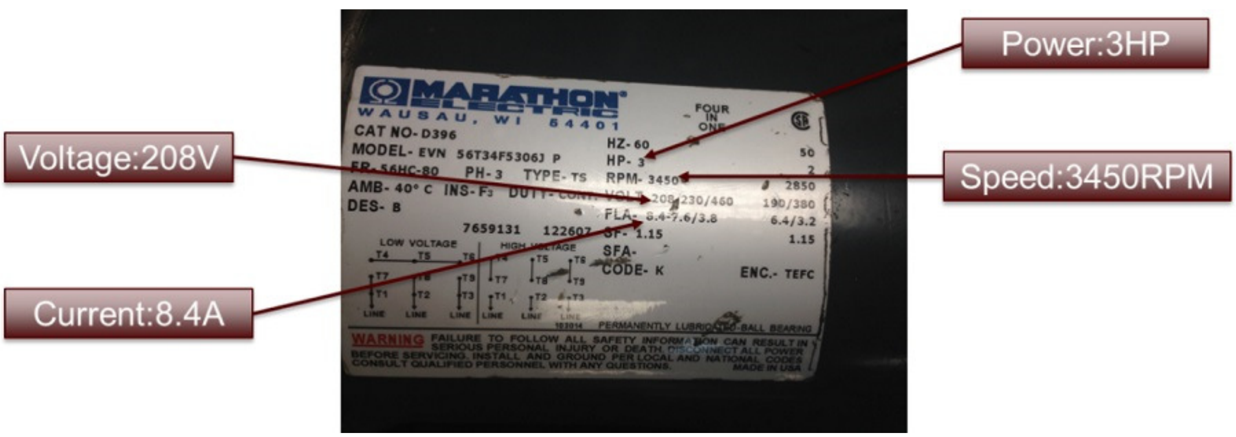

Figure 28 Nameplate of 3 HP motor

Table 20 Nameplate of 3 HP motor

	Speed	Load	Voltage	Current
Nameplate	3450 RPM	3 HP	208 V	8.4 A

Table 21 Estimated parameters of 3 HP motor

	R1	Rc	X1	X2	Xm	R2'
Estimated	0.01	1196.5	0.97245	1.24941	42.7552	0.63407

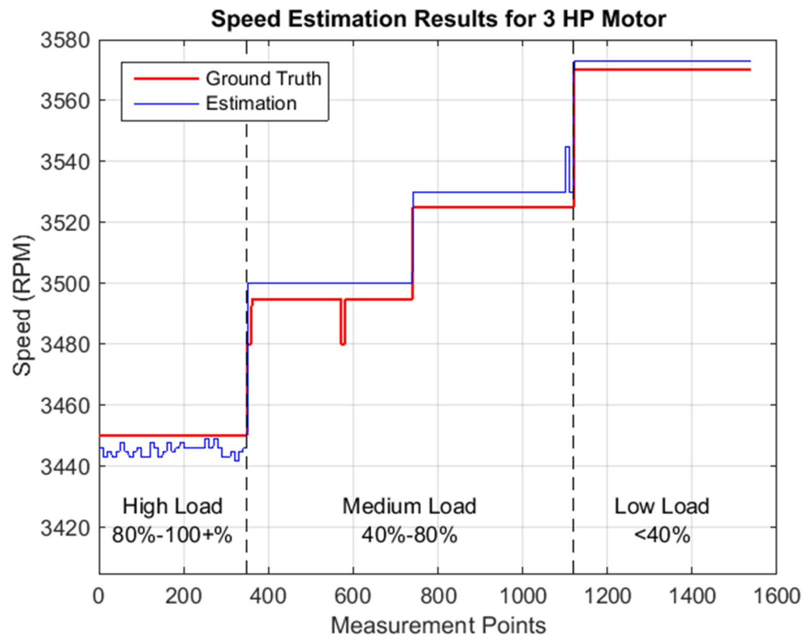

Figure 29 Speed estimation results for 3 HP motor

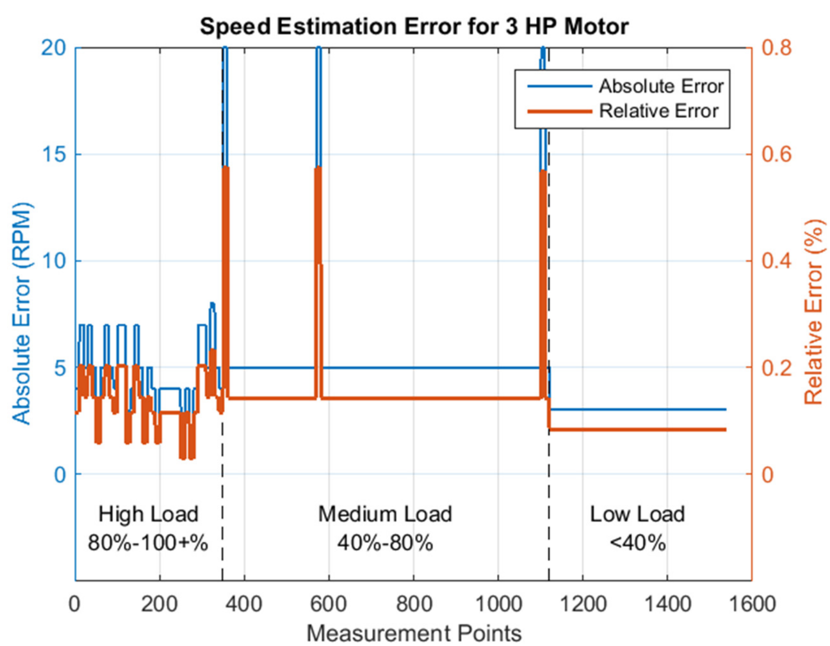

Figure 30 Speed estimation errors for 3 HP motor

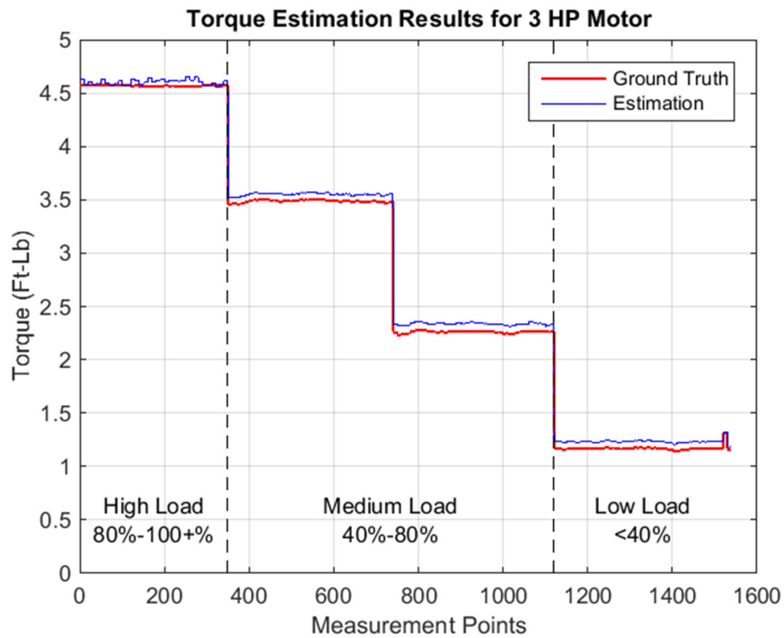

Figure 31 Torque estimation results for 3 HP motor

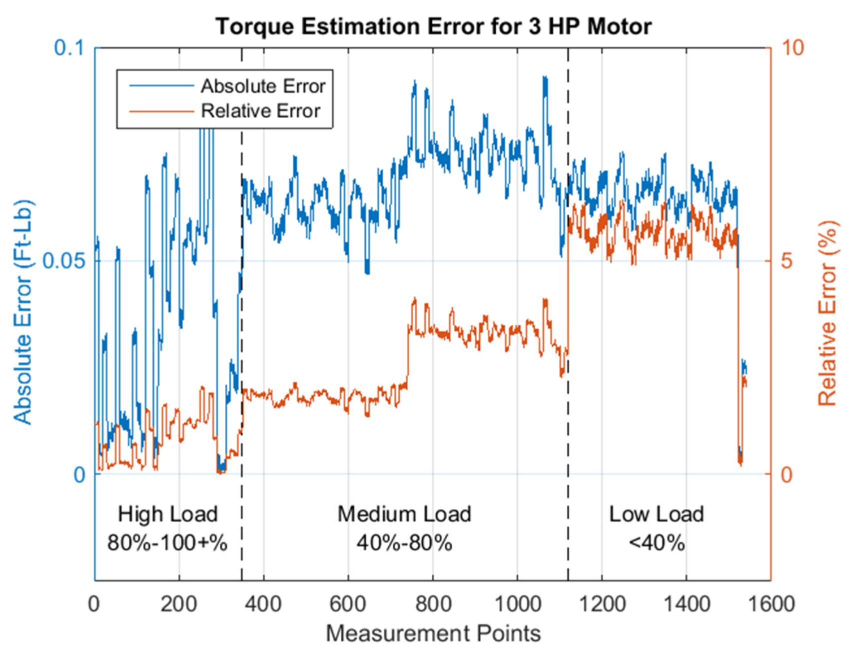

Figure 32 Torque estimation errors for 3 HP motor

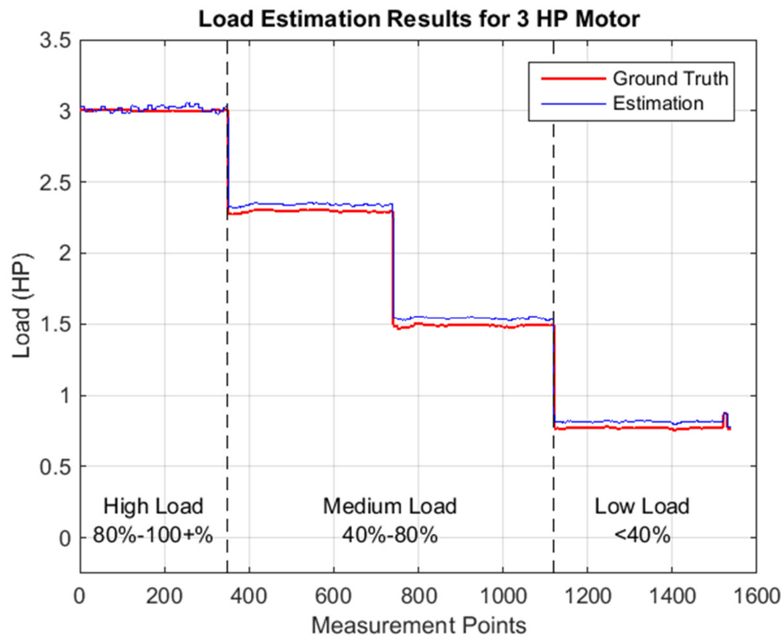

Figure 33 Load estimation results for 3 HP motor

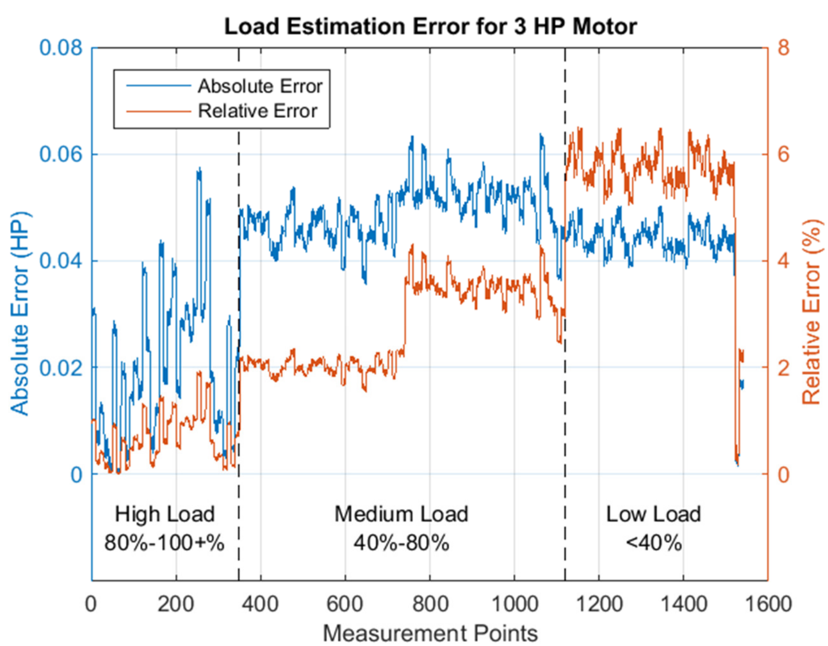

Figure 34 Load estimation errors for 3 HP motor

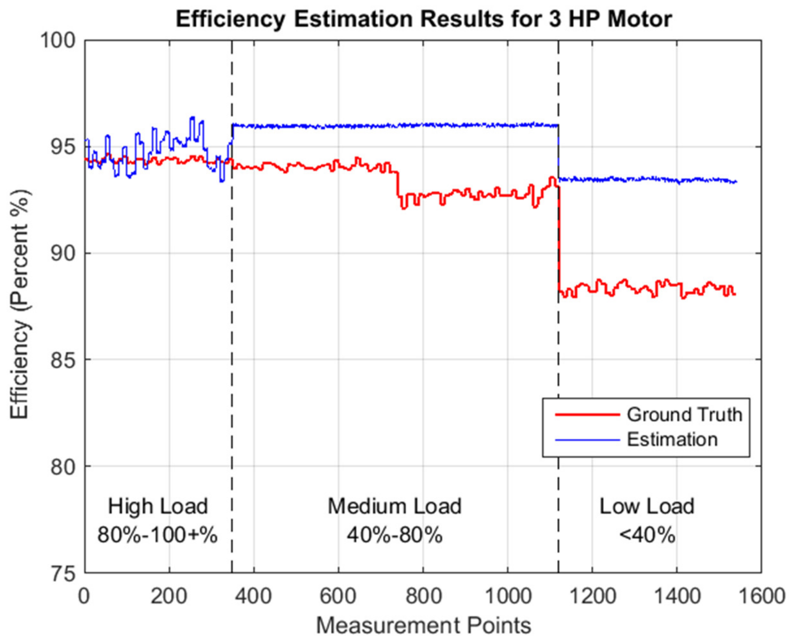

Figure 35 Efficiency estimation results for 3 HP motor

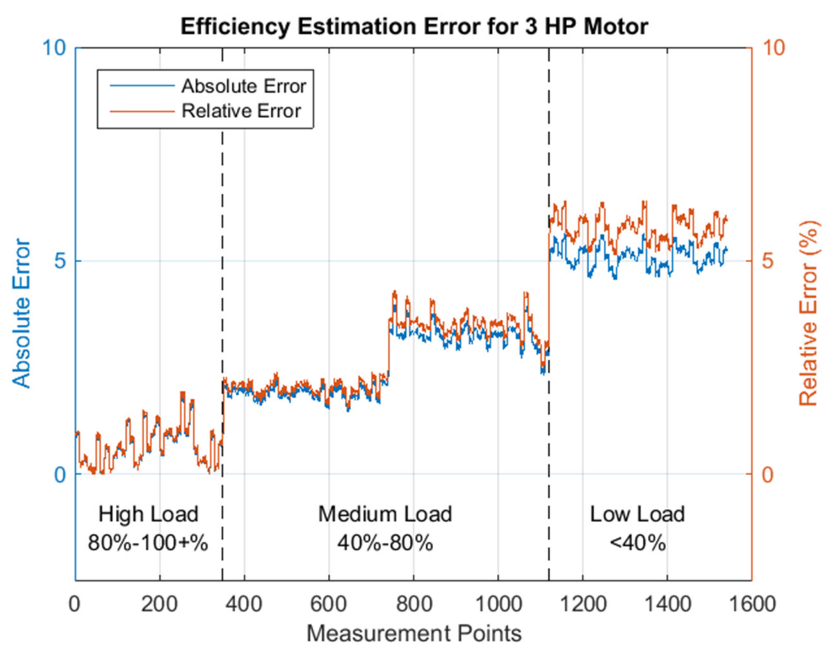

Figure 36 Efficiency estimation errors for 3 HP motor

Table 22 Summary of test results of 3 HP motor
(Average errors vs load)

Load	100.10%	76.50%	49.60%	25.80%
Speed	5 RPM	6 RPM	5 RPM	3 RPM
Torque	0.80%	1.80%	3.30%	5.40%
Load	0.70%	2.00%	3.50%	5.50%
Efficiency	0.70%	2.00%	3.50%	5.80%

3 HP motor in lab was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±6 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±0.7-3.5% for high (>25%) loads, and up to ±5.8% errors for low (<25%) loads.

4.5 Motor Shop Experiments

4.5.1 Experimental Setup

This experiment selects two larger motors, 100 HP and 200 HP, with a torque transducer, a speed tachometer and a DAQ system as shown in Figure 39, to test the proposed approach in this dissertation.

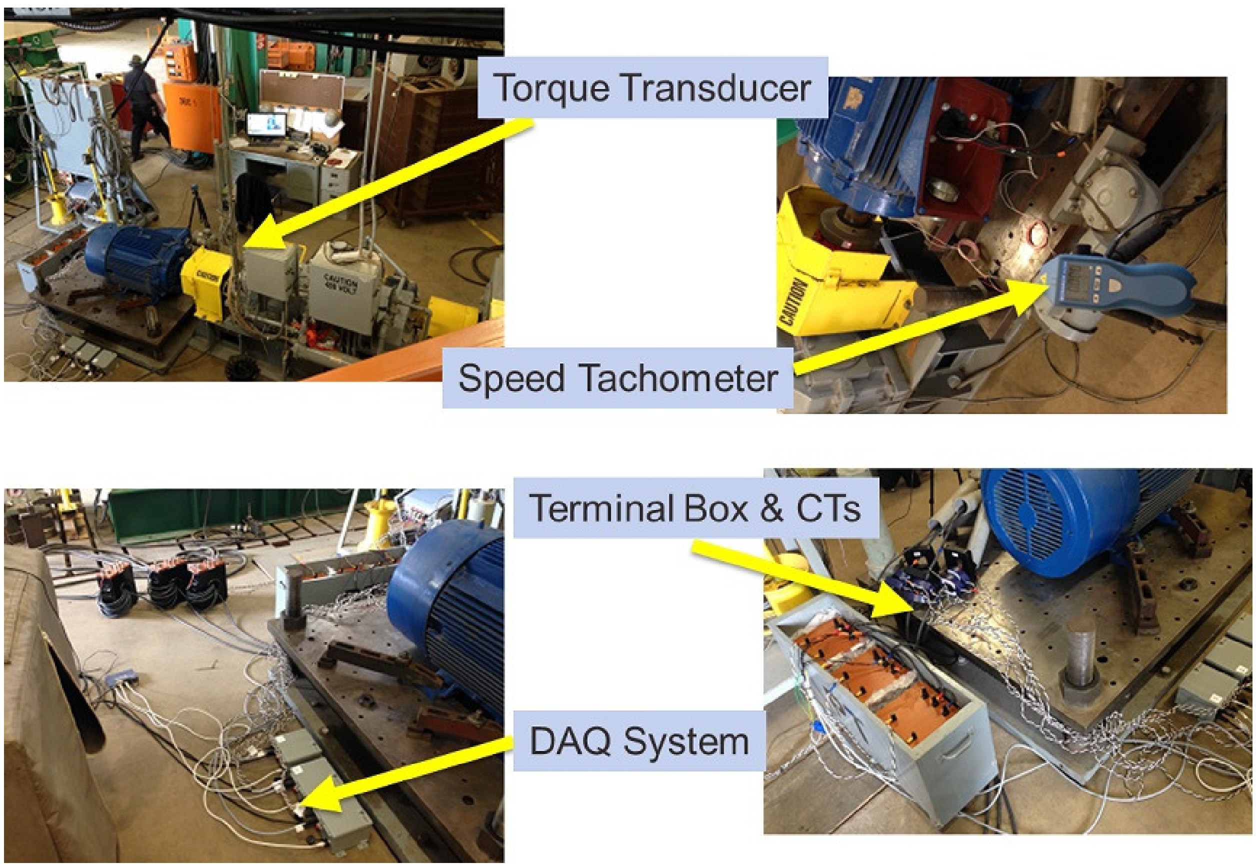

Figure 37 Experimental setup in motor shop

4.5.2 Experiment of 100 HP Motor

As shown in Figure 40, this motor is manufactured by SIEMENS, the horse power 100 HP, the current 118 A, the speed 1790 RPM, and the voltage 460 V.

According to the formula and model described in 3.5 and 4.2 of this study, the 100 HP motor in the motor shop is selected as the object of the experiment. The speed, load, torque and efficiency of the motor are estimated and tested, and there are some results of experimental processes that shown as follows: Table 24, Table 25, Figure 39 to Figure 46.

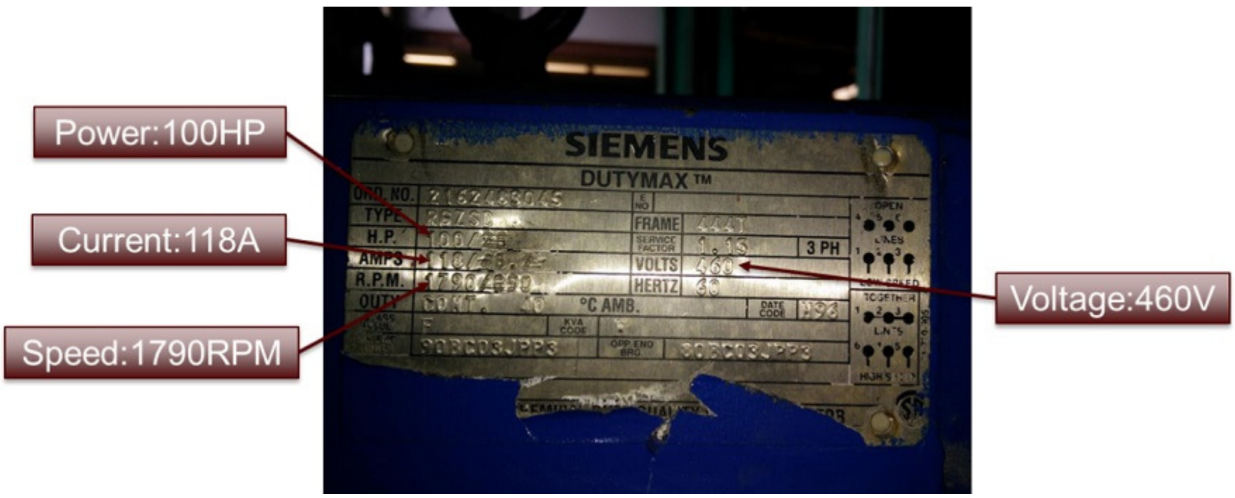

Figure 38 Nameplate of 100 HP motor

Table 23 Nameplate of 100 HP motor

	Speed	Load	Voltage	Current
Nameplate	1790 RPM	100 HP	460 V	118 A

Table 24 Estimated parameters of 100 HP motor

	R1	Rc	X1	X2	Xm	R2'
Estimation	0.11303	520.613	0.24508	0.45898	20	0.01152

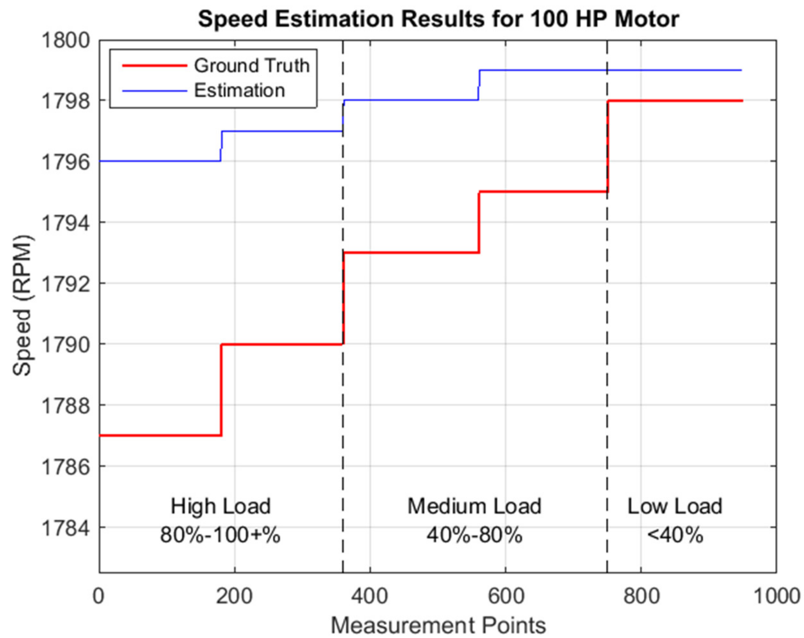

Figure 39 Speed estimation results for 100 HP motor

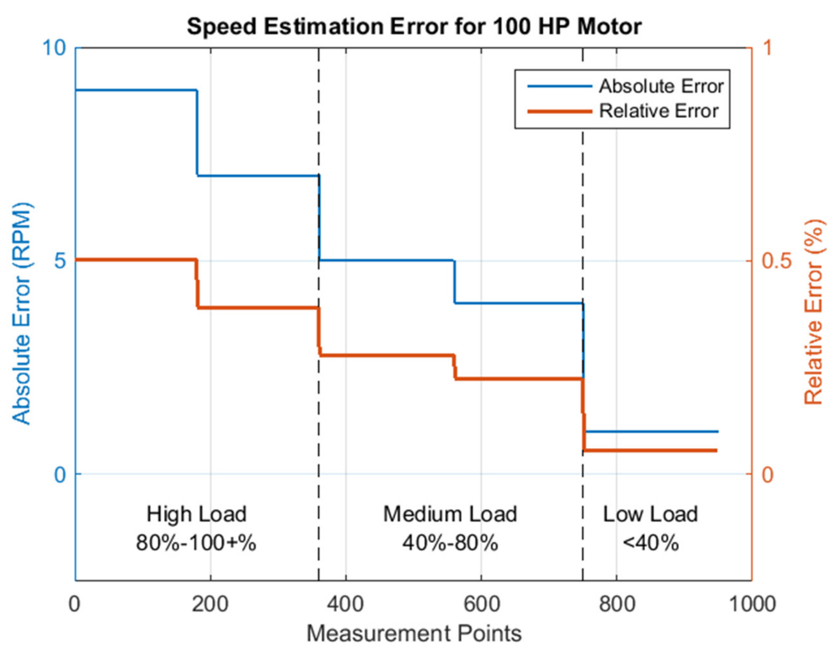

Figure 40 Speed estimation errors for 100 HP motor

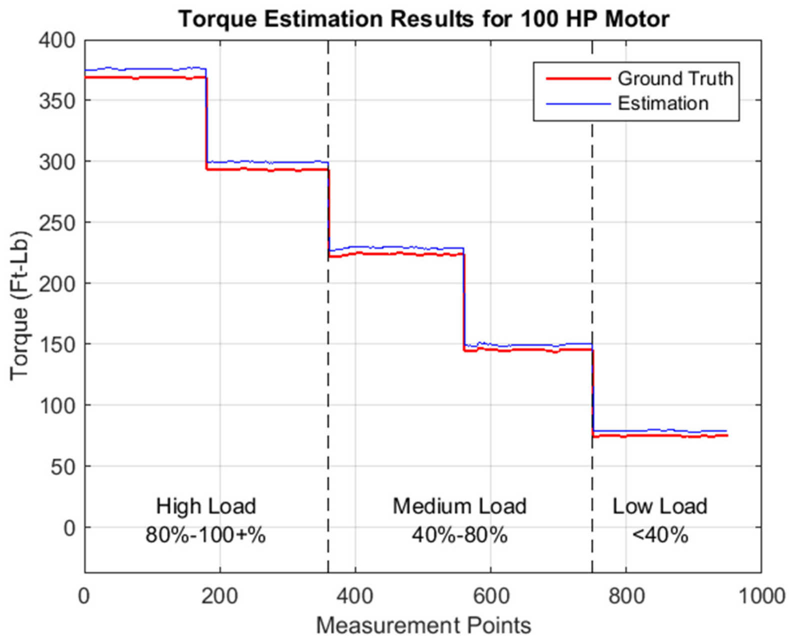

Figure 41 Torque estimation results for 100 HP motor

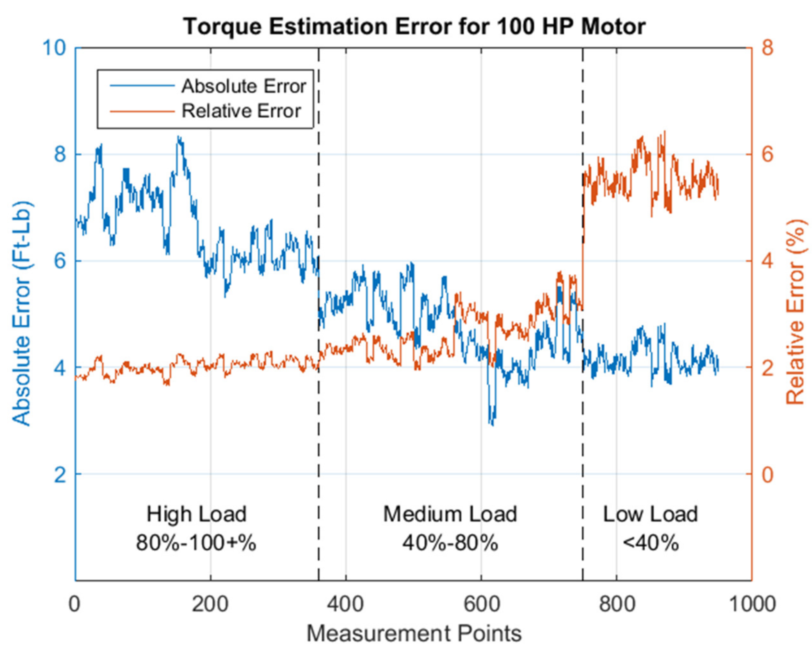

Figure 42 Torque estimation errors for 100 HP motor

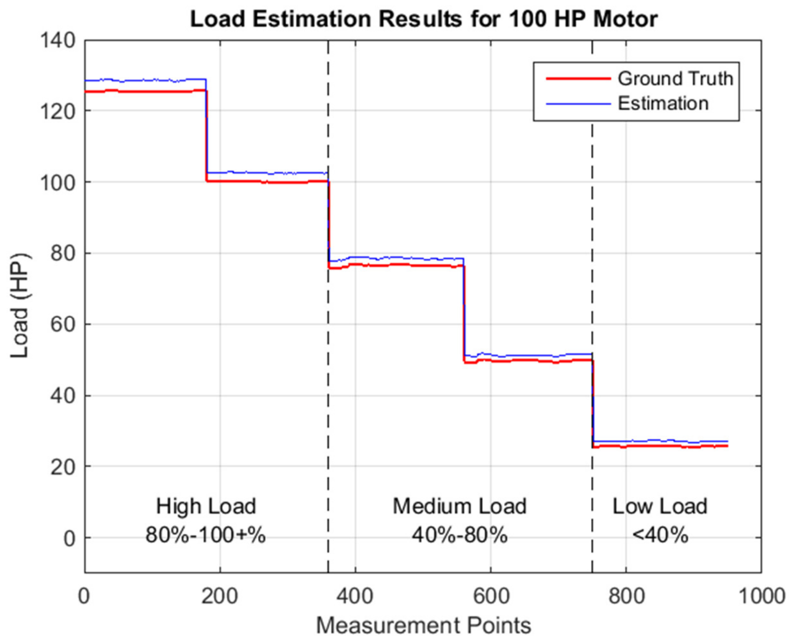

Figure 43 Load estimation results for 100 HP motor

Figure 44 Load estimation errors for 100 HP motor

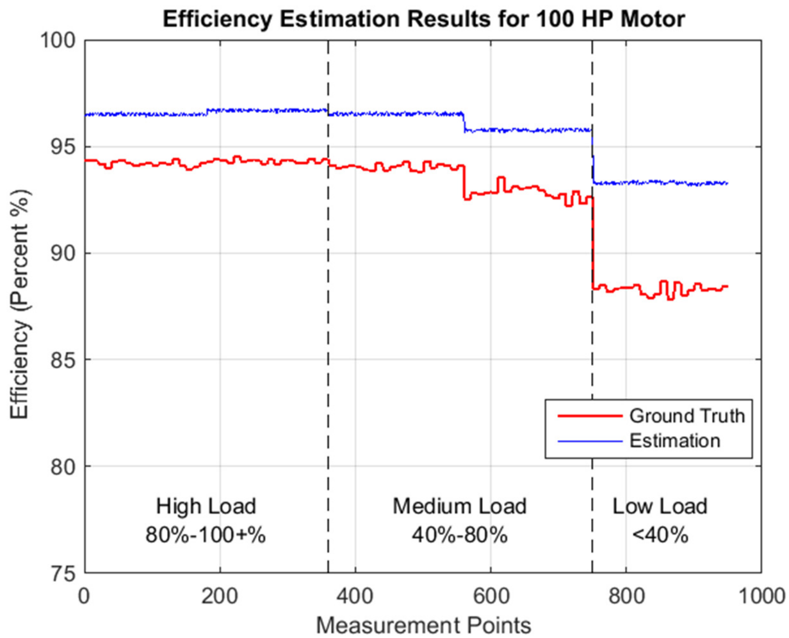

Figure 45 Efficiency estimation results for 100 HP motor

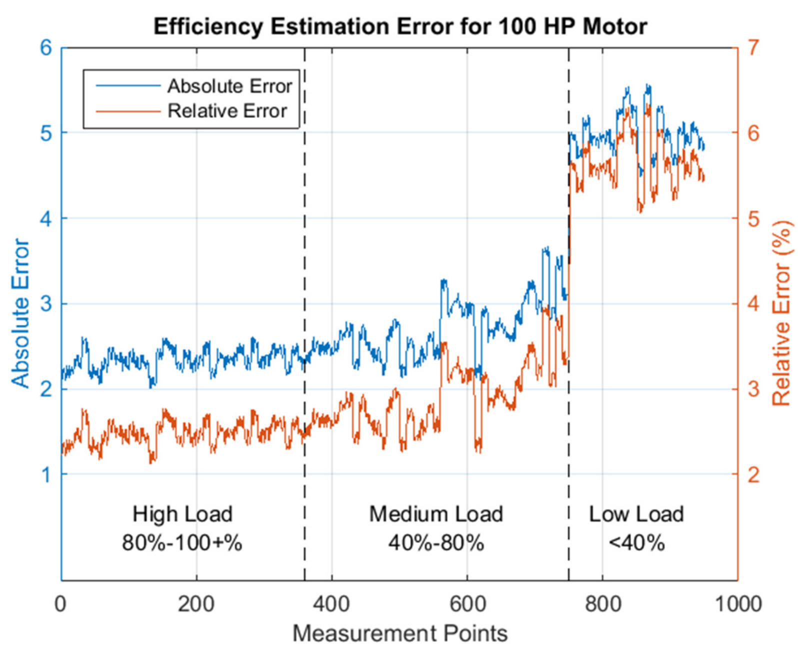

Figure 46 Efficiency estimation errors for 100 HP motor

Table 25 Summary of test results of 100 HP motor
(Average errors vs load)

Load	125.50%	100.10%	76.50%	49.60%	25.80%
Speed	9 RPM	7 RPM	5 RPM	4 RPM	1 RPM
Torque	1.90%	2.10%	2.30%	3.00%	5.50%
Load	2.50%	2.50%	2.60%	3.20%	5.70%
Efficiency	2.50%	2.50%	2.60%	3.20%	5.70%

100 HP motor in motor shop was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±9 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±1.9-3.2% for high (>25%) loads, and up to ±5.7% errors for low (<25%) loads.

4.5.3 Experiment of 200 HP Motor

As shown in Figure 49, this motor parameters are Power 200 HP, current 118A, speed 1786RPM, and voltage 460V.

According to the formula and model described in 3.5 and 4.2 of this study, the 200 HP motor in the motor shop is selected as the object of the experiment. The speed, load, torque and efficiency of the motor are estimated and tested, and there are some results of experimental process that shown as follows: Table 27, Table 28, Figure 48 to Figure 55.

Figure 47 Nameplate of 200 HP motor

Table 26 Nameplate of 200 HP motor

	Speed	Load	Voltage	Current
Nameplate	1786 RPM	200 HP	460 V	220 A

Table 27 Estimated parameters of 200 HP motor

	R1	Rc	X1	X2	Xm	R2'
Estimation	0.05944	243.109	0.0702	0.4	20	0.00601

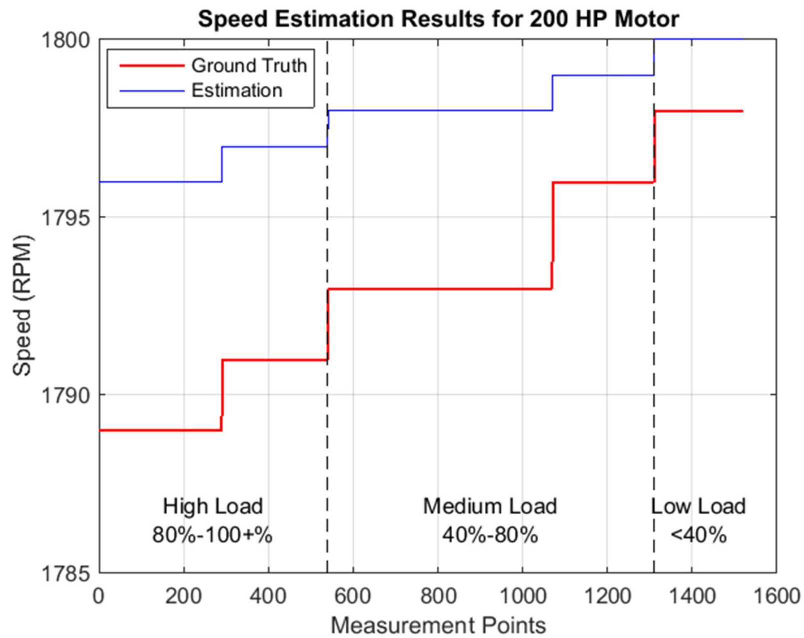

Figure 48 Speed estimation results for 200 HP motor

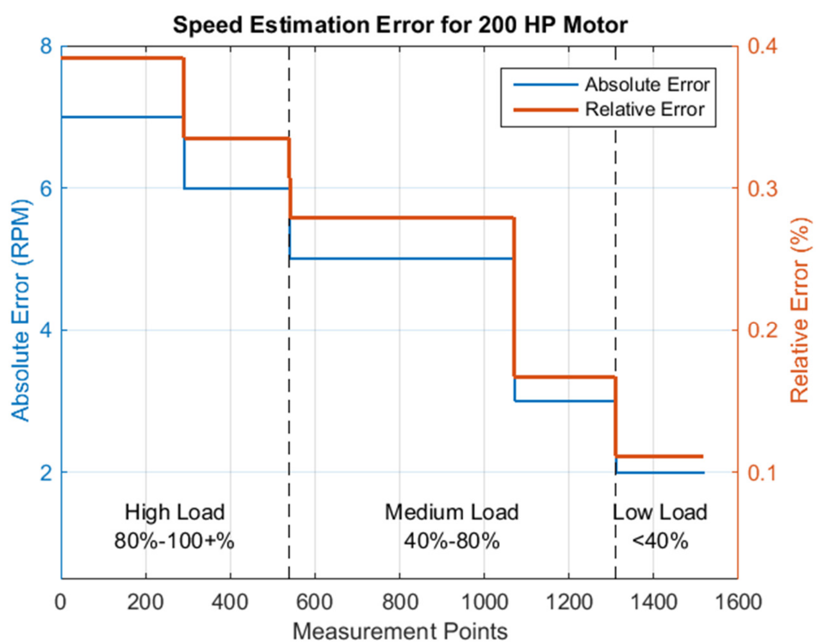

Figure 49 Speed estimation errors for 200 HP motor

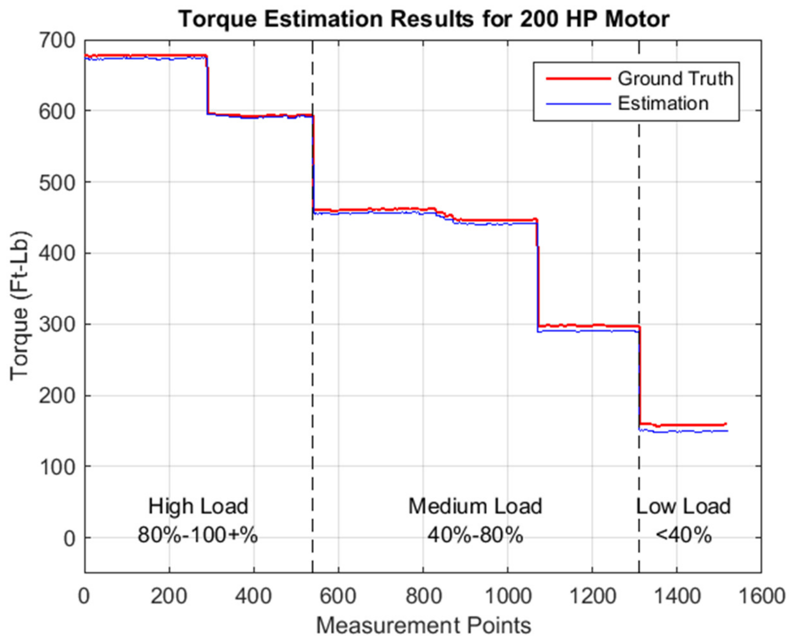

Figure 50 Torque estimation results for 200 HP motor

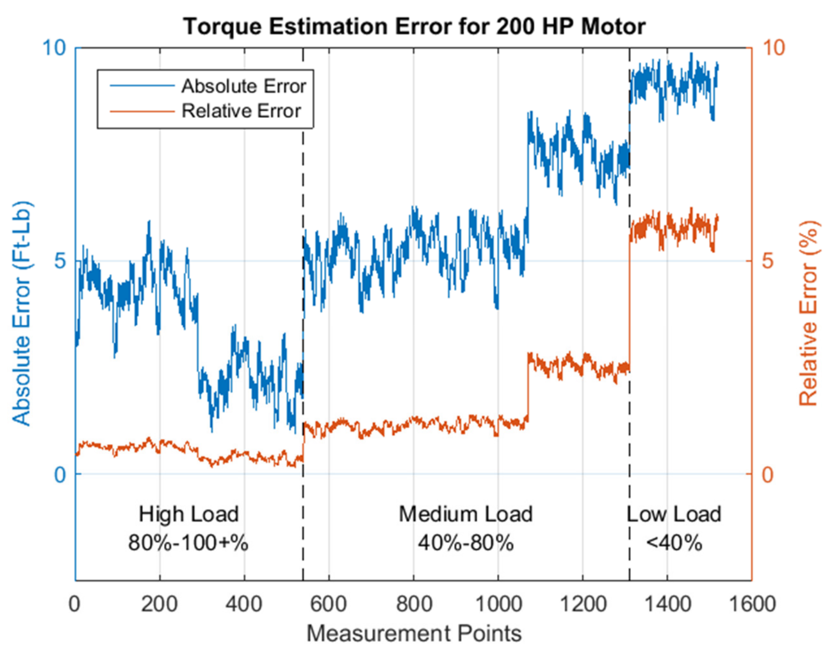

Figure 51 Torque estimation errors for 200 HP motor

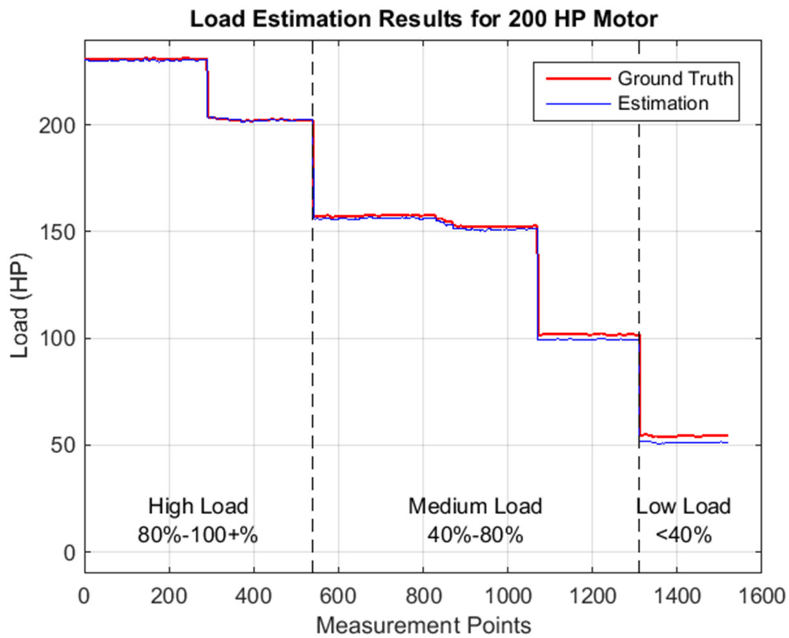

Figure 52 Load estimation results for 200 HP motor

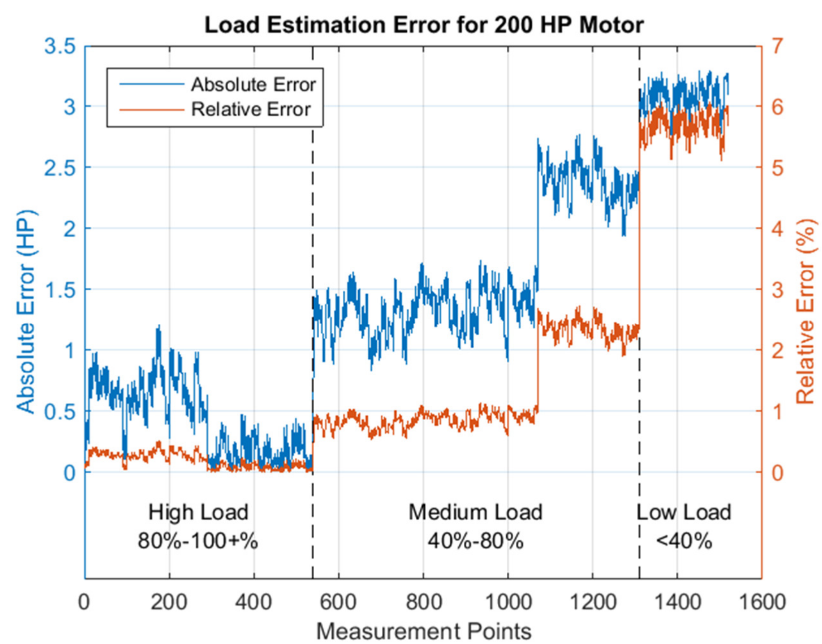

Figure 53 Load estimation errors for 200 HP motor

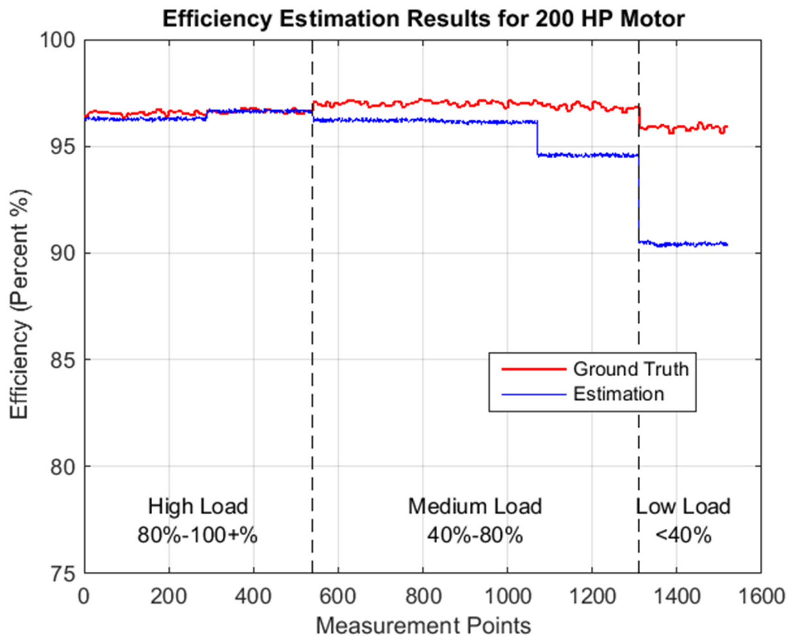

Figure 54 Efficiency estimation results for 200 HP motor

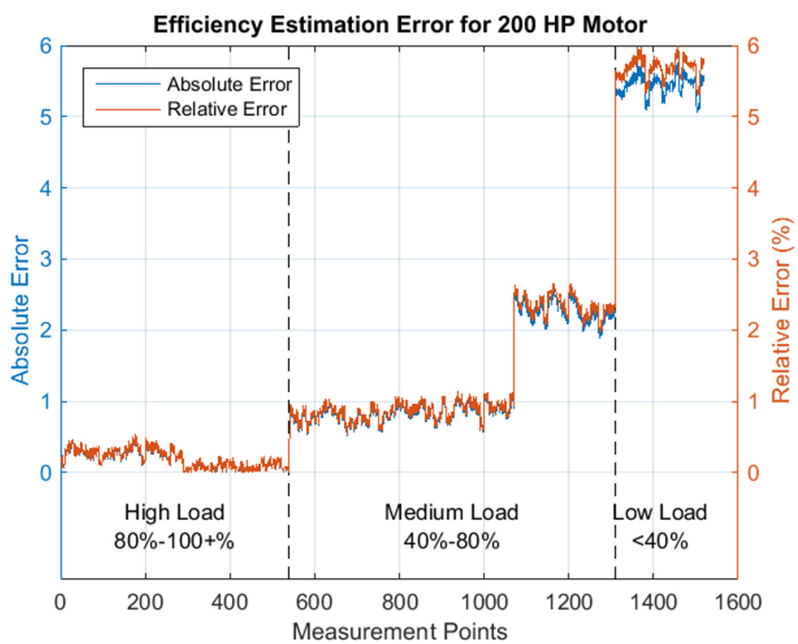

Figure 55 Efficiency estimation errors for 200 HP motor

Table 28 Summary of test results of 200 HP motor
(Average errors vs load)

Load	115.50%	101.20%	77.70%	50.90%	27.20%
Speed	7 RPM	6 RPM	5 RPM	3 RPM	2 RPM
Torque	0.60%	0.40%	1.10%	2.50%	5.80%
Load	0.30%	0.10%	0.90%	2.30%	5.70%
Efficiency	0.30%	0.10%	0.90%	2.30%	5.70%

200 HP motor in motor shop was used to test the proposed approach. The experimental results demonstrate that the proposed method achieves speed estimates within ±7 RPM of the sensor readings. For torque, load and efficiency, the proposed method achieves accuracy within ±0.3-2.5% for high (>25%) loads, and up to ±5.8% errors for low (<25%) loads.

4.6 Summary of Results

Table 29 Summary of test results of all motors

Efficiency		High Load	Medium Load	Low Load
Catalog Data	3 HP	0.40%	1.10%	4.50%
	300 HP	1.60%	1.00%	4.60%
	450 HP	0.70%	1.60%	5.10%
	700 HP	2.40%	2.20%	5.50%
	1500 HP	3.10%	3.50%	6.90%
Lab Data	1 HP	1.70%	3.60%	6.30%
	3 HP	1.40%	3.50%	5.80%
Motor shop Data	100 HP	2.50%	3.20%	5.70%
	200 HP	0.40%	2.30%	5.70%
Average		1.60%	2.40%	5.50%

Five (5) manufacturer's catalog data sheets, two (2) small motors, 1 HP and 3 HP, and two (2) larger motors, 100 HP and 200 HP, are used to test the proposed approach against direct mechanical measurements of torque and speed. The experimental results demonstrate that the proposed method achieves speed estimates within ±5 RPM of the sensor readings, which is comparable to existing non-intrusive methods. For torque, load and efficiency, the proposed method achieves accuracy within ±2-3% for high (>25%) loads, and up to ±5% errors for low (<25%) loads. The presented shaft torque accuracy is an improvement over existing, non-intrusive techniques and in the case of load and efficiency estimation is an improvement over existing, non-intrusive and even some intrusive techniques.

5. SUMMARY AND CONCLUSIONS

5.1 Summary and Conclusion

As the proposed method, Chapter 3 has presented a nonintrusive parameter-based method by introducing a modified induction-motor equivalent circuit. To obtain the equivalent circuit, the motor parameters, including the stator resistance, leakage inductances, magnetizing inductance, core resistance, and the rotor resistance, are regarded as unknown variables. The stator line-voltage and phase-current phasors at multiple different load levels are used to form a five-dimensional system of equations. Due to the highly nonlinear characteristic of these equations, CMA-ES method is adopted to guarantee the solution of the motor parameters under various situations. It has been experimentally verified that this method can achieve accurate mechanical measurements estimates within ±3% errors during the normal load range. The experimental results show that the proposed methods achieve accurate speed estimates within 5 RPM, which is comparable with existed non-intrusive method. For torque, load and efficiency, the proposed methods achieve accurate within ±2-3% errors under >25% load conditions while ±5% errors for low load conditions, using only a few level of input voltages and currents. And it does improve the accuracy compared with existed non-intrusive technique. A remarkable advantage of the method is that, after the motor parameters are estimated, the motor efficiency can be conveniently computed at almost negligible computational efforts. This makes this method ideal for on-chip real-time implementations with limited computational resources.

5.2 Contributions

According to the reaching objectives, the investigation implements the above-mentioned research schematic, so, the three characteristics of this research can be described as the following: It is a frontier research project on estimation of efficiency in electric motor driven system; it is a research project with higher application prospects in plant's motors and energy management; and it develops a novel integrated system which integrates four fields: artificial intelligent, IT, signal processing, electronics into energy and device management. Further, the research has the following attributes:

- A novel contribution of this research is expected to be the estimation of mechanical measurements, e.g. speed, torque, efficiency and load, based only on motor electrical measurements and motor nameplate information.
- A torque transducer and speed sensor are to be eliminated, because they are very costly and highly intrusive.
- A systematic error analysis on proposed non-intrusive method will be conducted and compared with the errors obtained from existing non-intrusive methods.

5.3 Recommendations for Future Work

The ultimate goal of applying the mechanical-measurements-estimation technology in U.S. industry is to improve the overall energy savings and reduce industrial emissions. Although this dissertation has presented contributions to various areas that are important to this goal, such as the nonintrusive efficiency estimation, there are still several directions, in which further research work could build on the results of this work.

- Combine parameters of equivalent circuit to reduce the number of dimension and complexity of CMA-ES optimization.
- Extent application to more unbalance and high THD electrical measurements.
- Extent application of constant frequency motors to variable-frequency driven motors.
- Extent application of estimating equivalent circuit parameters to health condition monitoring by tracking historical records of parameters.

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