Energy savings on single-phase induction motors under light load conditions

Fatima Bouzidi
University of Nevada, Las Vegas

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ENERGY SAVINGS ON SINGLE-PHASE INDUCTION MOTORS UNDER LIGHT LOAD CONDITIONS

by

Fatima Bouzidi

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Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Energy Savings on Single-Phase Induction Motors under Light Load Conditions

by

Fatima Bouzidi

Dr. Yahia Baghzouz, Examination Committee Chair
Professor of Electrical & Computer Engineering
University of Nevada, Las Vegas

It is estimated that electric motors consume approximately two-third of all the electric energy generated in the United States. It is also a known fact that induction motors found in residential and commercial applications are often oversized and operate well below their rated capacity. Because the efficiency of an electric motor is reduced at lighter load, numerous studies have been conducted in the past to reduce motor losses under such load conditions by either lowering the supply voltage (and in some cases, supply frequency) by means of static power converters. But some articles reported conflicting results in terms of energy savings for different duty cycles.

The objective of this thesis is to determine the most efficient way to operate a number of common single-phase induction motors when operating below their horsepower ratings. To accomplish this, the following steps are taken: A) Characterize the motors in terms of their performance (at nominal voltage) and model parameters. B) Simulate the steady-state performance under lower voltage (by SCR control) and lower load.
C) Determine a way to smooth out both voltage and current distortion. E) Verify the simulations with laboratory experiments.

It is asserted that most efficient way to run a motor for a given load is to vary the voltage until minimum input power is achieved. However, unlike the Nola concept, the implementation of such strategy is not as simple as this requires a micro-processor with memory.
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CHAPTER 1

INTRODUCTION

The need for energy savings is increasing and receiving more attention in recent years. Restrictive legislation on CO₂ emission, environmental considerations, rebate programs and improved industry standards are now the motivators behind energy conservation and saving. It is estimated that electric motors consume approximately two-third of all the electric energy generated in the United States [6], and, induction motors account for 96% of this consumption. The wide use of this type of motors is well justified; they are cheap, rugged and practically maintenance free; furthermore, in the case of single phase induction motors, they inherently have, a constant speed over a large range of operation. These motors can be found in industrial, commercial and residential applications as well. It undeniable that this represents an important potential energy saving.

On the other hand, it should be understood that increasing the power generating capacity is very difficult; requires large investments and thus very slow. Hence the need for energy conservation at end-users is more and more crucial and will have an impact on postponing those energy generation investments.

In the case of induction motors, if the power losses can be reduced by just a few percents, this will have a major impact on the total energy consumption.
In most installations where the motor is connected directly to the power source without any control means, constant voltage is applied across the motor's terminals. It is well known that an induction motor operates at optimum efficiency when the load is at or near the motor full-load rating. The motor efficiency declines rapidly as the load decreases; for single phase motors this decline is noticeable at 70% of the rated load. The power losses, small at rated load become predominant when the motor is operated at lighter loads, resulting in lower efficiency.

With the decreased cost and increased performance of power electronic devises, the interest in motor controllers is economically justifiable, if the motor is operated at light load conditions for an extended period of time.

In June 2003, the Department of Energy released a report “Analysis of Energy Conservation Standards for Small Electric Motors”. The data showed that in most applications, the motors are loaded at 60 % or less, with an average of 30 % duty cycle (around 3000 hours a year).

It is important to know that in most applications, the motors used are oversized and that fractional horsepower single phase motors are built with very poor efficiency compared to larger single-phase and three-phase motors. This means that energy savings are more important for:

- Inherently low-efficiency motors
- Motors oversized for their applications
- Motors operated at light load for extended periods of time (i.e, low duty cycle)
This work focuses on single phase motors, specifically split-phase, capacitor-start and capacitor-start-capacitor-run motors. First, some theoretical concepts on single phase motors are needed to understand their construction, operation and properties.

1.1 Single phase induction motors

Single phase induction motors are built in the fractional and integral horsepower range. They, inherently, have a nearly constant speed over their range of operation. Single phase induction motors are used in many residential appliances such as: refrigerators, washing-machines and HVAC. Today, the number of fractional-horsepower motors exceeds the number of integral horsepower motors of all types.

Even though single phase motors are simple to construct, they are not always easy to analyze. The single phase induction motor has no inherent locked-rotor or starting torque. In contrast to a two-phase motor, a single phase motor has only one winding on the stator; hence this winding can set up only one component of the two components required for a rotating field. When the stator winding is excited with an alternating current, a stationary field will be set up by the stator. This stationary field will pulsate in magnitude but will not revolve. Therefore, the rotor will have no tendency to turn; hence the single phase induction motor has no inherent locked-rotor torque. If the rotor is given a spin or started by any auxiliary means, the single phase induction motor will develop a starting torque because of the action of the cross field set up by the rotor.

The operation of a single phase induction motor can be analyzed by the cross field theory or the double revolving theory. The latter will be used in this study and will be explained hereafter.
1.2 The Double Revolving Field Theory

The Double Revolving Field Theory, also called the Forward-Backward Theory, states that a pulsating field or mmf can be decomposed into two rotating fields of half magnitude, but rotating at the same synchronous speed in opposite directions. Therefore, the pulsating stator flux $\Phi_s$, pulsating along the stator winding axis, is equivalent to two rotating fluxes $\Phi_f$ and $\Phi_b$, as illustrated in Figure 1.1 below.

![Diagram showing pulsating field and equivalent rotating fields](image)

Figure 1.1 Pulsating Field and Equivalent Rotating Fields

For a sinusoidally distributed stator winding, the mmf along an angle $\theta$, with respect to the axis of the stator winding, is given by:

$$ F(\theta, t) = N \cdot i(t) \cdot \cos \theta $$

Where $N$ is the effective number of turns the stator winding and $i(t)$ is the instantaneous supply current.

Assuming $i(t) = I_m \cos \omega t$, then:

$$ F(\theta, t) = N \cdot I_m \cdot \cos \theta \cdot \cos \omega t $$
F(θ,t) can be decomposed into:

\[ F(\theta,t) = \frac{N \cdot I_m}{2} \cdot \cos(\alpha - \theta) + \frac{N \cdot I_m}{2} \cdot \cos(\alpha + \theta) \]

\[ = F_f + F_b \]

where \( F_f \) represents the rotating mmf in the direction of \( \theta \) (forward direction), and \( F_b \) represents the mmf in the opposite direction. At standstill the forward and backward torques, produced by these mmfs are opposite and equal; therefore the resulting torque is zero. This is illustrated in Figure 1.2.

\[ \text{Torque} \quad \uparrow \]
\[ \text{Forward component} \]
\[ \text{Slip} \]
\[ \text{Bacward component} \]
\[ \text{Figure 1.2 Torque-Speed Characteristic of Single Phase Induction Motor} \]

1.3 Classification of single phase induction motors

Depending on the auxiliary mean used to produce a starting torque, single phase induction motors can be classified into the following major types: [12] [13]
1.3.1 Split-phase motor

The split-phase motor is widely used in the ratings from 1/20 to 1/3 hp. It has two windings, main and auxiliary as shown in Figure 1.3. The phase shift is created by using a higher resistance-to-reactance ratio, usually obtained by using a finer wire in the auxiliary winding. A centrifugal switch disconnects the auxiliary winding when the speed reaches 70 to 80% of the synchronous speed. This motor has a low to moderate starting torque.

![Figure 1.3 the Split-Phase Motor](image)

1.3.2 Capacitor-start motor

This motor is generally available in 1/8 hp rating and up, and is usually built for single or dual voltage (115 V and 230 V). As shown in Figure 1.4, the capacitor-start motor has two windings like the split-phase motor, with a capacitor inserted in the auxiliary winding, to obtain a higher starting torque. A centrifugal switch is also used to
disconnect the auxiliary winding. Typical values of the capacitor for a ½ hp motor is 300 μF.

![Figure 1.4 the Capacitor-Start Motor](image)

1.3.3 Capacitor-run motor

Also called the permanent-split capacitor motor; the capacitor used in series with the auxiliary winding operates continuously; therefore its value is kept low, 20 to 50 μF, a compromise between best starting torque and running performance. This motor has a lower starting torque than the capacitor start motor, but because the motor runs like a two-phase motor, it has better power factor and efficiency.

1.3.4 Capacitor-start capacitor-run motor

Also called the two-value capacitor-run motor; two capacitors are used, one for starting and the other for running condition. The starting capacitor Cs is larger and is ac electrolytic type. The running capacitor Cr is oil type and permanently connected in series with the auxiliary winding. Typical values for a ½ hp motor are 300 μF for Cs and...
40 μF for Cr. Compared to the other types, this motor is more expensive and provides the best performance.

![Phasor diagram at zero speed](image1)

![Phasor diagram at rated speed](image2)

**Figure 1.5** the Capacitor-start Capacitor-run motor

1.3.5 Shaded pole motor

This motor is limited to the 1/20 hp range. It has one main winding wound on salient poles, with a shaded band consisting of short-circuited copper strap wound around part of the pole, as shown in Figure 1.6. As a result, the flux in the shaded band lags the flux in the unshaded portion of the pole. This is similar to a rotating field moving from the unshaded to the shaded portion of the pole.
1.4 Single phase induction motor equivalent circuit

Based on the double revolving theory, the equivalent circuit of a single phase induction motor is split into two halves, representing the effect of the forward and the backward fields.

The following equivalent circuit is given for any running condition, as defined by the slip “s”. Assuming that the rotor is rotating at a speed “n” in the same direction as the forward rotating field, the slip with respect to the forward field is:

\[ s_f = \frac{n_s - n}{n_s} = s \]

where \( n_s \) is the synchronous speed.

The rotor would be rotating in opposite direction with respect to the backward rotating field and the slip with respect to the backward field is:

\[ s_b = \frac{n_s - (-n)}{n_s} = 2 - s \]

The complete equivalent circuit is shown in Figure 1.7, where:
$R_1$ and $jX_1$ are the resistance and the leakage reactance of the stator.

$R_2$ and $jX_2$ are the resistance and the leakage reactance of the rotor referred to the stator.

$jX_{mag}$ is the magnetizing reactance.

$R_c$ is the core resistance.

Figure 1.7 Equivalent Circuit of a Single Phase Induction Motor

The above equivalent circuit is valid for the split-phase motor and the capacitor-start motor. For the capacitor-start capacitor-run motor, the equivalent circuit includes the auxiliary winding and the internal voltages induced in both windings.
1.5 Methodology and Organization

All work published to date is either based on one control strategy (constant power factor control) proven to be far from optimum [3], or some other control schemes that require dynamic changes in the motor configuration. This work explores the minimum input power control strategy that has been successfully applied to a three-phase motor in [3]. The experiments will be conducted on three types of single phase motors, using an SCR-based voltage controller to assess the energy savings and efficiency improvement. The results will be compared to the ideal case (i.e. sinusoidal voltage source) to identify further improvements to the voltage control technique.

The objective is to assess the efficiency improvement that can be practically achieved, using just voltage and current monitoring and thus resulting in a simple inexpensive method of voltage control. Through experiments and simulations using MATLAB, the harmonic losses are addressed and investigated. The uniqueness of this work consists of the following: First, in applying the minimum input power control to the tested motors; second, identifying the harmonic losses introduced by the voltage controller and investigating solutions to mitigate these losses. Third the simulations using MATLAB are based on an improved equivalent circuit that includes core losses that were previously ignored.

The content of this thesis is as follows: Chapter 2 discusses previous work on motor efficiency improvement and published articles relevant to the subject, and summarizes the results and findings. Chapter 3 addresses the equivalent circuit parameters identification of single phase induction motors that will be used in the simulations. In chapter 4, the concept of energy savings under light load conditions is presented and
verified through experiments on the three motors; the results of efficiency improvement are presented as well. Chapter 5 presents a detailed discussion on harmonic losses and investigates solutions. Chapter 6 is reserved to the conclusions related to this work and proposed development.

To show the energy improvement in single phase motor applications, the approach that is adopted in this thesis is as follows:

1. Determine the motors parameters to be used to build a model for the simulations.
2. Experiment with a voltage controller to assess the efficiency improvement and power losses that can be reduced for further improvement.
3. Experiments with a variable voltage source to compare with the results obtained above and assess the power losses due to harmonics.
4. Investigate the possibility to eliminate or reduce the harmonic losses.
5. Propose other voltage control configuration that can be used to avoid harmonic losses.
CHAPTER 2

REVIEW OF PRIOR WORK ON MOTOR EFFICIENCY IMPROVEMENT

The concept of energy savings in single-phase motors applications was prompted by the work of F. Nola [1], who developed the Energy Saver Power Factor Controller, patented by NASA Marshall Space Flight Center. As published in their Brief No. MSF-23280, “Power Factor Controller” in 1979, energy saving is accomplished by reducing the voltage applied to the motor at light loads, by means of a triac.

2.1 Concept of the Nola Controller

Induction motors inherently operate with nearly constant airgap flux and therefore constant core losses. When the loading conditions do not require full flux, only a small part of the power consumed will be converted to mechanical power while the rest will be lost as heat in the core and windings of the motor.

The concept of the controller developed by NASA is based on continuous monitoring of the voltage and current of the induction motor [1]. At lighter loads, the motor seems to be more inductive and the angle corresponding to the time between the zero crossings of the voltage and the current increases. This angle is erroneously called “power factor angle”; this definition is only true in the case of sinusoidal conditions.
A signal proportional to the angle corresponding to the time between the zero crossings of the voltage and the current is compared to a reference or a set point signal, and used to control the firing angle of the triac.

As the load decreases, the phase angle will increase causing the firing angle of the triac to increase and voltage supplied to the motor to decrease. Conversely, if the load increases, the firing angle will decrease and the voltage supplied to the motor will increase. Laboratory tests showed that the Power Factor Controller could reduce power used by 6% to 8% under full load and as much as 65% at no load [2].

2.2 Published Work on Single Phase Motor Efficiency Improvement

In 1981, J. N. Anderson and G. Radman [2] published their final report on "Power Factor Controller Performance Evaluation". An interesting observation was brought up in the report: the Power Factor Controller has little or no effect on the true power factor. A consequence would be, if the consumed power is reduced and the power factor remains constant, then the reactive power consumed is also decreased, thus not only the consumer would benefit from this technology but also the utilities. The report also showed that substantial power input decrease was noticed especially in the case of single phase motor. The decrease in power input in the three-phase motor was small in comparison, leading to an important conclusion that the Power Factor Controller may not have been the best match for the three-phase motor and in the absence of adjustments, the performance of the Power Factor Controller was less than expected in the case of the three-phase motor.

In 1983, L. D. Jones and D. Blackwell [1] adapted the same concept to the synchronous motors. Although the savings obtained were less than 10%, their work
concluded that substantial energy savings can be achieved for synchronous motors with higher armature winding resistance. More importantly, their work showed the need for more power factor settings and recognized that energy savings can be more substantial in the case of induction motors.

In the same year, T. M. Rowan and T. A. Lipo, published a “Quantitative Analysis of Induction Motor Performance Improvement by SCR Voltage control” [3]. Even though the study was applied to three-phase motors, their analysis showed that the constant power factor controller does not result in optimum efficiency and that the other proposed control schemes such as minimum power factor, minimum stator current, minimum input power and maximum efficiency. They showed that the minimum input power algorithm could be easily implemented and results in efficiency close to the ideal case (using a variable sinusoidal voltage), over the entire operating range. Among the control algorithms that were analyzed, the most satisfactory overall control algorithm was found to be the minimum input power.

In the following years, new voltage control schemes for single phase induction motors have been developed. It is worth noticing the work of J. D. Law and T. A. Lipo, on developing a new improved power factor control scheme, in 1986 [4], accomplished by dynamically switching the motor winding configuration. Their work indicated that improved efficiency over the conventional voltage controller can be achieved with significant decrease in the harmonic distortion. Thyristor-based voltage controllers tend to introduce harmonics in the voltage and current waveforms. By dynamically changing the motor windings configurations, adapted for heavy loads and light loads, reduction in
harmonic distortion was achieved. However, this scheme requires the use of three Triacs or three sets of back-to-back thyristors.

In 1988, Hideo Tomita, Toshimasa Haneyoshi, Osamu Miyashita and Akeshi Maeda [5] published a paper describing a method for energy saving based on optimal efficiency control, obtained by analyzing the voltage-current pattern. The parameters for this voltage-current pattern could be determined from the motor's ratings, by taking the ratio of the rated voltage and current. By keeping the impedance constant, their work showed efficiency improvement and minimum input power can be achieved using a simplified control scheme. Although the authors claim optimal efficiency control, no comparison to the optimal case, i.e., using a variable sinusoidal voltage, was made.

In their article, published in 1996, M.E.H Benbouzid, R. Beguenane and G. A. Capolino [6] demonstrated the benefits of phaseback control and presented a control strategy that is still based on the constant phase angle. However, their study showed interesting results in regards to the limitation of voltage reduction. It was observed that more than 50% reduction in voltage tends to stall the induction motor; that the efficiency and current seemed to reach their extrema at the same value of the motor input voltage, also a reduction of voltage beyond a certain value had a negative effect on the motor efficiency.
CHAPTER 3

MOTOR EQUIVALENT CIRCUIT PARAMETERS

3.1 Introduction

The single phase induction motor modeling is based on the Forward-Backward theory or Double-Revolving Field Theory. In order to obtain the motors equivalent circuit parameters, the following tests are usually performed: No-Load Test, Locked Rotor Test, and DC Test or direct measurement for the resistances.

Many articles and books published in the recent years [9], [10], [11] and [12], proposed methods for determining single-phase motors parameters. However, the proposed traditional models lack the consideration of the core losses. Many assumptions such as ignoring the non-linearities of the circuit parameters and saturation are required, which will certainly affect the model accuracy and account for performance error; but the primary source of error, would be ignoring the core losses [7].

Modeling single phase motors requires that the equivalent circuit parameters be known accurately. Furthermore, predicting their behavior while used in conjunction with frequency or voltage controllers becomes difficult with parameters uncertainty. The use of the traditional model (i.e ignoring the core losses) will result in a great error in motor performance prediction. E.R Collins and P.B Boys [7, 8] presented several methods for determining motors parameters, with and without core losses and if an equivalent core losses resistance is considered, where that resistance should placed and whether or not
that would affect the model performance. While ignoring the core losses was proved to definitely introduce significant errors, the placement of the core losses resistance has little effect on the performance prediction.

The process of determining the motor's parameters is fairly simple, however, the computation of the parameters, when the core losses resistance is taken into account, requires solving non-linear equations. MATLAB was used in solving those equations; detailed determination of the motors parameters, equivalent circuits used and equations, are presented hereafter.

3.2 Tests performed

In order to determine the motor's equivalent circuit parameters, the following tests need to be performed:

3.2.1 No-Load Test

In this test, the motor is driven by a synchronous machine at synchronous speed (corresponding to a slip S=0) while rated voltage is applied at the motor's terminals. The current, input real power, reactive power and voltage across the auxiliary winding terminals are recorded. The motor equivalent circuit under this condition (S=0), is given in Figure 3.1
3.2.2 Locked Rotor Test

In this test, the shaft of the motor is blocked, and a reduced voltage is applied gradually to the main winding until rated current is reached. The motor input power is recorded, along with the voltage and current. The motor equivalent circuit under this condition is given in Figure 3.2

Figure 3.1 Equivalent Circuit under No-Load and S = 0
3.2.3 Resistances Measurement

The main winding resistance and auxiliary winding resistance can be measured directly using an Ohm-meter. Another alternative would be to perform a DC test on each winding separately. In this case, a DC current equal to the rated current is applied to the winding; the DC voltage across the winding is measured. The resistance is obtained by dividing the DC voltage by the DC current.

The above mentioned tests were conducted on two commercial single-phase motors. The data on the motors nameplates is given in Table 1. Motor A, rated 1/3 hp, is a split-phase, while motor B, rated ¾ hp can be connected as a capacitor-start (B1) or a capacitor-start-capacitor-run (B2).
Table 3.1 Nameplates of Tested Motors

<table>
<thead>
<tr>
<th>Motor A</th>
<th>Motor B</th>
</tr>
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<tbody>
<tr>
<td>Brand name: EMERSON</td>
<td>Brand name: BALDOR</td>
</tr>
<tr>
<td>Type: Split-Phase</td>
<td>Type: Capacitor-Start/ Capacitor Run</td>
</tr>
<tr>
<td>Model No. SA55NXSFB-4866</td>
<td>Model No. 34G426Y094</td>
</tr>
<tr>
<td>Ratings: 1/3 hp, 115 V, 60 Hz, 1725 rpm, 6.4 A</td>
<td>Ratings: 3/4 hp, 115/230 V, 60 Hz, 1725 rpm, 8.4/4.2 A</td>
</tr>
</tbody>
</table>

Notes:

- The locked rotor test may be also performed on the auxiliary winding to determine its parameters.

- The turn ratio between the main winding and the auxiliary winding may be determined by applying voltage to the main winding and measuring the voltage across the auxiliary winding, and vice-versa. The ratio of the main winding voltage to the auxiliary winding voltage is calculated for each case and the effective turn ratio is determined by taking the square root of the product of the two ratios [10].

- The centrifugal switch in the split-phase motor and the capacitor –start motor disconnects the auxiliary winding around 70 to 80 % of the rated speed. The steady state equivalent circuit in both cases would include only the parameters of the main winding.

- For motor B, each capacitor value is measured directly.
The results of the tests are presented in Appendix A.

3.3 Parameters Calculation

By taking into account the core resistance, the computation of the equivalent circuit parameters is not a simple manual calculation. Unlike in a balanced three-phase induction motor, where nearly all of the no-load losses are attributed to the core resistance, in a single phase machine, power is lost in the rotor due to the backward rotating field even at synchronous speed. The parameters are determined from the equations of the motor's equivalent impedance, seen from the motor's terminals, under no-load and locked rotor conditions. The non-linear equations are solved simultaneously using numerical (optimization) method.

For the no-load and the locked rotor tests, the impedance seen from the motor's input terminals are:

\[ Z_{NL} = R_1 + jX_1 + \frac{R_\phi}{(R_2/4 + j(X_m+X_2)/2)} \]  
\[ Z_{LR} = R_1 + jX_1 + \frac{R_\phi}{jX_m/(R_2 + jX_2)} \]

where:

- \( Z_{NL} \) is the impedance seen from the motor's terminals, calculated from the no-load test.
- \( Z_{LR} \) is the impedance seen from the motor's terminals, calculated from the locked rotor test.
- \( R_1 \) is directly measured

The leakage reactances \( X_1 \) and \( X_2 \) are assumed to be equals.
Equations (1) and (2) are solved, using numerical method, for the unknown parameters $X_m$, $R_2$, $X_1$, $X_2$, and $R_c$ using the measured voltage, current and power values. The results are presented in Table 3.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Motor A</th>
<th>Motor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>2.4 Ω</td>
<td>0.9 Ω</td>
</tr>
<tr>
<td>$X_1$</td>
<td>2.3 Ω</td>
<td>1.2 Ω</td>
</tr>
<tr>
<td>$R_2$</td>
<td>1.8 Ω</td>
<td>0.9 Ω</td>
</tr>
<tr>
<td>$X_2$</td>
<td>2.3 Ω</td>
<td>1.2 Ω</td>
</tr>
<tr>
<td>$R_c$</td>
<td>575 Ω</td>
<td>598 Ω</td>
</tr>
<tr>
<td>$X_m$</td>
<td>30.9 Ω</td>
<td>25 Ω</td>
</tr>
</tbody>
</table>

Table 3.2 Calculated Motors' Parameters

In addition, the following parameters have been measured for both motors:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Motor A</th>
<th>Motor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary winding resistance</td>
<td>8.5 Ω</td>
<td>2 Ω</td>
</tr>
<tr>
<td>Start capacitor</td>
<td>280 μF and 180 mΩ</td>
<td></td>
</tr>
<tr>
<td>Run capacitor</td>
<td>19.48 μF and 28.5 mΩ</td>
<td></td>
</tr>
<tr>
<td>Turn Ratio “a”</td>
<td></td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 3.3 Additional Measured Motors' Parameters
3.4 Comparison of Simulations and Experimental Data - Model Confirmation

Although the experiments have been conducted on the three motors, the simulations were done only on the split-phase motor. The operation of capacitor-start motor is similar to split-phase motor at steady state.

The simulation of the motor current and input power of the split-phase motor, compared to the experiments at no-load are shown in Figures 3.3 and 3.4, and in loaded conditions, are shown in Figures 3.5 and 3.6. It should be noticed that the predicted input power does not include the mechanical losses. At rated voltage, for motors of similar ratings, those losses are approximately 22.5 W [8]. In our case, at 116.3 V, the measured power is 204 W and the predicted power is 181.5 W, the difference is 22.5 W, which would correspond to the mechanical losses.

The predicted values of motor input current and input power are mostly in agreement with measured values. The difference is due, besides the measurement errors and the voltage distortion in the power supply, to the nonlinearities in the motor parameters and the mechanical losses that have not been taken into account in the simulations.
Figure 3.3 Predicted and Measured Values of the Motor Input Current at No-Load

Figure 3.4 Predicted and Measured Values of the Motor Input Power at No-Load
Figure 3.5 Predicted and Measured Values of the Motor Input Current in Loaded Conditions

Figure 3.6 Predicted and Measured Values of the Motor Input Power in Loaded Conditions
4.1 Concept of efficiency improvement by means of voltage control

Improving induction motors efficiency under light load conditions has received considerable attention during the past two decades. Several studies have proved that energy savings under light load conditions are possible but depend on the duty cycle of the motor where the motor is operated at light load for substantial period of time.

In general, efficiency improvement by means of voltage control is achieved by reducing the RMS value of the input voltage applied to the motor terminals, whenever the motor is partially loaded. Ideally, controlling the voltage would require a variable sinusoidal voltage source. In practice, however, the voltage control can be achieved by using triacs or anti-parallel connected thyristors as illustrated in Figure 4.1

![Figure 4.1 Basic Illustration of a Single Phase Motor Voltage Control](image-url)
By increasing the firing angle $\alpha$, the voltage RMS value is reduced, hence reducing the losses for partial-load operating conditions. However, the use of the voltage controller will result in distortion of the voltage and current waveforms, producing harmonic currents that will result in additional losses.

Typical voltage and current waveforms are illustrated in Figure 4.2. The angle corresponding to the instant, at which the conducting thyristor is triggered, with reference to the zero crossing of the voltage, is called delay angle $\alpha$. The angle that corresponds to the time the current is zero is called the hold-off angle $\gamma$. The angle between the zero crossing of the voltage and the zero crossing of the current defined as $\phi$, is sometimes erroneously called power factor angle. Here, as many other published papers, this angle is called “phase delay angle”.

![Figure 4.2. Typical Voltage and Current Waveforms](image-url)
4.2 Experiments

4.2.1 Motors’ Efficiencies

The motors described in the previous chapter have been tested at different loading conditions to determine their efficiencies. It should be noted that the split-phase motor has poor efficiency compared to the two other motors. Its efficiency at full load is around 54%; this means that the losses represent 46% of the real power consumed by the motor.

![Motors Efficiency Curves](image)

Figure 4.3 Motors Efficiency Curves

In the next section, control algorithms for efficiency improvement, that would require monitoring, only the current and voltage across the motor, will be discussed.

4.2.2 Efficiency Improvement methods

There exist several control strategies, besides the fixed power factor angle in the Nola controller. This control strategy does not yield to optimum efficiency [3, 4]. To achieve the efficiency improvement of the motor with the variation of the load, the optimum

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algorithm would be based on the maximum efficiency, which is not practical to implement and requires monitoring the speed and mechanical torque of the motor. Other possible algorithms are:

- Minimum phase delay angle
- Minimum stator current
- Minimum input power

These control algorithms have been studied by T. M. Rowan and T. A. Lipo and described in their article entitled “Quantitative Analysis of Induction Motor Performance Improvement by SCR Voltage control” [3]. The minimum power factor control was noticed to be closer to the ideal case except at higher torque values where the efficiency deviates rapidly from the optimum. The minimum input power, although less than the ideal case has been proven to give overall satisfactory results over the entire operating range.

This control strategy based on the minimum input power is tested here, on the split phase motor. The results are detailed in the following sections.

4.2.3 Experiments with minimum input power

Experiments on the split-phase, capacitor-start and capacitor-start-capacitor-run motors have been conducted, in the Laboratory to determine the optimum voltage that will result in minimum input power, and consequently reduced losses, for different loading conditions.

The following equipment was used:

- Motor A and B described in the previous chapter.
- Power Analyzer (Dranetz/BMI 4300 Power Platform)
• Dynamometer (Magtrol Model HD-810-GN), Hysteresis Type
• Dyno controller (Magtrol Model DSP6001)

The load on the motor was increased, from no load to full load, in steps of 10% of the full load. For each load, the voltage applied to the motor terminals is reduced until the recorded input power is minimum. It should be noticed that too much reduction in the input voltage will result in motor stalling. The experiment was conducted using the voltage controller, which introduces a high THD in both voltage and current, depending on the delay angle $\alpha$. The results of the experiments are presented in Appendix B.

In Figure 4.4, efficiency at fixed voltage (without voltage controller) is shown for comparison. A substantial improvement in motor efficiency was obtained at reduced loads and even at full load, which proves that this type of motors are designed and built originally with poor efficiency.

![Figure 4.4 Efficiency Improvement of Split-Phase Motor Using Minimum Input Power Control.](image-url)
The same experiment has been repeated using a variable sinusoidal voltage source with a voltage THD recorded of 2.9% and a current THD of 2.6%.

Figure 4.5 Motor’s Efficiency with Voltage Controller and a Variable Sinusoidal Voltage Source (Ideal Case)

Figure 4.5, where efficiency with SCR control is shown for comparison, shows that minimum input power control scheme results in overall improvement efficiency over the whole range of operation, close to the ideal case.

For the capacitor-start motor and the capacitor-start-capacitor-run motor, as shown in Figures 4.6 and 4.7, the efficiency improvement is less than the previous motor, but is still noticeable at lighter loads. The efficiency curve is approximately flat over the whole...
range of operation and only a small decrease from the efficiency at rated load, which is the optimum efficiency of the motor, is noticed.

Figure 4.6 Efficiency Improvement of Capacitor-start motor Using Minimum Input Power Control.
4.3 Relation between Minimum Input Power and Phase Angles

Simulations for the split-phase motor, with the voltage controller have been conducted for different loads and from the plots of the voltage across the motor and the current waveforms, the angles defined in section 4.1 and shown on Figure 4.2, have been identified. Figure 4.8 shows the variation of the firing angle of the thyristors with respect to the minimum input power for each load. Interestingly, the obtained pattern is quite linear and can be easily programmed to obtain a control law this will result in improved efficiency. Unfortunately, this pattern may be specific to the tested motor.
As it was reported in reference [3], the variation of the phase delay angle, is not constant and thus a unique value of this angle used as a reference or a set point for voltage control cannot result in optimum efficiency. The power factor controller can be improved by adding different settings, in steps for each range of the load.
4.4 Discussion on further efficiency improvement

The power losses can be segregated as follow:

- Copper losses in the stator and rotor windings
- Core losses
- Harmonic losses introduced by the voltage controller
- Losses in the voltage controller itself.

The first and the second type of losses can be reduced using the voltage control to achieve minimum input power under light loads; however this control scheme results in voltage distortion thus creating harmonic currents that result in harmonic losses. These harmonic losses can be identified for each motor by comparing the experiment results with the voltage controller and those using a variable sinusoidal voltage source. Some mitigating solutions are presented in the next chapter, and the limitations and practicality of these techniques will be discussed.
CHAPTER 5

REDUCTION OF ENERGY LOSSES DUE TO HARMONICS

5.1 Harmonic losses

The improvement of motor efficiency while partially loaded, by means of thyristor-based voltage controller introduces additional losses due to the harmonics, in the voltage and current waveforms. The results obtained from the experiments of the motor input power, using the voltage controller and the variable sinusoidal voltage source, described in the previous chapter, are compared and the part of the power losses that is due to the harmonics introduced by the voltage controller, is determined.

For each load, the harmonic losses are defined as the difference between the corresponding input power values from the two tests, the one with the variable sinusoidal voltage source and the one with the thyristor-based voltage controller. This difference is identified in Figure 5.1 for the three motors. The difference between the two graphs defines the part of the power losses that are due to the harmonics introduced by the voltage controller.
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Figure 5.1 Estimation of Harmonic losses: (A) Split-Phase Motor, (B) Capacitor-start Motor, and (C) Capacitor-run Motor.

The harmonic losses could be reduced by filtering the dominant harmonic component in the voltage and current waveforms. By analyzing the harmonics contents of the voltage and motor current, it can be noticed that the third harmonic (180 Hz) is the dominant component. This subject is investigated in detail for the 1/3 hp, Split-phase motor. Figure 5.3 and 5.4 show the voltage and current waveforms and harmonic components, from the simulations and experiments at half of the motor full load.
Figure 5.2 Motor Input Voltage Waveform and Harmonic Components – Simulation.

Figure 5.3 Motor Input Current Waveform and Harmonic Components - Simulation.
Figure 5.4 Motor Input Voltage and current Waveforms – Experiment.

Figure 5.5 Motor Input Voltage Harmonic Components – Experiment.
The simulation at half load (Figure 5.2 and 5.3) gave the following results: for the voltage, the third harmonic amplitude is 53% of the fundamental and the THD is 63.54%; for the current, the third harmonic amplitude is 33% of the fundamental and the THD is 36.47%. The experiments on the 1/3 hp split-phase motor at half the full load, as shown on Figures 5.5 and 5.6, gave the following results: for the voltage across the motor terminals, the third harmonic amplitude is approximately 35% of the fundamental component while the total harmonic distortion THD is equal 38.92%. Similarly, for the current, the third harmonic amplitude is approximately 45% of the fundamental component while the THD is 46.38%. This difference in the respective THD values, between the simulations and experiments is due to the fact that the voltage controller had some filtering capabilities. However, the simulations were in agreement showing that the third harmonic is the dominant component.
To partially mitigate this problem, filtering the harmonics would result in cleaner waveforms of the voltage and current, thus reducing the power losses. Although filtering the third harmonic component with a tuned filter, would require a large and bulky filter, this solution is worth the investigation.

5.2 Single-tuned filter calculation

The filter is tuned at the third harmonic, which has been determined as the dominant harmonic component, is designed with the following constraints:

- The impedance of the filter is lowest at the third harmonic frequency, i.e 180 Hz
- The filter should provide the reactive power needed at the fundamental frequency. It should be noticed that more than needed reactive power at the fundamental will increase the current which will increase the power losses.

At half load, the fundamental component of the voltage is approximately 68.9 V and the reactive power (Q) at the fundamental frequency is 227 VAR. With this data, the filter’s components can be determined by solving the following equations:

\[
L \cdot C = \frac{1}{\omega_i^2} \quad (1)
\]

\[
= 7.8 \times 10^{-7}
\]
\[ X_r = \frac{V_1^2}{Q} \]
\[ \frac{1}{377C} - 377L = 20.9 \]

The filter's components are then calculated by solving equations (1) and (2) and determined as:

\[ C = 113 \mu F \text{ and } L = 6.9 \text{ mH} \]

Simulations at half the motor full load were performed to evaluate the effectiveness of the filter. The filter's frequency/impedance response, given in Figure 5.7, shows that the filter is tuned at 180 Hz.

Figure 5.7 Single-Tuned Filter's Frequency Response
The waveforms of the voltage across the motor's terminals and the motor current are shown on Figure 5.8 and 5.9.

Figure 5.8 Motor Input Voltage Waveform and Harmonic Components

Figure 5.9 Motor Input Current Waveform and Harmonic Components
It can be noticed that the third harmonic component has been eliminated completely from the both voltage and current waveforms; however, the motor input power has increased from 214 W with no filter to 287 W with the placement of the single tuned filter. Similarly, an increase in the RMS values of voltage and current have been noticed, 90.5 V and 5.3 A respectively.

The single tuned filter was further improved by adding a series inductor, between the voltage controller and the single tuned filter. This inductor in combination with the filter will limit the flow of harmonic currents to the motor, thus smoothing the current waveform. The series and shunt branches will form a low pass filter, therefore reducing the peak-to-peak ripple of the voltage waveform.

The size of the series inductor determines the smoothing effect on the current waveform. The larger the inductor, the more improved and clean is the current waveform. A compromise between the series inductor size, the current THD and the filter's effect on reducing the fundamental components can be reached. In this case, a current THD around 5 %, and approximately 28 % in fundamental component reduction are used as constraints; which lead to a series inductor's size of 15 mH.

5.3 Simulation of Filter's performance

The new simulations at half the motor full load, with the modified filter are shown in Figure 5.10 and 5.11.
Figure 5.10 Motor Input Voltage Waveform and Harmonic Components

Figure 5.11 Motor Input Current Waveform and Harmonic Components
In here, the voltage THD has been reduced to 12.69% and the current THD to 5.59%. Moreover, the input power has been reduced to 143.5 W, indicating a reduction in the power losses due to the harmonic components.

Simulations of the minimum input power have been performed under different loading conditions and shown on Figure 5.12. A comparison of the minimum input power, using the voltage controller with and without the filter, defines the filter’s performance.

Figure 5.12 Filter’s Performance. Comparison between the Minimum Input Power of the Motor with and without Filter - Simulation.

It should be noticed that the reactive power value used as a constraint to calculate the filter’s parameters was determined for half the load condition. When the load is less, there will be an over-compensation from the excess of the reactive power supplied by the
filter. Conversely, when the load is more than half the load, there will be undercompensation and filter will not be able to supply all the needed reactive power to the motor, at the fundamental frequency.

Passive filters have several disadvantages: cost, size and losses. These losses have ignored in the simulations. In reality, the average losses on an inductor of 15 mH can reach 26 W at rated voltage. Obviously, passive filtering is not an ideal solution to reduce the harmonic losses. An alternative solution is addressed next.

5.4 Voltage Controller with IGBTs

The voltage controller based on two back-to-back thyristors that was used previously had the disadvantage of introducing significant harmonic losses. In the previous section, a solution of harmonic filtering was investigated and found out to be impractical; the size and the cost were the major drawback.

As alternative to minimize harmonic injection, IGBTs can be used instead of thyristors. The voltage and the current waveforms would be less distorted, as a single digit THD can be obtained; by using high switching frequency.

Several configurations of controllers based on IGBTs can be used as presented in [16], however, they requires four or more IGBTs and some of them use a combination of AC/AC or DC/AC converters.

The proposed configuration, here uses two IGBTs and one pulse generator. It is a fact that these types of controllers, as shown in Figure 5.13, have difficulties to commutate while supplying inductive loads, due to finite switch on/off times. A small shunt
capacitor is used to reduce the voltage and current spikes, provide power factor compensation ad can also act as a high frequency filter.

Figure 5.13 New Voltage Controller's Configuration

The waveforms of voltage across the motor terminals and the motor current are shown on Figure 5.14. The harmonic contents of the voltage and current, are given on Figure 5.15 and 5.16.
Figure 5.14 Motor's Voltage and Current Waveforms

Figure 5.15 Motor Input Voltage - Waveform and Harmonic Content
The harmonic content of the voltage and current are very low; the THD is only 2.68% for the voltage and 0.19% for the current. The only significant harmonic components exist at the switching frequency (10 kH in this case). If needed, they can be filtered and the size of filter in this case, would be small because of the high order of the harmonics.

As a comparison between the two controllers, the voltage, current and input power are presented in the following table. As it can be noticed, the input power is less in the case of the voltage controller with IGBTs.
The controller with the IGBTs has better performance than the thyristor-based controller and does not require bulky and costly filter. However, the voltage in the case the thyristors can be easily adjusted by controlling firing angle. In the case of the IGBTs, controlling the voltage is more complex and requires adjusting both the switching frequency and the width of the pulse. The losses due to the switching frequency are higher in the case of the IGBTs, requiring the use of heat sinks.

Table 5.1 Comparison between Two Controllers

<table>
<thead>
<tr>
<th></th>
<th>IGBTs</th>
<th>Thyristors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V rms)</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>Current (A rms)</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Input Power (W)</td>
<td>200</td>
<td>236</td>
</tr>
</tbody>
</table>

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CHAPTER 6

CONCLUSIONS

A voltage control method for efficiency improvement in single phase induction motors, based on minimizing the input power has been tested. Laboratory experiments have proved that indeed efficiency improvement can be achieved. The energy savings will depend on the motor's rated efficiency, sizing for the application and period of operation at light loads.

The first proposed voltage controller based on back-to-back thyristors was found to result in significant harmonics which introduced additional power losses. Filtering the harmonics with a shunt filter, tuned at the third harmonic, with a series inductor has then been investigated. Simulations showed the filter's performance in reducing the harmonics but this solution was found to be impractical because of the size and the cost of the filter. An alternative solution involved changing the voltage controller by using IGBTs instead of thyristors. The voltage and current waveforms obtained were much less distorted in this case. Further work is needed to obtain an adequate and practical correlation between the voltage control and the switching of the IGBTs.

Along the experiments on efficiency improvement, other experiments on the motors have been conducted to identify the motors parameters. An improved equivalent circuit that includes the core losses has been presented and used for the simulations in MATLAB and SIMULINK.
A more detailed model that includes the electromagnetic and mechanical properties of the motors will enable investigating the implementation of voltage control algorithms based on minimizing the input power.
APPENDIX A

TESTS RESULTS FOR THE MOTORS PARAMETERS

CALCULATION

1/3 HP SPLIT-PHASE MOTOR

Resistances measurements

Main winding: $R_1 = 2.4 \, \Omega$, Auxiliary winding: $R_2 = 8.5 \, \Omega$

No-load test, at synchronous speed (1800 rpm)

<table>
<thead>
<tr>
<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.5</td>
<td>0.835</td>
<td>3.11</td>
</tr>
<tr>
<td>50.25</td>
<td>1.85</td>
<td>12.38</td>
</tr>
<tr>
<td>75.65</td>
<td>2.91</td>
<td>30.12</td>
</tr>
<tr>
<td>100.38</td>
<td>4.49</td>
<td>67.8</td>
</tr>
<tr>
<td>115.6</td>
<td>6.029</td>
<td>120.95</td>
</tr>
</tbody>
</table>

No-load test with variable input voltage (At different speeds)

<table>
<thead>
<tr>
<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
<th>Speed(rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>115.12</td>
<td>5.81</td>
<td>174</td>
<td>1792</td>
</tr>
<tr>
<td>100.68</td>
<td>4.4</td>
<td>109</td>
<td>1791</td>
</tr>
<tr>
<td>75</td>
<td>2.85</td>
<td>54.4</td>
<td>1789</td>
</tr>
<tr>
<td>50.28</td>
<td>1.82</td>
<td>26.5</td>
<td>1788</td>
</tr>
<tr>
<td>25.69</td>
<td>1.096</td>
<td>15.71</td>
<td>1756</td>
</tr>
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</table>
Locked-rotor test on main winding (auxiliary winding open)

<table>
<thead>
<tr>
<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
<th>Ea (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4</td>
<td>0.49</td>
<td>1.09</td>
<td>70.8</td>
</tr>
<tr>
<td>10.5</td>
<td>1.37</td>
<td>7.52</td>
<td>120.3</td>
</tr>
<tr>
<td>15.4</td>
<td>2.23</td>
<td>20.05</td>
<td>207</td>
</tr>
<tr>
<td>20.2</td>
<td>3.08</td>
<td>38.27</td>
<td>244.2</td>
</tr>
<tr>
<td>24.9</td>
<td>3.9</td>
<td>62.2</td>
<td>301.6</td>
</tr>
<tr>
<td>30.08</td>
<td>4.82</td>
<td>94.92</td>
<td>366</td>
</tr>
<tr>
<td>35.06</td>
<td>5.69</td>
<td>133.68</td>
<td>423</td>
</tr>
</tbody>
</table>

¾ HP CAPACITOR-START / CAPACITOR-START CAPACITOR-RUN MOTOR

Resistances measurements:

Main winding: $R_1 = 0.9 \, \Omega$, Auxiliary winding: $R_2 = 2 \, \Omega$

No-load test, (At synchronous speed) on main winding (auxiliary winding open)

<table>
<thead>
<tr>
<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
<th>Ea (V)</th>
</tr>
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<tbody>
<tr>
<td>24.88</td>
<td>1.2</td>
<td>3.29</td>
<td>20.25</td>
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<td>39.12</td>
<td>2.06</td>
<td>7.9</td>
<td>35.31</td>
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<td>50.7</td>
<td>2.79</td>
<td>13.3</td>
<td>47.95</td>
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<td>75.2</td>
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<tr>
<td>85.5</td>
<td>5.1</td>
<td>39.5</td>
<td>86.8</td>
</tr>
<tr>
<td>100</td>
<td>6.3</td>
<td>58</td>
<td>103.2</td>
</tr>
<tr>
<td>115.5</td>
<td>8.05</td>
<td>91.5</td>
<td>119.3</td>
</tr>
</tbody>
</table>

No-load test, (At synchronous speed) on auxiliary winding (main winding open)

<table>
<thead>
<tr>
<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
<th>Em (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.7</td>
<td>0.445</td>
<td>0.11</td>
<td>6.15</td>
</tr>
<tr>
<td>24.16</td>
<td>0.78</td>
<td>1.16</td>
<td>11.25</td>
</tr>
<tr>
<td>40.75</td>
<td>1.35</td>
<td>5.06</td>
<td>22.15</td>
</tr>
<tr>
<td>51.1</td>
<td>1.72</td>
<td>8.78</td>
<td>29.27</td>
</tr>
<tr>
<td>76.2</td>
<td>2.68</td>
<td>22.3</td>
<td>46.78</td>
</tr>
<tr>
<td>86.3</td>
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<td>53.84</td>
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<tr>
<td>100.39</td>
<td>3.72</td>
<td>42.7</td>
<td>63.82</td>
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<td>114.7</td>
<td>4.48</td>
<td>61.6</td>
<td>74.1</td>
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No-load test with variable input voltage (At different speeds)

<table>
<thead>
<tr>
<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
<th>Speed(rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.56</td>
<td>1.35</td>
<td>12.6</td>
<td>1751</td>
</tr>
<tr>
<td>25.9</td>
<td>1.5</td>
<td>14</td>
<td>1785</td>
</tr>
<tr>
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<td>1.94</td>
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<td>1795</td>
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<td>6.34</td>
<td>111.05</td>
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<td>1795</td>
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<td>7.96</td>
<td>161</td>
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Locked-rotor test on main winding (auxiliary winding open)

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<th>V (V)</th>
<th>I (A)</th>
<th>P(W)</th>
<th>Ea (mV)</th>
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<tr>
<td>22.63</td>
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<td>103.11</td>
<td>379.8</td>
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<td>20.5</td>
<td>6.81</td>
<td>80.8</td>
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<tr>
<td>15.5</td>
<td>4.7</td>
<td>38.7</td>
<td>337.4</td>
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<tr>
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<td>20.78</td>
<td>327.4</td>
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Locked-rotor test on auxiliary winding (main winding open)

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<th>I (A)</th>
<th>P(W)</th>
<th>Em (mV)</th>
</tr>
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<td>345.6</td>
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<td>29.86</td>
<td>4.99</td>
<td>93.2</td>
<td>297.7</td>
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<td>24.39</td>
<td>3.91</td>
<td>57.3</td>
<td>252.7</td>
</tr>
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<td>19.8</td>
<td>3.03</td>
<td>34.2</td>
<td>212.9</td>
</tr>
<tr>
<td>14.2</td>
<td>1.93</td>
<td>14</td>
<td>160.5</td>
</tr>
<tr>
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<td>1.46</td>
<td>8.14</td>
<td>135.7</td>
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APPENDIX B

EFFICIENCY IMPROVEMENT EXPERIMENTS RESULTS

1/3 HP SPLIT-PHASE MOTOR

Experiment with voltage controller

<table>
<thead>
<tr>
<th>Pout (hp)</th>
<th>Pin (W)</th>
<th>V (V)</th>
<th>V THD (%)</th>
<th>I (A)</th>
<th>I THD (%)</th>
<th>Speed (rpm)</th>
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<tbody>
<tr>
<td>0.011</td>
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<td>38</td>
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<td>2.1</td>
<td>86</td>
<td>1707</td>
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<tr>
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<td>78</td>
<td>49</td>
<td>81</td>
<td>2.7</td>
<td>74</td>
<td>1715</td>
</tr>
<tr>
<td>0.064</td>
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<td>67</td>
<td>3.3</td>
<td>66</td>
<td>1717</td>
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<td>59</td>
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<td>4</td>
<td>52</td>
<td>1725</td>
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<tr>
<td>0.166</td>
<td>236</td>
<td>82</td>
<td>40</td>
<td>4.4</td>
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<td>1727</td>
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<td>4.7</td>
<td>42</td>
<td>1727</td>
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<tr>
<td>0.227</td>
<td>307</td>
<td>91</td>
<td>33</td>
<td>5</td>
<td>39</td>
<td>1721</td>
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<tr>
<td>0.265</td>
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<td>96</td>
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<td>29</td>
<td>1714</td>
</tr>
<tr>
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<td>432</td>
<td>102</td>
<td>22</td>
<td>5.9</td>
<td>25</td>
<td>1707</td>
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</table>
Experiment with a sinusoidal variable voltage source with a voltage THD of 2.9% and current THD of 2.6%

<table>
<thead>
<tr>
<th>Pout (hp)</th>
<th>Pin (W)</th>
<th>V (V)</th>
<th>I (A)</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
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<td>27</td>
<td>1.8</td>
<td>1673</td>
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<td>56</td>
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<td>135</td>
<td>60</td>
<td>3.1</td>
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<td>175</td>
<td>63</td>
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<td>1704</td>
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<tr>
<td>0.161</td>
<td>212</td>
<td>71</td>
<td>4</td>
<td>1710</td>
</tr>
<tr>
<td>0.195</td>
<td>252</td>
<td>77</td>
<td>4.4</td>
<td>1702</td>
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<tr>
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<td>293</td>
<td>81</td>
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<td>1703</td>
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<tr>
<td>0.266</td>
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<td>5</td>
<td>1709</td>
</tr>
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<td>379</td>
<td>95</td>
<td>5.5</td>
<td>1709</td>
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<td>96</td>
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¾ HP CAPACITOR-START MOTOR

Experiment with voltage controller

<table>
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<tr>
<th>Pout (hp)</th>
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<th>V (V)</th>
<th>V THD (%)</th>
<th>I (A)</th>
<th>I THD (%)</th>
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<tbody>
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<td>2.4</td>
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<tr>
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<td>183</td>
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<tr>
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<tr>
<td>0.6</td>
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<tr>
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Experiment with a sinusoidal variable voltage source with a voltage THD of 2.9 % and current THD of 2.6 %

<table>
<thead>
<tr>
<th>Pout (hp)</th>
<th>Pin (W)</th>
<th>V (V)</th>
<th>I (A)</th>
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<tbody>
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<tr>
<td>0.15</td>
<td>166</td>
<td>48</td>
<td>4.2</td>
</tr>
<tr>
<td>0.225</td>
<td>246</td>
<td>58</td>
<td>5.7</td>
</tr>
<tr>
<td>0.3</td>
<td>323</td>
<td>66</td>
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</tr>
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<td>399</td>
<td>75</td>
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¾ HP CAPACITOR-START CAPACITOR-RUN MOTOR

Experiment with voltage controller

<table>
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<tr>
<th>Pout (hp)</th>
<th>Pin (W)</th>
<th>V (V)</th>
<th>VTHD (%)</th>
<th>I (A)</th>
<th>I THD (%)</th>
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<tbody>
<tr>
<td>0.02</td>
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<td>4.4</td>
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<tr>
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<td>42</td>
<td>5.2</td>
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<tr>
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<td>93</td>
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Experiment with a sinusoidal variable voltage source with a voltage THD of 2.9 % and current THD of 2.6 %

<table>
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<th>Pout (hp)</th>
<th>Pin (W)</th>
<th>V (V)</th>
<th>I (A)</th>
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REFERENCES


VITA

Graduate College
University of Nevada, Las Vegas

Fatima Bouzidi

Local Address:
721 Fiesta Del Rey Ave
North Las Vegas, NV 89081

Degree:
Engineer Diploma, 1993
Centre Universitaire Amar Telidji, Algeria

Thesis Title: Energy Savings on Single-Phase Induction Motors under Light Load Conditions

Thesis Examination Committee:
Committee Chair, Dr. Yahia Baghzouz, Ph. D.
Committee Member, Dr. Rama Venkat, Ph. D.
Committee Member, Dr. Sahjendra Singh, Ph. D.
Graduate Faculty Representative, Dr. Georg Mauer, Ph. D.