AIR CONDITIONERS PERFORMANCE

USING SOFT STARTER

BY

Abdullah Saeed Al-Amoudi

A Thesis Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

Electrical Engineering

Jun 28, 2003

UMI Number: 1416274

UMI®

UMI Microform 1416274
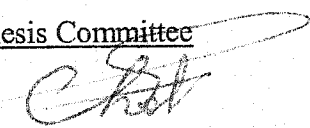
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DAHARAN, 31261   SAUDIA ARABIA

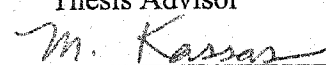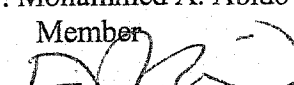## COLLEGE OF GRADUATE STUDIES

This thesis written by Abdullah S. Al-Amoudi under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN ELECTRICAL ENGINEERING.

Thesis Committee

_____

Dr. Chokri Belhaj Ahmed
Thesis Advisor

_____
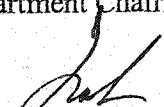
Dr. Mahmood Kassas
Member

_____

Dr. Mohammed A. Abido
Member

_____

Dr. Ibrahim M. El-Amin
Member

_____

Dr. Ibrahim O. Habiballah
Member

_____

Dr. Jamil M. Bakhashwain
Department Chairman

_____

Dr. Osama A. Al-jannadi
Dean, of Graduate Studies

2/7/2003

Date

إهداء

﴿ قل إن صلاتي ونسكي ومحياي ومماتي لله رب العالمين ﴾

أهدي هذا العمل المتواضع إلي والداي العزيزين وزوجتي الغالية
وإبنتاى شفاء وريم وأخوتي الأعزاء

Dedicated to

My Parents

My wife

My daughters Shefa & Reem

And my brothers

Acknowledgement

Contents

LIST OF FIGURES

LIST OF TABLES

THESIS ABSTRACT

Name of student : Abdullah Saeed Al-Amoudi
Title of Study : Air Conditioners and soft starter Performance
Major Field : Electrical Engineering
Date of Degree : January 2003

In almost all over the kingdom of Saudi Arabia, the hot and humid environment persists using air conditioners from four to six months annually. And the Air Conditioner (AC) could represent 80% of the residential electrical load. The AC compressor is switching ON and OFF several times a day and the compressor start up causes a very high starting inrush current associated with a voltage dip. The objective of this thesis is to study the starting performance of the compressor induction motor and to design a soft starting scheme in order to reduce the inrush current and consequently improving the voltage dip. A soft starter circuit was designed to be integrated with the induction motor, which drive the compressor. Then two different firing circuits were designed and implemented for the soft starter. An experimental investigation was then conducted to validate the relevant simulation results.

The analysis of the simulation and the experimental investigation show a reduction of 30% of the inrush current and 20% improvement in the voltage dip at the compressor start up when the suggested designed model was used without compromising the starting torque pulsation. The presented soft starter would be cost effective and could easily be contained within the residential air conditioner unit frame.

بسم الله الرحمن الرحيم

خلاصة البحث

اسم الطالب	:	عبد الله سعيد العمودي
عنوان البحث	:	مكيفات الهواء وأداء مخفض التيار البدائي لها
التخصص	:	الهندسة الكهربائيه

نظراً لأن الجو الحار والرطب معاً يسود علي معظم مناطق المملكة العربية السعودية وبعض الدول المجاورة فإنه يتحتم علي المقيم في هذه المناطق استخدام مكيفات الهواء من أربعة إلي ستة اشهر في السنة تقريباً. وتشكل المكيفات ما يقارب 80% من إجمالي الطاقة المستخدمة في المنازل. وبما أن ضواغط المكيفات تعمل باستخدام المحركات الحثيه التي تعمل وتتوقف عدة مرات في اليوم وذلك حسب الطلب فأن عمل الظاغط يتسبب في تيار بدئي عالي ويتزامن معه انخفاض في الجهد.

وهذا البحث يهدف إلي دراسة الأداء اللحظي لظاغط المكيف وتصميم نموذج يساعد في خفيض التيار اللحظي وبالتالي يحسن انخفاض الهبوط الذي يحدث في الجهد.

في هذا البحث تم تصميم دائرة التشغيل التدريجي وهو ما يسمي بـ (Soft starter) واستخدمت مع نموذج للمحركات الحثية التي تستخدم في تشغيل ظواغط المكيفات. ثم تم تصميم نموذجين يقومان بتشغيل دائرة التشغيل التدريجي. و تطرق البحث إلي تحليل أداء مكيفات الهواء باستخدام وبدون استخدام دائرة التشغيل التدريجي. ثم عملت بعض التجارب العملية التي تدعم النتائج المشتقة من البحث نسبياً.

وقد أظهرت التحليلات النظرية والعملية انه باستخدام النماذج المقترحة نصل إلي خفض في التيار اللحظي بمقدار 30% وإلي تحسن في انخفاظ الجهد بمقدار 20% بدون أي تأثير علي تذبذب العزم. علماً بأن النموذج المقترح من السهل تطبيقه في المكيفات المنزلية وذلك بسبب سهولة تصنيعه وقلة تكلفته.

CHAPTER 1

1.   INTRODUCTION

1.1   GENERAL

In almost all over the kingdom of Saudi Arabia and other neighboring countries, the hot and humid climate persists which necessitates the use of air conditioners from four to six months annually and the Air Conditioner (AC) could represent 80% of the residential electrical load. The major load of the Air Conditioners is the compressor which is mainly driven by a squirrel cage induction motor. Moreover, in addition to the existence of these motor in the air conditioners it also represents more than 60% of the worldwide industrial electrical motor load [1]. Because of the huge existence of such a high load, especially in the industrial countries with hot and humid weather and lately, due to new energy policies, almost all motor manufacturers implement ways to increase the energy efficiency of motors by reducing the induction motor copper losses and also by using improved core material to reduce the motor core losses [2]. However, as a result of these energy-efficiency measures there is an increase in the starting current due to reduced resistance in the stator and rotor circuits. In fact, energy-efficient motors may draw almost 50% more inrush current than standard-efficiency motors. Another consequence is the voltage dip phenomenon that is associated the high starting current [2].

The current at the start up of the AC standard motor can reach several times the rated current. Furthermore, the starting torque can increase up to 400% of the rated value. A

voltage dip of 10 to 20% is always experienced. The dip affects the electrical appliances connected to the same supply. In many cases, utilities have to significantly oversize their transformers in order to reduce the voltage dip. This oversizing of transformers defeats the purpose of energy efficiency because transformer losses (No-load losses) increase as the transformer size increases. Therefore, the oversizing of transformers does not result in the optimum utilization of the utility's generated energy.

Actual products, as those described in chapter 2 which are marketed as solutions to the inrush problem are in some cases not cost-effective and may not even be effective in solving the problem mentioned above. There is also no standard that limits the inrush current for appliances and other electrical appliances used in homes [2]. Therefore, the need to address the problem of the high inrush current of residential AC units still persists.

1.2   THE BASIC PRINCIPLES OF AN AIR CONDITIONER

An air conditioner is basically a refrigerator without the insulated box. It uses the evaporation of a refrigerant, like Freon, to provide cooling. Freon is a word which is used for any of the various nonflammable fluorocarbons used as refrigerants and as propellants in aerosols. Figure 1.1 shows the basic principle of an air conditioner. Technically the operation of the Freon evaporation cycle of a refrigerator is similar to that of an air conditioner. Through these steps we shall understand how the evaporation cycle in an air conditioner works.

1. The compressor compresses cool Freon gas, causing it to become hot, high-pressure Freon gas (discharge line).

2. This hot gas runs through a set of coils called condenser coils (heat exchanger) so that it can dissipate its heat, and condense into a liquid (hot liquid).

3. The Freon liquid runs through an expansion valve, and in the process it evaporates to become cold, low-pressure Freon gas.

4. This cold gas runs through a set of coils called evaporator coils (heat exchanger) that allow the gas to absorb heat and cool the air inside the building.

5. Finally the cooled gas, with a low pressure, will go out from the evaporator and is ready to enter the compressor again through the suction line.

Refrigeration Cycle
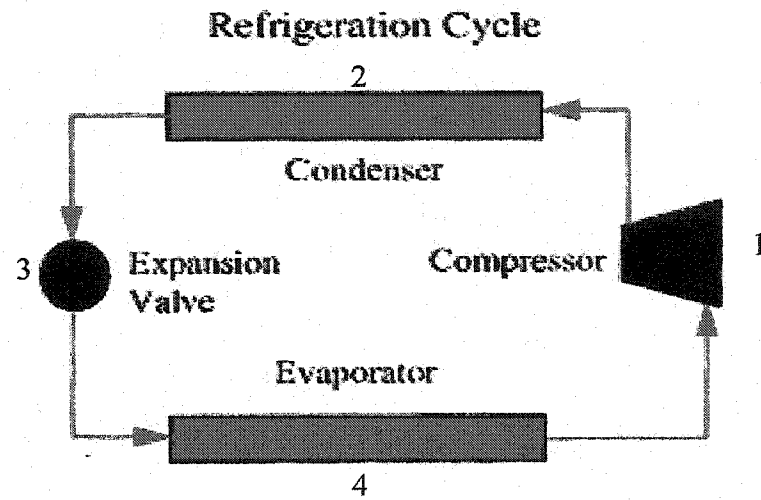
1- Evaporator, 2- Compressor, 3- Condenser, 4- Expansion valve
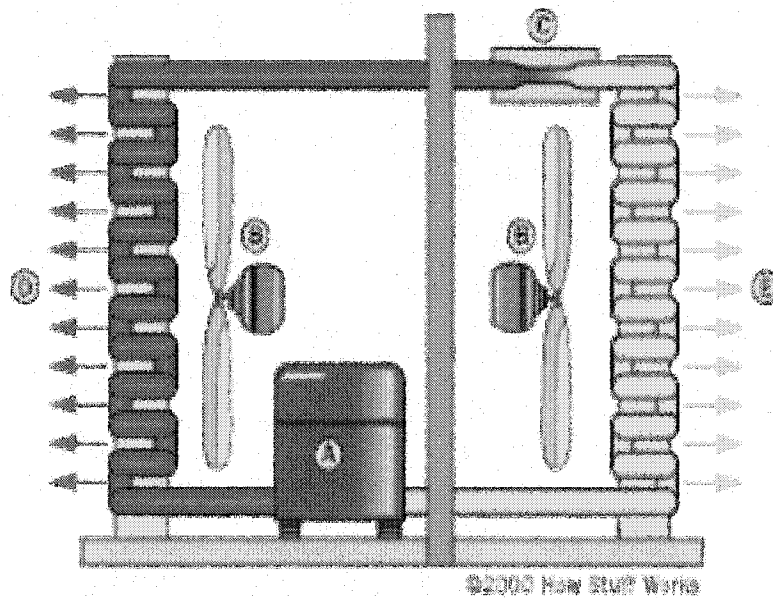
A: compressor B: fans C: Expansion valve D: Hot air to outside E: cool air to inside

Figure 1.1 : Basic Air Conditioner Circuit

1.3 THE ELECTRONIC SOFT STARTER

The purpose of the soft starter is to bring the motor up to running speed at rated voltage with a reduction in the current transient which comes about through connecting a stationary motor directly to a power supply of rated frequency and voltage. The Thyristors method for limiting the inrush currents to the AC motor on startup is of particular interest here. The power supply to the motor is altered so that a lower average voltage appears across the windings of the motor. Due to the fact that the current should flow in both directions through the load (motor winding) the use of a Triac which is similar to two anti-parallel Thyristors is used.

Thyristors passes the current in one direction only. This makes the SCR useful for rectifying an AC signal, but it is of no value if the objective is to vary the AC voltage appearing at some motor windings. So, putting two Thyristors back to back will form a Triac device, as it is clear in figure 1.2. Figure 1.3 shows the main circuit of the soft starter. The voltage waveform resulting from the use of the Triac in an AC circuit is depicted in figure 1.4. The dotted waveform is the unaltered input to the soft starter. At the firing angle the Triac is switched on producing a load voltage, which is illustrated by a continues waveform and is denoted as the soft starter output.
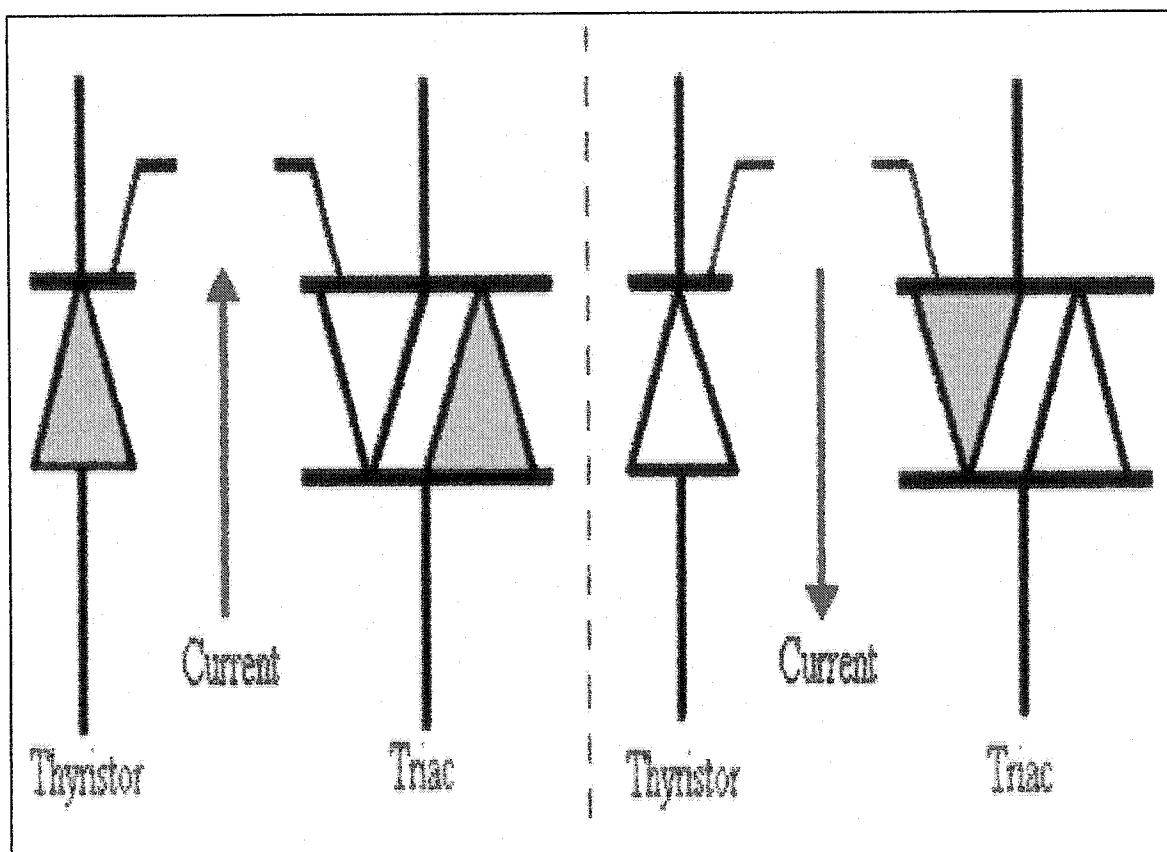
Figure1.2 Thyristors and Triac
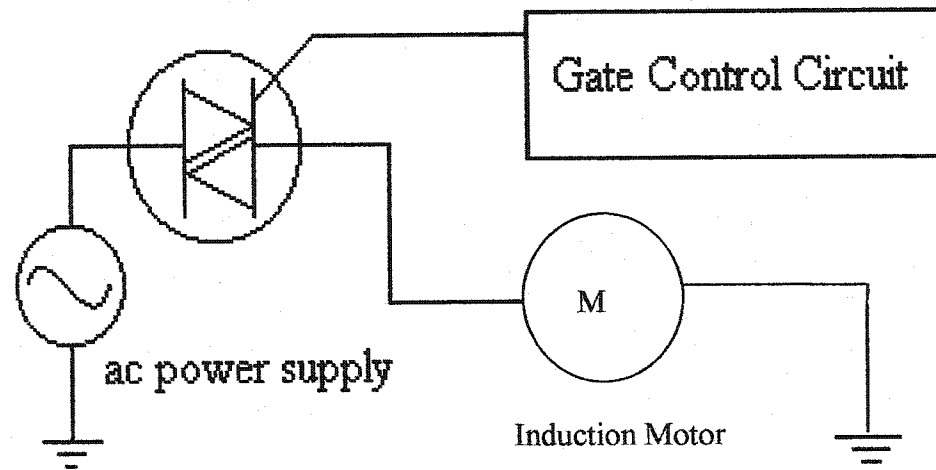
Figure1.3 : Main circuit of the soft starter
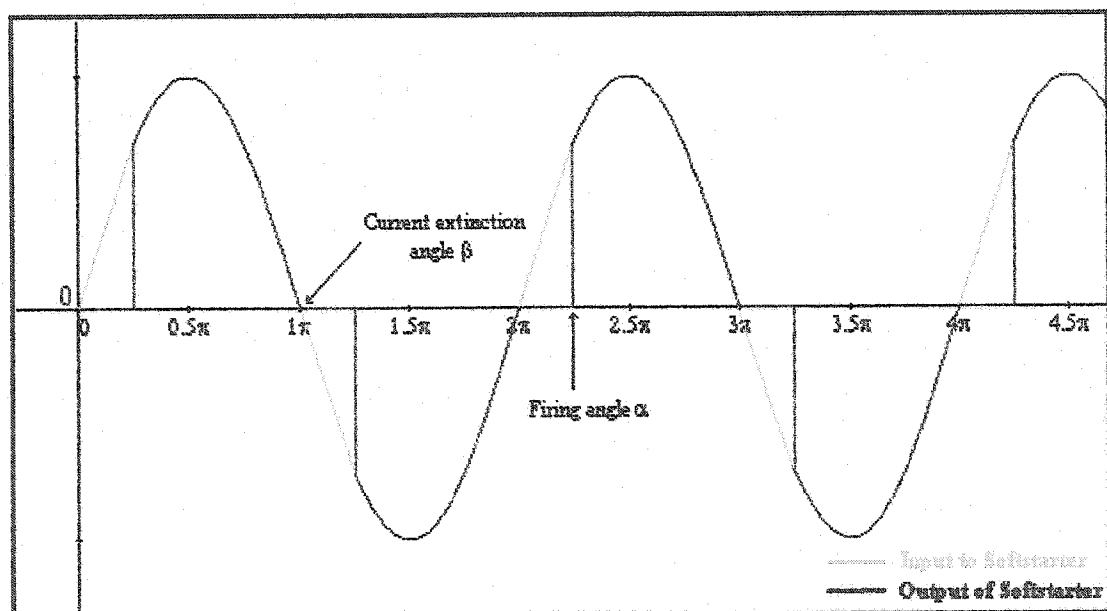
Figure1.4 : Soft starter Waveform

1.4 LITERATURE REVIEW:

An increased number of induction motors are used in the industry and in residential appliances, especially air conditioners which consume about 60% of the power generated in the kingdom of Saudi Arabia and other hot countries. Many utility and industrial firms try to reduce the inrush current effects by oversizing the transformer while in fact we only need to reduce the inrush current [2]. Several studies and techniques were introduced to reduce the inrush current of induction motors.

Blaabjerg, F. Pedersen, J.K. Rise, S. Hansen and H.-H. Trzynadlowski, A.M. [1], raised an important question to researchers and to industry, which stated, " Can soft-starter help save energy?"

They mentioned the advantages and the disadvantages of the more common ways, which are used as an approach to the minimization of energy consumption in their paper entitled, "Can soft-starter help save energy?" Firstly an inverter, which adjusts both the supply frequency and the voltage so that the motor speed can be controlled and the energy usage can be reduced, is employed. However, this method is expensive and it is not worth the cost in some applications. Secondly, the motor can be equipped with a soft starter instead. In that case the supply frequency is fixed and the stator voltage is controlled, in dependence of the load, to limit the starting current and to reduce motor losses. Then they described the experimental result of evaluating seven commercial soft starters used with three motors of different ratings. Finally they came to the following conclusions:

First, a Soft-Starter reduces the stator current and the developed torque at the start up, allowing a reduction in the power rating of the supply system and increasing the life

expectancy of the drive. The lifespan of the systems with frequent start-ups (like air conditioners) will increase because the torque oscillations are significantly dampened and mechanical stress is alleviated. Secondly, the dip in the motor speed due to the soft-starters is not significant. Thirdly, energy savings achieved by soft-starters are small and the simple payback period is long. Therefore, the discussion on the use of soft starters should not be based on the anticipated energy cost saving alone. Fourth, Soft-starters distort currents drawn from the utility grid, the fifth harmonic being particularly pronounced at about 20% higher, which may cause conflict with stringent power quality standards. Finally, they said that the energy saving properties of soft-starters may adversely affect the stability of certain drive systems due to the reduction of the developed torque.

A.J.J. Rezek and C.A.D Coelho conducted a study on the energy conserved with the use of the soft starter [3]. The authors mentioned that the soft starter is aimed at reducing the voltage to the motor at its start and the reduction of the voltage when the motor is at low load. In this case the iron losses are reduced and energy conservation is achieved. They measured the active power consumed by the motor at full voltage applied to the motor, and they compared it with the required power when the reduced voltage is applied to the motor when using the soft starter. In this case they evaluated the energy conservation. The same value of the reduced voltage when the soft start is being used was applied to the motor when using an autotransformer. The power was measured for comparison with the required power when the soft start had been used.

As a result, iron losses are then reduced and an energy saving is achieved. The use of an autotransformer instead of a soft starter has enabled a high energy saving. This is due to the additional losses attributed to the harmonic currents in the soft starter.

Energy savings have been achieved until a load torque at about 42% of the rated torque. With the higher torque no energy conservation was achieved. Moreover, when the autotransformer was used the power factor and efficiency were better than in other instances.

In 1997, Robbie McElveen and Mike Tony reviewed the common methods which are used to start the AC induction motors, including across-the-line starting and reduced voltage starting by autotransformers, wye-delta, or resistor reactor starting [4]. They stated the benefits and limitations of each method they had examined, concentrating on the effect of the high inertia loads on both the acceleration time and motor heating. Moreover, they presented a case history of starting a centrifuge with an electronic soft starter. Finally they made the recommendation, taking into consideration the four important factors which are purchasing price (40%), motor heating (35%), adjustable acceleration (15%) and physical size (5%) as table 3.1 indicates. A 1 is given to the method considered being the best option in a given category and a 5 is given to the least desirable.

Table 1. 1 : Comparison of different motor starting methods

Starting Method	Purchasing Price (40%)	Motor Heating (35%)	Adjustable Acceleration (15%)	Physical Size (5%)	Weight Average
Full Voltage	1	5	5	1	2.95
Auto-Transformers	3	4	5	3	3.5
Wye-Delta	2	4	5	3	3.1
Resistor-Reactor	3	5	5	3	3.85
Soft-Starter	3	3	1	4	2.6
Inverter	5	1	2	5	2.9

In 1991, Mohamed Akherraz presented a linear sub-optimal control technique applied to a voltage source induction motor [5]. The main function of that controller was to counteract external disturbances and to reduce the magnitude of the inrush current during frequency and voltage perturbation and load fluctuation. The input of the controller is directly related to measurable variables such as current and speed. The output of the controller are can be implemented as variables such as the power converter's voltage and frequency. The simulation result of the dynamic model showed that the proposed controller reduced the inrush current to 1.3 Pu of the rated value of the stator current. Moreover, it dampened out any undesirable transient oscillation and reduced speed variation to less than 0.1%.

In 1999 Walter J Lukitsch, reviewed the basic operation principles of soft starters and AC variable frequency drives (VFD) [6]. A study was conducted on the motor's performance using both operational principles. The factors that affect the motor's performance were compared in order to provide insight into the proper selection of either soft starters or VFD's. This study concluded that the soft starter can be used in all applications except the following:

- When the speed of the motor needs to be varied. The soft starter applies only to line frequency so the motor will operate at one speed while the inverter can vary the speed because it can vary the output frequency.

- When there is a need for speed adjustment for various loads.

- In a situation where the acceleration and stopping times are critical. This is because the acceleration times for soft starter will vary from the selected ramp time due to motor loading.

- When there are restrictions on the quantity of the current that can be drawn from the power line and the load requires higher torque than it available with the soft starter.

In 1997, M. Rajendra Prasad and V. V. Sastry defined an optimal soft starting device as one that starts the motor with a minimum allowable voltage and reduces starting current limit [7]. Starting current limit is different for motors of different ratings and also different for the same motor but under different initial load conditions. Moreover, they introduced a new fuzzy logic, which is adapted with a triangular membership function with a finite overlap between two membership grades to achieve the adaptive parameter setting

capability. It featured an automatic setting of current limit and the optimum result was achieved by performing the task with appropriate settings for a maximum firing angle. In addition, the new system will take care of the starting current of different motors with different ratings and for the same motor with different load conditions.

The algorithm involved in the earlier developed soft-starter schemes involved a gradual increase of voltage across the motor until the rated voltage appeared across the motor at the end of the soft starting method. It was observed that the efficiency and power factor were poor in this kind of soft starting under no load and high load conditions.

In 2000, David Gritter and G. Thomas presented a simulation of a Thyristor based reduced voltage starter operation inside a delta connected induction motor [8]. The behavior of the reduced voltage starter was shown to be different, when the Triac operated inside the delta, than when it was operated directly in the AC lines. They also presented a simulation of conventional control strategies based on the delay of firing from voltage zero crossing and delay of firing from current zero crossing. In addition to that, the control problem was described. In addition a control strategy, based on the combination of these two presented methods, was discussed with a simplified current limit control algorithm. The specific soft starter, which was designed, had to meet two major requirements and they were:

- ❑ Reduce motor torque pulsation at start up. Small torque pulsation translates to less mechanical strain on the applications.

- ❑ Reduce motor inrush current at start up. Small inrush current places less stress on the upstream electrical systems.

Finally, they concluded that the behavior of reduced voltage starter was shown to be different when operated inside the delta than when operated in the AC lines.

J.B Woudstra and W. Deleroi introduced an improved soft starter with Thyristors chopper [9]. Different time varying functions for the firing angles had been developed to speed up the induction motor with a chosen constant torque without current and torque peaks. The firing angle function influences the building up of the main flux, in order to avoid the normal transient problems. Moreover, they provided the transients based on the analytical solution of the machine differential equation of all modes of operation. They came to the following conclusions:

□ Soft starter starting an induction motor, without the transient problems associated with high current and pulsating torque, was achieved with a Thyristors chopper.

□ By using different time functions for the firing angle of the Thyristors chopper, it was possible to speed up an induction motor with a chosen constant torque.

□ The initial value of the firing angle ($110°$-$120°$) ensured that the first current peak did not exceed the rated value and the final value of the firing angle, from the first function, will set the starting torque on the desired value. By keeping this firing angle constant for a while, the motor speeded up with the chosen constant torque.

S Bolognani, M Zigliotto and K. Unterkofler presented a soft starter technique for capacitor-run, single phase induction motors to improve the starting transient in order to limit the inrush current within the allowed maximum for household appliances [10]. They

used a Triac system on both main and auxiliary windings with two different firing angles $\alpha 1$ and $\alpha 2$ respectively. They conducted different analyses by changing the value of the firing angles and they concluded that:

- Higher value of α (($\alpha 1 = \alpha 1 = \alpha$) further improved the starting transient if the torque was taken into account. However, the higher value of α will lead to considerably higher auxiliary current during the starting.

- The improved starting transient can also achieved by connecting the main phase to the power supply at $\alpha 1 = \pi/2$ and delay the insertion of the auxiliary phase until the main voltage passed zero ($\alpha 2 = 0$ or π).

- The improved starting transient also, can be achieved if ($\alpha 1 = \alpha 1 = \alpha = \pi/2$) provided that the capacitor was pre-charged to $V_c = 220 * \sqrt{2}$ V to improve the impedance of the auxiliary winding. This is justified considering that at standstill and with the parameter of the motor the impedance of the auxiliary phase is small compared with the impedance of the capacitor.

In 1997, Sastry V.V , Prasad M. R. and Sivakumar, T.V. presented a method of identifying the end of soft starting of an AC voltage controller feeding induction motor drive based on the voltage across the non-conducting Thyristor through a dynamic simulation of the whole system [11]. They also introduced a new technique which will select the value of the firing angle which will give the optimum current. Their contribution to optimal soft starting techniques can be summarized as follows: during soft starting the thyristor is initially fired at an α equal to α_{max}. When the motor was at a standstill, the voltage across the non-conducting Thyristors was measured and stored as

VREF, then α is decreased by 0.50^O/Cycle (ALPSTP1) until α reaches $\alpha_{max} - 4^O$. This ensured an initial rise in motor current. The fundamental component of the line current drawn was rectified and sampled once every 30ms. If the current was less than the current limit (CURLIM) for a given motor, then α decreased by 0.10^O/Cycle (ALPSTP2) until the identification of the end of soft starting. If the current exceeded the current limit then α will not be decreased until the motor accelerated or the current limit was not seen. The falling of the voltage across the non-conducting thyristor by about75% of the value when the motor was at standstill identified the end of soft starting. In addition to that they supported the dynamic simulation result of the whole drive system with experimental data.

In 2000, Mr. John A. Kay, Mr. Richard H. Paes, Mr. Seggewiss J.G. and Ellis R. G. introduced considerations and guidelines for different methods of controlling large Medium-Voltage Motors because an appropriate motor and controller were becoming increasingly critical as industries and utilities attempted to maximize their distribution systems capabilities [12]. Starting and controlling large medium voltage motor required the consideration of the following points.

- The characteristic of the power source and the effects the motor starting currents will have on the source line and the stability of the system voltage

- The source line and the stability of the system voltage.

- The starting and breakdown torque characteristics of the motor.

- The load torque characteristics including breakaway torque, accelerating torque and load torque at different speeds.

❑   The operating speed range of the connected load.

❑   Process consideration, shock and vibration and mechanical hammer.

❑   The control and maintenance of different starting methods.

The technical Manual of the REO (UK) LTD summarized the different starting techniques as follows [13]:

When direct on-line starting is used with the standard AC motor, the current at the start up can be 8 times that of the rated motor current. Furthermore, the starting torque can be increased by up to 400%. This means that any machine drive component has to be much stronger than usual. Reduced voltage methods of starting, such as star/delta or autotransformer, do reduce the start up current, but severe shock loads are still imposed at the switching moment, leading to increased maintenance. And because the initial starting torque is lower, starting under load can be a problem in the worst case the motor must be over rated.

The generation of an adjustable voltage ramp provides a smooth start-up, and at the same time limits the inrush current is. So, the motor and mechanical drive components are protected by step less adjustment of the torque.

1.5 PROBLEM DESCRIPTION

As mentioned before electric motors are predominantly the three phase, squirrel cage type. They consume about 60% of the electrical energy generated in industrialized countries. In Saudi Arabia, the air conditioner load, which is mainly high torque induction motors, consume about 60% of the electrical energy generated in Saudi Arabia.

Because of this, almost all motor manufacturers are looking at ways to increase energy efficiency in motors by reducing the copper losses and by using improved core material to reduce the core losses. However, the result of these energy-efficiency measures is that an increase in the starting current because of reduced resistance in the stator and rotor circuits of the motor. Energy-efficient motors may in fact draw almost 50% more inrush current than standard-efficiency motors [14]. When these motors are served from the typical residential distribution circuit, the voltage dip during motor starting can cause undesirable side affects, from the dimming of lights to the shutdown of sensitive equipment. In many cases utilities have to significantly oversize their transformers to reduce the voltage dip. This over sizing of transformers defeats the purpose of energy efficiency because transformer losses increase as the transformer size increases. The starting of an air conditioner compressor is a very frequent event during all hours of the day and night. Therefore, over-sizing the transformers does not result in optimum utilization of a utility. Current products such as that which will be described in chapter 2 which are marketed as solutions to the inrush problem are, in some cases, not cost-effective and may not even be effective in solving the problem at all. There is also no standard that limits the inrush current for appliances and other electrical equipment used

in residences [14]. Therefore, the need to address the inrush current of residential Heat and Ventilation of Air Conditioners (HVAC) units persists.

1.6 THE SCOPE OF THE RESEARCH:

This study is intended to meet the following objectives:

1. A compressor Performance Study of air conditioners with and without a soft starter.

2. The design of a soft starting scheme to reduce the inrush current and consequently reduce the voltage dip.

The work is to be conducted over the following three overlapping phases:

1. Designing different firing angle schemes,

2. Integrating the firing angle scheme with the soft starter circuit and conducting the simulation using MATLAB Power system block sets,

3. Experimental setup preparation,

4. Experimental measurement and implementation in a typical window type air conditioner widely used in the kingdom of Saudi Arabia,

5. The comparison and analysis of the designed scheme and

6. Conclusion, observation and recommendations

CHAPTER 2

2. OVERVIEW OF THE DIFFERENT STARTING TECHNIQUES OF INDUCTION MOTORS

2.1 GENERAL

When the supply is connected directly to a stationary motor the resulting starting current surge is very high, and should the supply cables be very long or of insufficient section, there is often a severe sudden voltage dip at the motor and at any other electrical equipment connected to the same supply.

To overcome this problem some supply authorities will not allow induction motors above a specified power rating to be started by "direct on-line" (DOL) devices. Others will insist that starting surges be limited to a proportion of the motors full load current. Squirrel cage motors are the only types which are allowed with DOL starters.

The starting characteristics of standard squirrel cage motors are well understood and are virtually the same irrespective of the manufacturer.

Access to the stator winding is only possible at the motor terminal block and therefore, the only practical method of controlling the starting current surge is to control the supply voltage. The effect of doing this will also be limiting the starting torque.

2.2   DIRECT ON-LINE STARTING (DOL):

With this type of starter, the stator windings are connected straight across the mains of the 3-phase supply. The motor will start and accelerate, following its standard characteristic. At the instant of switching the motor will act like a low- resistance transformer, whose secondary winding (effective the rotor cage) is short-circuited. The primary and secondary currents being proportional, the motor will draw more current from the supply:

Peak I (Current) = 5 to 8 times nominal current.

Peak T (Torque) = 0.5 to 1.5 times nominal torque.

Despite many advantages associated with DOL starters (Simple, Low cost, High Starting torque, fast run up), their use will thus be confined to applications where:

- ❑ Low power motors are being used and where the supply capacity is high, thus limiting the local effect of the starting current surge.

- ❑ The machine being controlled is fitted with a gearbox or some other mechanical device which will soften the effects of the starting torque.

- ❑ A very high starting torque is required by the application.

- ❑ The peak starting current could cause a serious voltage dip which could create a problem for other electrical equipment connected to the same supply line.

- ❑ The machine being driven may not be able to accept very high peak torque loading.

Figure 2.1 will show more details of the DOL Speed/current characteristic. So, it becomes necessary to use alternative ways of starting the motor in order to reduce the peak starting current and thus the peak starting torque of any given installation. This is normally done

by forcing a motor to be started at a reduced voltage. However, a variation in the voltage at the motor will have the following effects [15]:

- The change in the voltage supplied to the motor will cause a proportional change in the starting current.

- The change in the voltage supplied to the motor will cause a change in the starting torque, which is proportional to the square in the change of the supply.
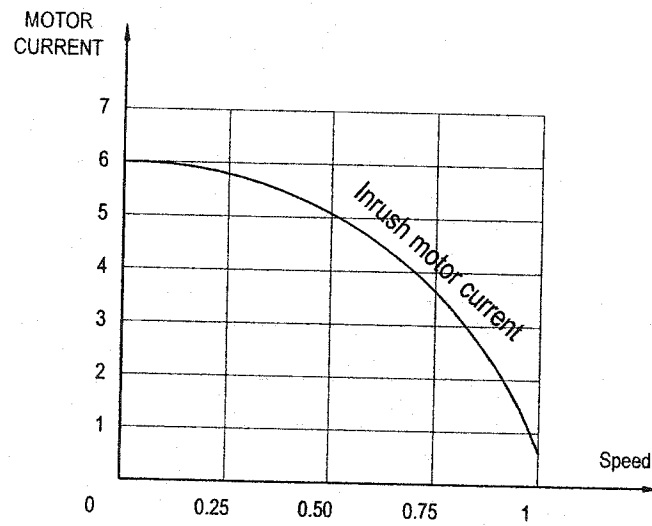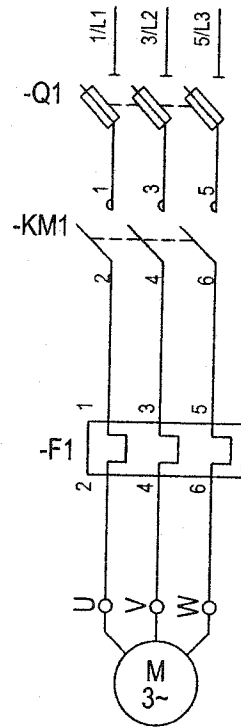
Figure 2.1: Direct On Line Starting

2.3 STAR-DELTA STARTING

This type of starter may only be used where access is possible to both ends of each of 3-stator windings. In addition, the winding must be rated for the supply voltage when connected in delta. For example, where a 3- phase 415V supply is to be used the winding must be suitable for 240V in Star / 415 in Delta.

Therefore, the principle of this type of starter is that at the start-up the motor windings are connected in star (by using a suitable contactor). Now despite the fact that the supply voltage is 415V, each winding will be fed with 240V (the supply voltage divided by 1.73, which is approximately about 58 % of the supply voltage. This is due to the fact that the motor is coupled in star. The effect of this is to reduce the starting torque by a factor of three. This reduction in torque is due to the combined effects of the reduction in both voltage and current.

Star-Delta Starter is typical 1.5 to 2.6 for the peak current and from 0.2 to 0.5 for the peak torque. As the torque accelerates its speed will stabilize when its developed torque becomes equal to its load torque, and this usually happens at about 75% -85% of its nominal speed. The starter will then disengage the star contactor and engage the delta contactor to connect the motor into Delta. Each winding will now be fed with the full load supply voltage and the motor will adopt its normal running characteristic.

The run up time in star is controlled by a timer, which may be adjusted between 0 to 30 seconds to give the optimum period in star.

In addition, the transition time from star to delta is also important and a special timer is incorporated to ensure a period of 30 - 50 milliseconds between the opening of star

contactor and the closing of the Delta contactor. This will allow any arcs to be extinguished during the transition switching.

Star-Delta starters are specifically suited to machines which do not present a high load torque at start up or which normally start off load. The relatively high peak current during the start to Delta transition, which is characteristic of the starters, means that where large motors above a certain rating are to be used, some form of current limiting techniques may be necessary.

It is necessary to have a time delay of 1 to 2 seconds during the star to delta transition. This will effectively reduce the level of peak transient current. It should be noted that this solution may only be applied to low inertia loads, to avoid a too large dip in speed during the transition from three stages starting to Star-delta to resistance stage in star. In this case the transient peak of the current still exists but the resistance being left in the circuit limits its value for about 3 seconds after the star to delta transition.

The resistance bank is put into the circuit just before the star contactor opens. In this way the motor current is never actually broken and so the transient peak is eliminated. The adoption of the above technique will obviously result in a need for more components for a given starter and the cost could increase quite considerably [15].
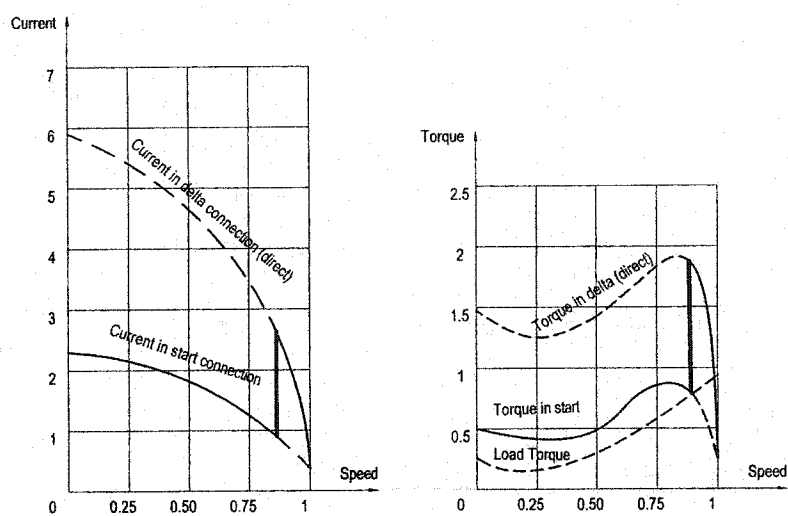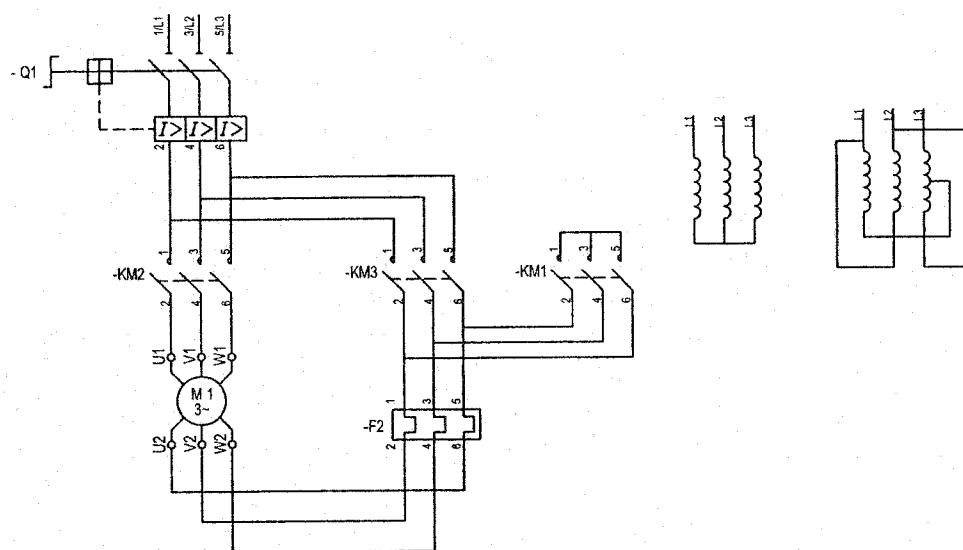
Figure 2.2 : Star-Delta Starting

2.4   THE STARTING MOTOR WITH PART-WINDING

This type of motor has stator windings, which are divided into ends which are all accessible through six or twelve separator terminals. A motor of this type is equivalent to two and a half motors of equal power rating. To start the motor one set of windings is connected to the full supply voltage but since this is equivalent to a half-motor the starting current and hence the starting torque are effectively halved. Despite this effect, the starting torque is still higher than that of an equivalent squirrel cage motor being controlled by a star-delta starter. At the end of the run-up period a second contactor switches in the other winding and the motor is never actually disconnected from the supply (unlike star-delta) so the transition peak current is low and is of a very short duration [15].
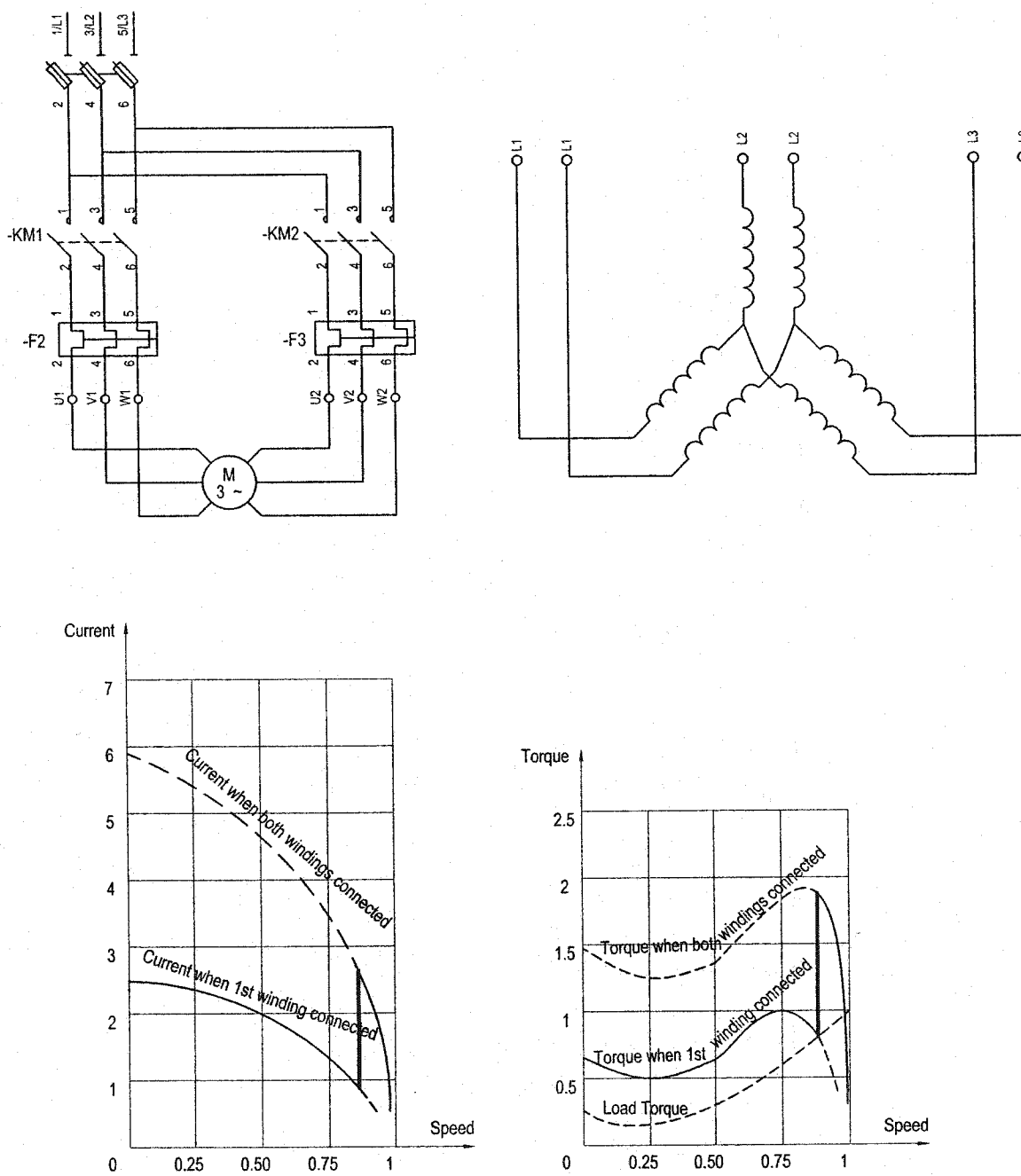
Figure 2.3 : Starting of motor with Part-winding

2.5 PRIMARY RESISTANCE STARTER

The principle used here is to start the motor at a reduced voltage by connecting a resistance bank in series with the motor windings. Once the motor has run-up to and stabilized its speed the resistance bank is shunted and the motor becomes directly connected to the full supply voltage. An adjustable timer incorporated into the starter normally controls this changeover. This technique does not require the motor winding to be connected in different ways, so access is not required to both ends of each stator winding. The values of the resistors are calculated depending upon the maximum peak starting current allowed or the minimum starting torque required by the load. In general, peak values of current (Ip) and peak values of torque (Tp) for a typical starter would be 4.5In and the torque will be 0.75Tn. Where In and Tn are the nominal current and nominal torque respectively.

Once the motor has started to turn the voltage applied to it will change. This voltage at the motor is in fact the supply voltage less the dip across the resistance bank, which in itself is changing since it is proportional to the current flowing through it. As the motor accelerates, the current reduces, as does the voltage dip across the resistor. This means that the voltage at the motor increases proportionally. The voltage at the motor is thus at a minimum at the start and increases progressively during the motor run-up. The motor torque is proportional to the square of the motor current, so it will increase more rapidly than with a star-delta starter, where the starting voltage stays the same throughout the star period. This type of starter is especially suitable for applications where the load torque increases with speed. One disadvantage is the high peak current at the moment of starting but increasing the resistor values can minimize the effects of this. Care must be taken

however, since a reduction in current could diminish the starting torque quite dramatically. When the resistance bank is finally shunted at the end of the start sequence this transition is closed so the motor is never disconnected from the supply and therefore, does not invoke a peak transition current [15].
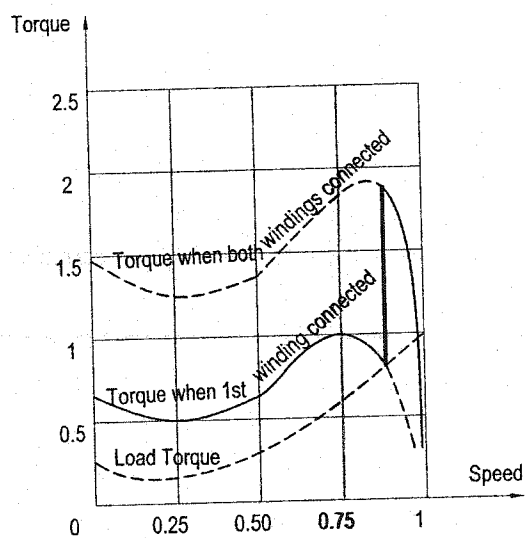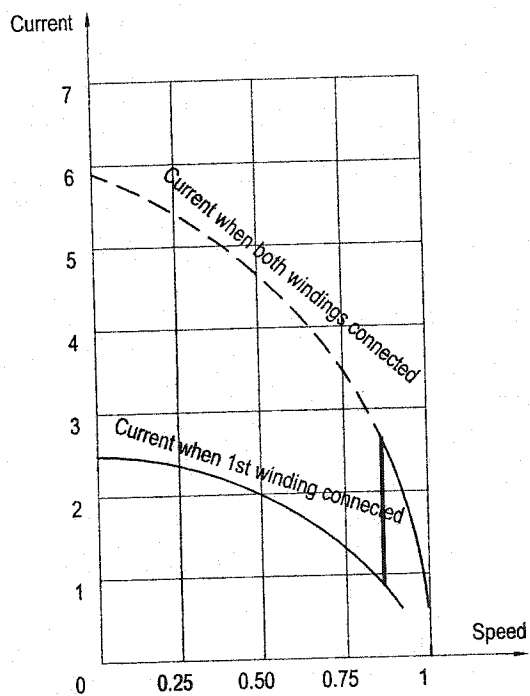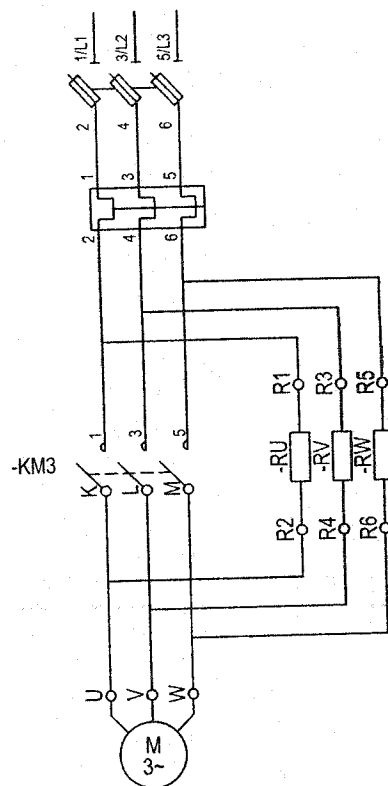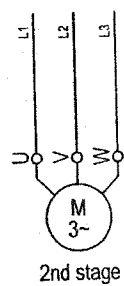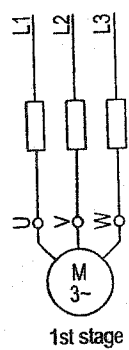
Figure 2.4 : Primary Resistance Starter

2.6 AUTOTRANSFORMER STARTERS

The principle used here is to start the motor at the reduced voltage by connecting a suitable autotransformer into the motor circuit. The starting sequence has three stages:

- During the first stage the autotransformer is coupled in star and the line contactor is closed. This then starts the motor at the reduced voltage, which depends upon the transformer ratio selected. Autotransformers usually incorporate tapings at various points along their windings so that the correct ratio can be selected, depending upon the needs of the application.

- During the second stage the star connection is opened so that a section of the autotransformer winding becomes simply an inductor, connected in series with the motor. This transition is normally timed to occur when the motor speed has stabilized at the end of the run up.

- The third stage follows almost immediately (within a fraction of a second) and entails shunting the autotransformer out of circuit all together so that the motor is now connected directly to the supply.

The peak starting current and torque are reduced as a function of a reduced starting and run up voltage (U supply / U starting) and usually, the values are 1.4 to 4 In and 0.5 to 0.85 Tn. When the autotransformer is finally shunted at the end of the start sequence this transition is closed so the motor is never disconnected from the supply and therefore, does not invoke a peak transition current due to open circuiting of the motor. A peak current could occur at this stage when the motor is switched directly to the supply if certain precautions are not taken. In fact, the inductance of the autotransformer winding is very high compared to that of the motor. As a result, when the start coupling is opened the

subsequent volt dip causes a high peak transient current when the motor is connected directly to the supply. The autotransformer is normally fitted with suitable magnetic components, which reduce its overall inductance to a point where a volt-dip is inhibited at the moment of switchover. The addition of these components however, leads to the autotransformer having a slightly higher magnetizing current, which increases the peak current at the start of the first stage. This method of starting is used in high power motors greater than 100 kW but it tends to be an expensive solution, mainly due to the cost of the autotransformer itself [15].
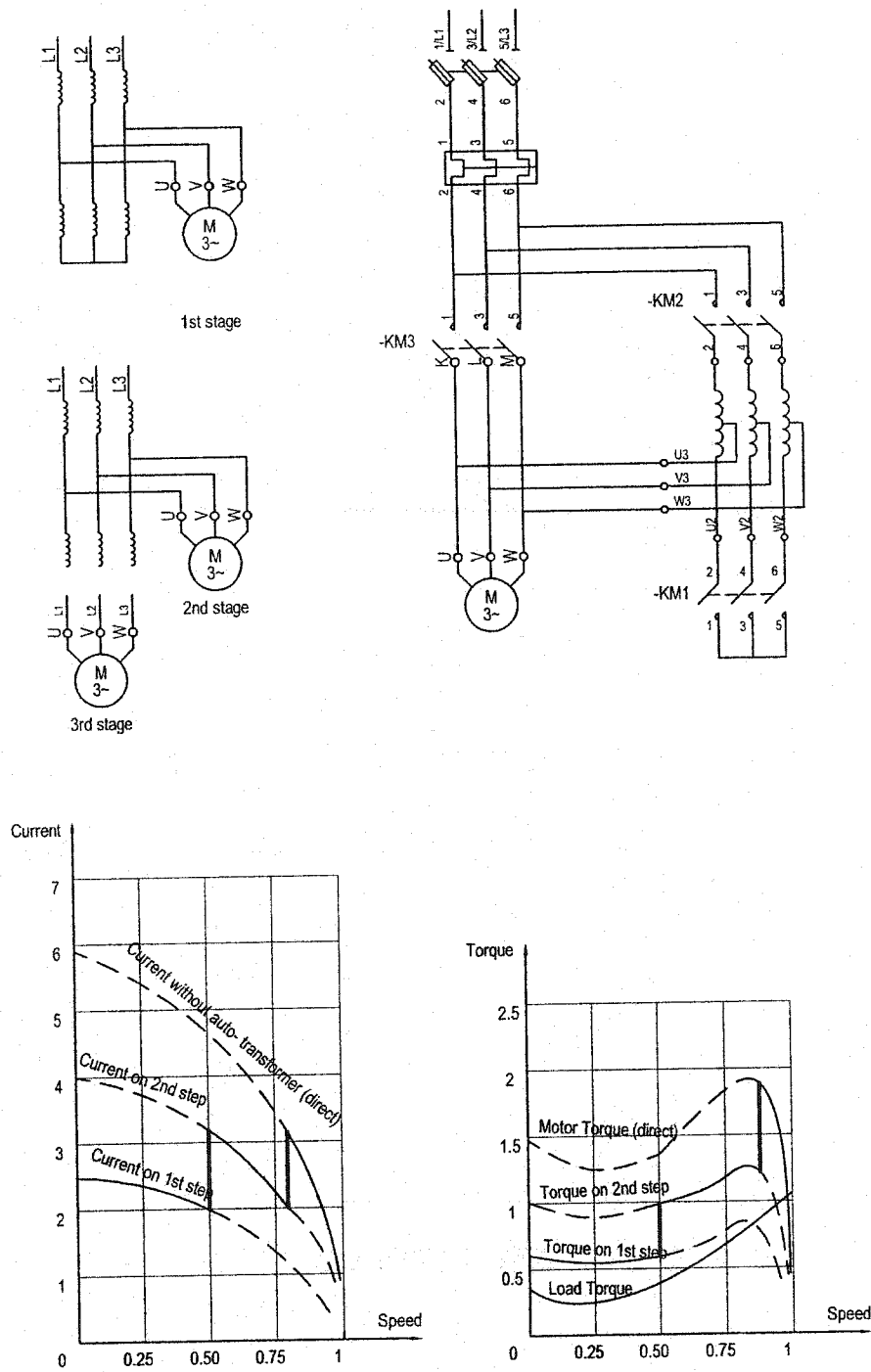
Figure 2.5 : Autotransformers Starter

2.7 ROTOR RESISTANCE STARTER

A slip-ring motor cannot be started using a DOL single phase stage starter due to its inherent starting characteristics. The peak starting current would be too high at the moment of energisation. The principle adopted therefore, is to start the motor at a reduced voltage by connecting a resistance bank in series with the rotor winding.

The starter is designed so that at start up there is maximum resistance in the circuit and the various sections of the resistance bank are then shunted out progressively until no resistance remains and the rotor windings are simply connected in star. Adjustable timers incorporated into the starter normally control the points at which the resistors are shunted-out. For this type of motor, the torque of 2 Tn, the current is approximately 2 In. Where In and Tn are the nominal current and nominal torque respectively.

It can be seen that this torque to current relationship is considerably better than for a DOL starter, using a squirrel cage motor, where 1.5Tn needs typically 6In. Slip-Ring motors with rotor resistance starters are therefore ideal for high-inertia loads which need to be started on-load but where the peak current needs to be limited [15].
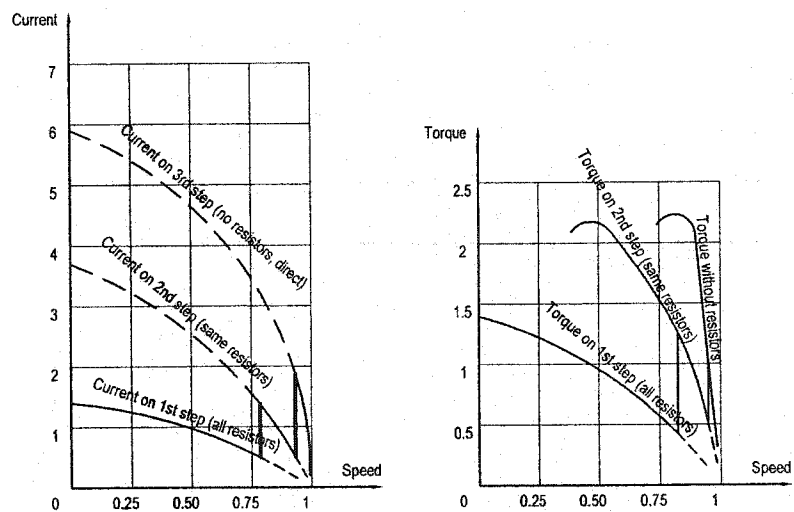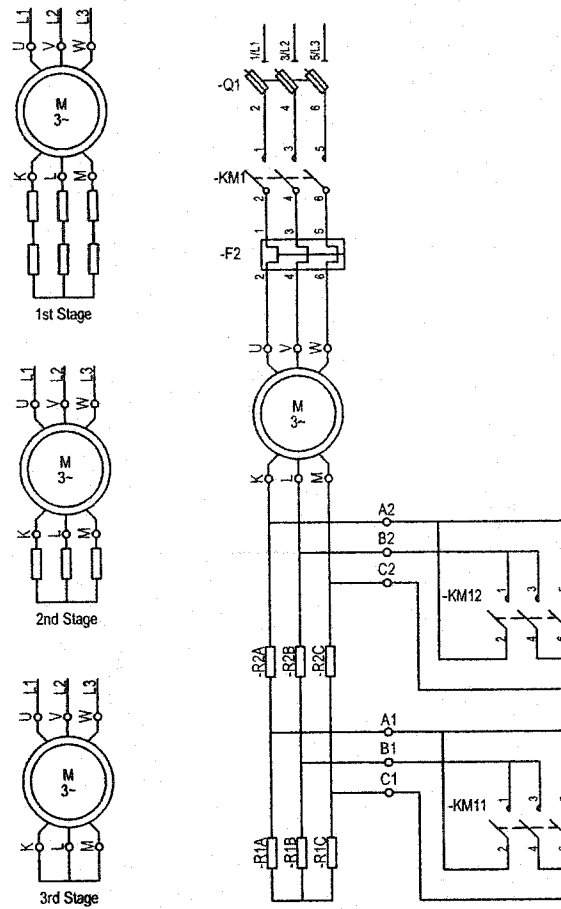
Figure 2.6 : Rotor resistance starter for 3-Phase Slip Ring motors

2.8   ELECTRONIC SOFT STARTERS

The principle used here is to start the motor by increasing its voltage gradually, so as to cause a smooth, steady speed. This technique eliminates sudden changes in voltage which could lead to peak starting current and torque.

This is achieved by using a Thyristors bridge (Triac) which has two Thyristors mounted back to back in each phase. By varying the firing angle of each set of the Thyristors, it is possible to control the starting voltage and thus the starting current and keeping the frequency constant. The supply voltage is normally increased gradually to follow an acceleration ramp period so as to maintain the starting current at a predetermined limit. Conversely, a combination of these two criteria (current and ramp period) could be used to calculate the optimum acceleration rate.

This type of starter may be used with any asynchronous motor and it is usually bypassed by contactors at the end of the acceleration ramp to eliminate any full running, Thyristors heat losses.

Current

7

6   Td

5   Tc

4   1

3   2

2

1

0   0.25   0.50   0.75   1   Speed

2: ATS current
torque at 3 in

Torque

2.5

2

TD   Tdc
        Tde

TN   Tc
                2
TA   Ta   3

0   0.25   0.50   0.75   1   Speed

1:DOL motor torque
2:Motor torque at 3in
2:Load torque
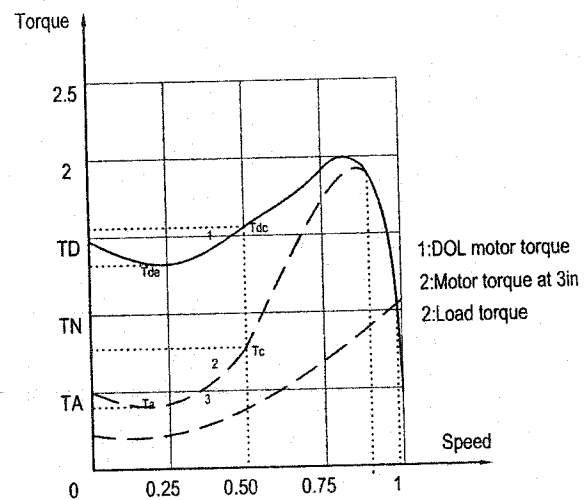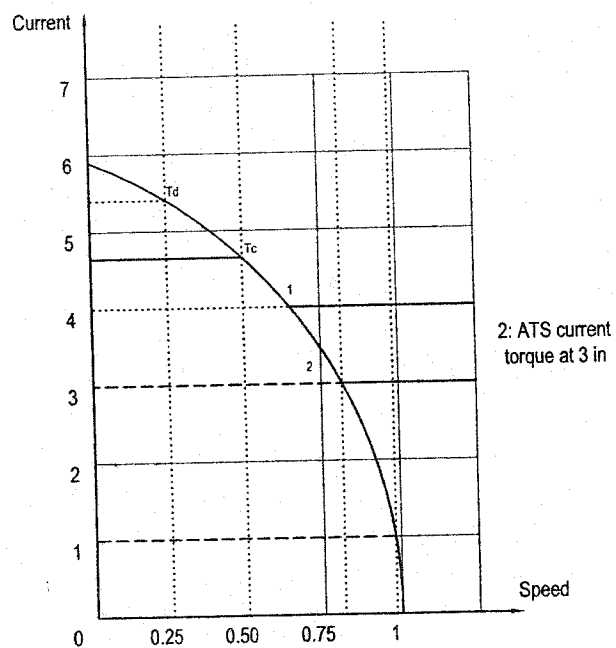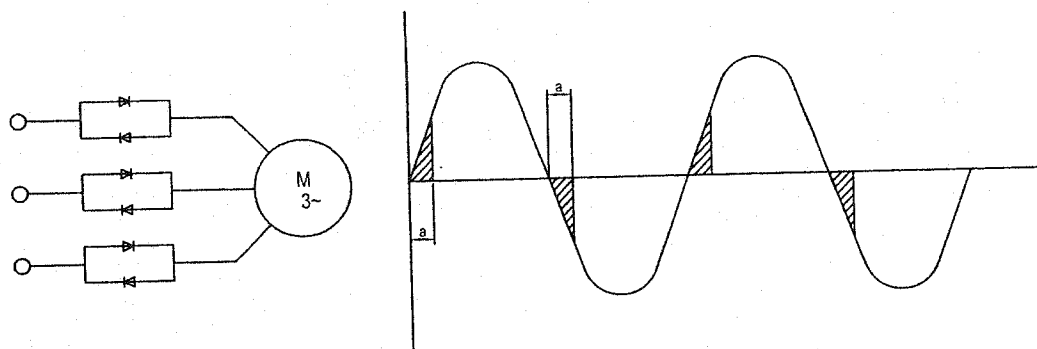
Figure 2.7 : Electronics Soft Start

2.9 SUMMARY OF THE DIFFERENT STARTING TECHNIQUES:

The following table will summarize the different starting methods and their advantages and disadvantages. It is clear from the comparisons below that the soft starter is the best option.

Table 2.1 : The Comparison of existing motor starting techniques

S/N	Description	Comment
1	Direct On Line Starting	□ Asynchronous motors, low/med power, 3 connection □ High starting Torque. □ Very high mechanical stress. □ Voltage dip. □ Simple switching equipment.
2	Star-Delta Starter	□ Asynchronous motors, low/med power, 6 connection □ Reduced Start up Torque. □ High current peaks when switching from Y to Δ □ Higher mechanical stress during torque change when switching from Y to Δ □ switchgear required
3	Rotor starter With Resistors	□ Asynchronous motors, low/med power, 6 connection □ Reduced start up torque. □ High current peaks. □ High switchgear cost. □ Intensive maintenance required.
4	Starting Transformers	□ Asynchronous motors, low/med power, 6 connection □ High current peaks. □ Voltage sags. □ Complex and extensive switchgear □ Extensive maintenance required
5	Electronics Soft starter	□ Asynchronous motors, low/med power, 6 connection □ Variable starting torque □ No current spikes □ Negligible voltage fluctuation □ Simple switchgear □ Maintenance free

CHAPTER 3

3. SIMULATION AND DISCUSSION OF THE RESULTS

3.1 GENERAL OBJECTIVE:

The objective of this simulation is to reduce the inrush current of an induction motor as well as the voltage dip as they are appearing in the figure 3.1
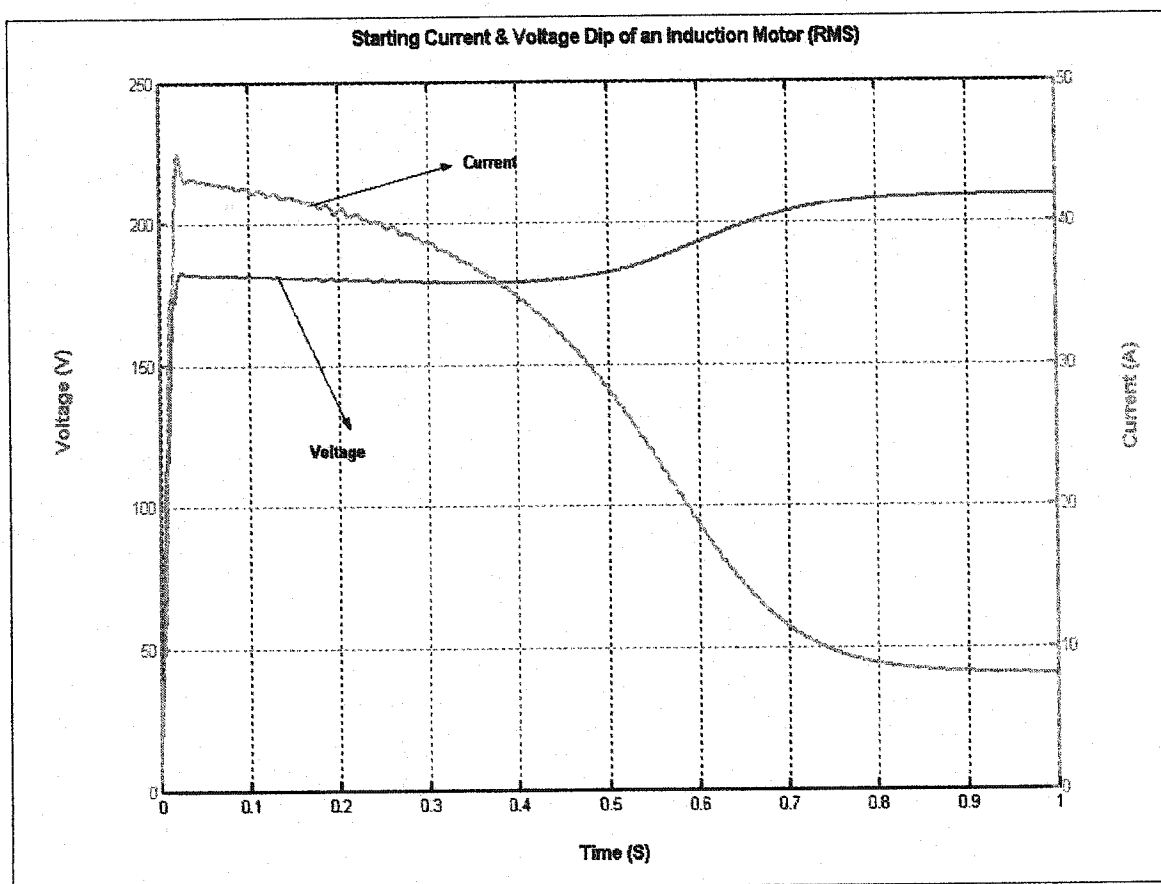
Figure 3.1 : Inrush Current & Voltage dip of Induction motor

3.2 DESIGNED CIRCUIT OVERVIEW:

1. SOFTWARE:

The software used for the simulation and analysis is MATLAB 6.1. A power System Blocksets were used to simulate the soft starter circuits. The three-phase induction motor model was used to represent the compressor drive.
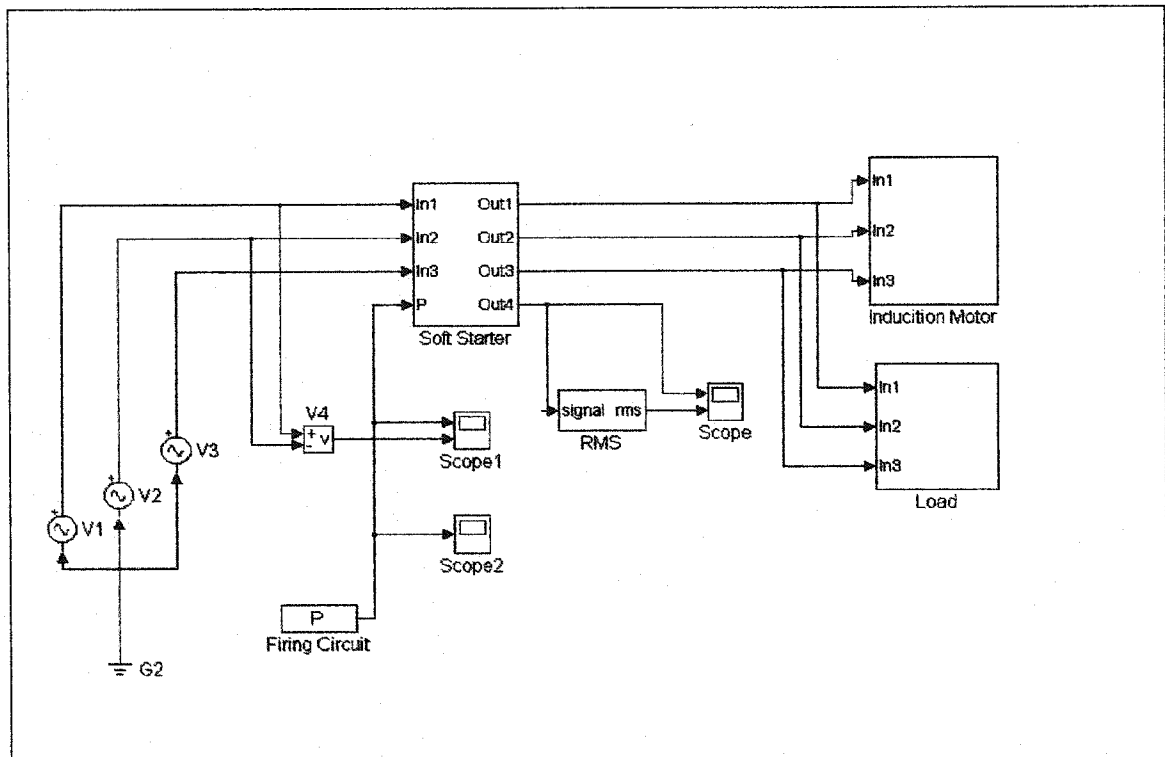
Figure 3.2 : MATLAB designed circuit for soft starter simulation

2. CIRCUIT:

Figure 3.2 shows the complete simulation circuit that was used to simulate different designs of firing angles integrated with the soft starter circuit.

3. POWER SOURCE

The data entry window in figure 3.3 shows the source used, as a sinusoidal voltage wave with 180V peak amplitude (phase to ground) and with a 60Hz rated frequency.
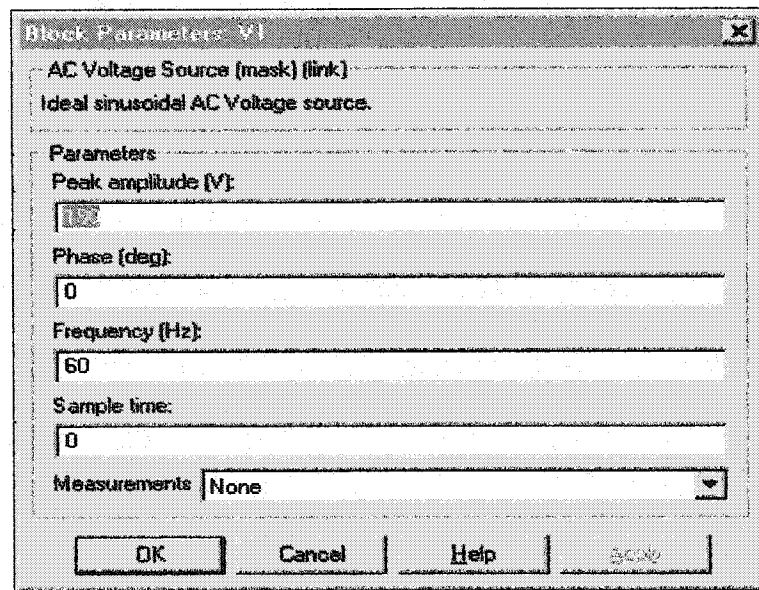
Figure 3.3 : The block that was used as AC voltage Source

4. SOFT STARTER AND TRIGGERING MODELS:

The Gate Turn-Off (GTO) thyristor is the basic element of the soft starter circuit. It is a semiconductor device that can be turned on and off via a gate signal. Like a conventional thyristor, the GTO thyristor can be turned on by a positive gate signal (g>0). However, unlike the thyristor which can be turned off only at a zero crossing of current, the GTO can be turned off at any time by applying a gate signal equal to zero. Two GTO's were installed to form the Triac in order to control both half wave voltage amplitudes.
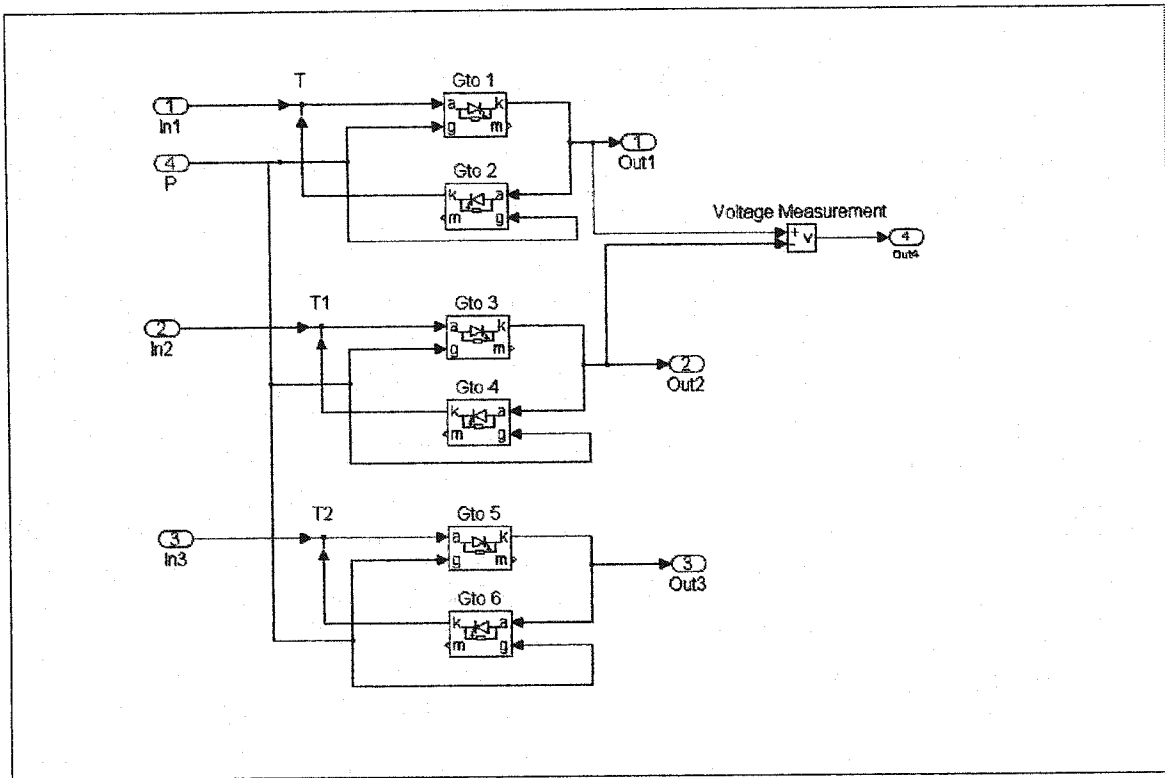
Figure 3.4 : The thyristors circuit which was used in the simulation circuit

Figure 3.4 represents the entire three phase integrated Triac system necessary for controlling the three phase voltages. To complete the soft starter circuit the firing control circuit had to be designed and its output had to be connected to the gate of each of the above Triacs. Since the duty cycle and pulse width of the firing angle are playing a major role in our design two different schemes (model A and model B) of the firing angle were designed, simulated and analyzed. These two different designs will cover almost all approaches of varying the voltage ramp wise. This is the standard practice in the existing higher rating soft starter.

5. THYRISTORS TRIGGERING PULSE MODEL A:

This controller pulse was designed to be applied when the applied Root Mean Square (RMS) of the source voltage reaches 60% of the rated voltage, since the compressor is not capable of being engaged in the starting mode for a voltage level before 60%. The first two-pulse width is taken wide enough to secure the required and necessary initial startup voltage as shown in figure 3.5. The subsequent pulse width will increase at every period in a linear manner until it reaches the full rated voltage at predetermined, full rated time or at a predetermined full rated cycle. The frequency of these pulses is 120 pulse/sec. or a rate of 2 pulse/cycle.
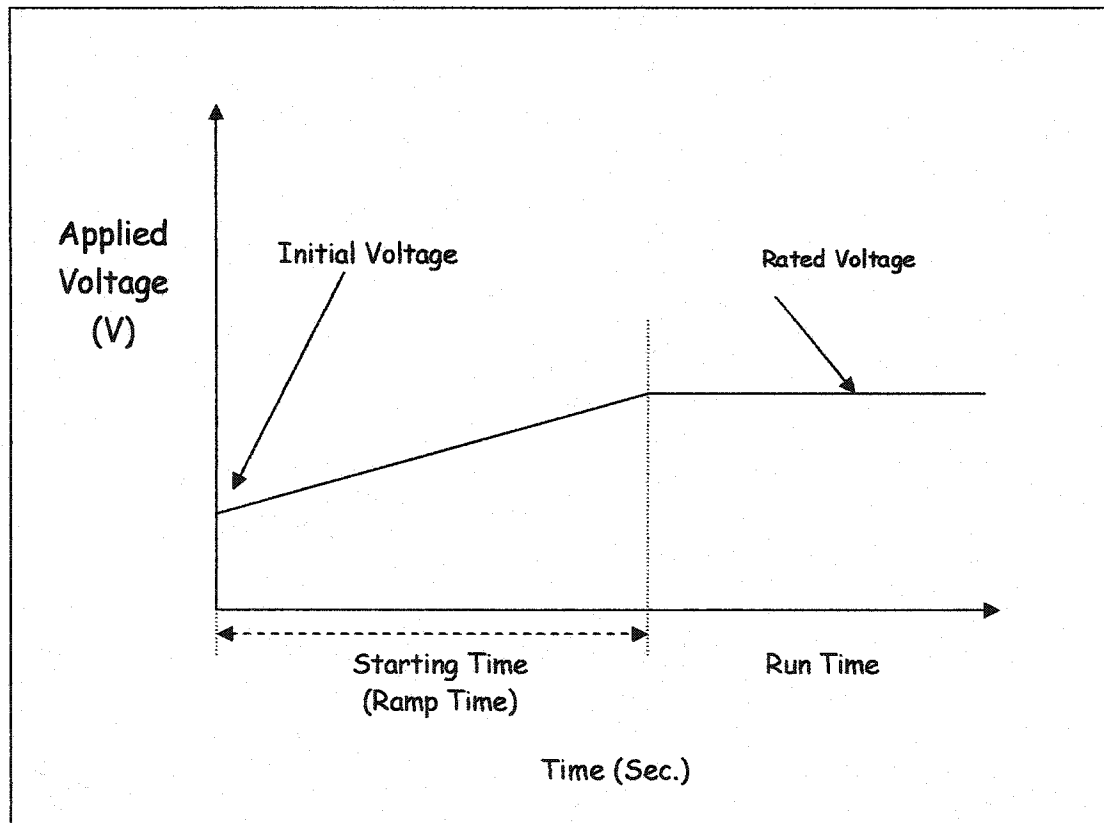
Figure 3.5 : Model A

6. THYRISTORS TRIGGERING PULSE MODEL B:

This model uses an entirely different and non-increasing pulse width approach. As shown in figure 3.6 the initial pulse width is applied every half cycle without any increase for a relatively large number of cycles. The first two pulse widths are taken wide enough to secure the required and necessary initial startup voltage, and then a sudden step function was injected at intermediate times to bring the applied voltage to the rated value.
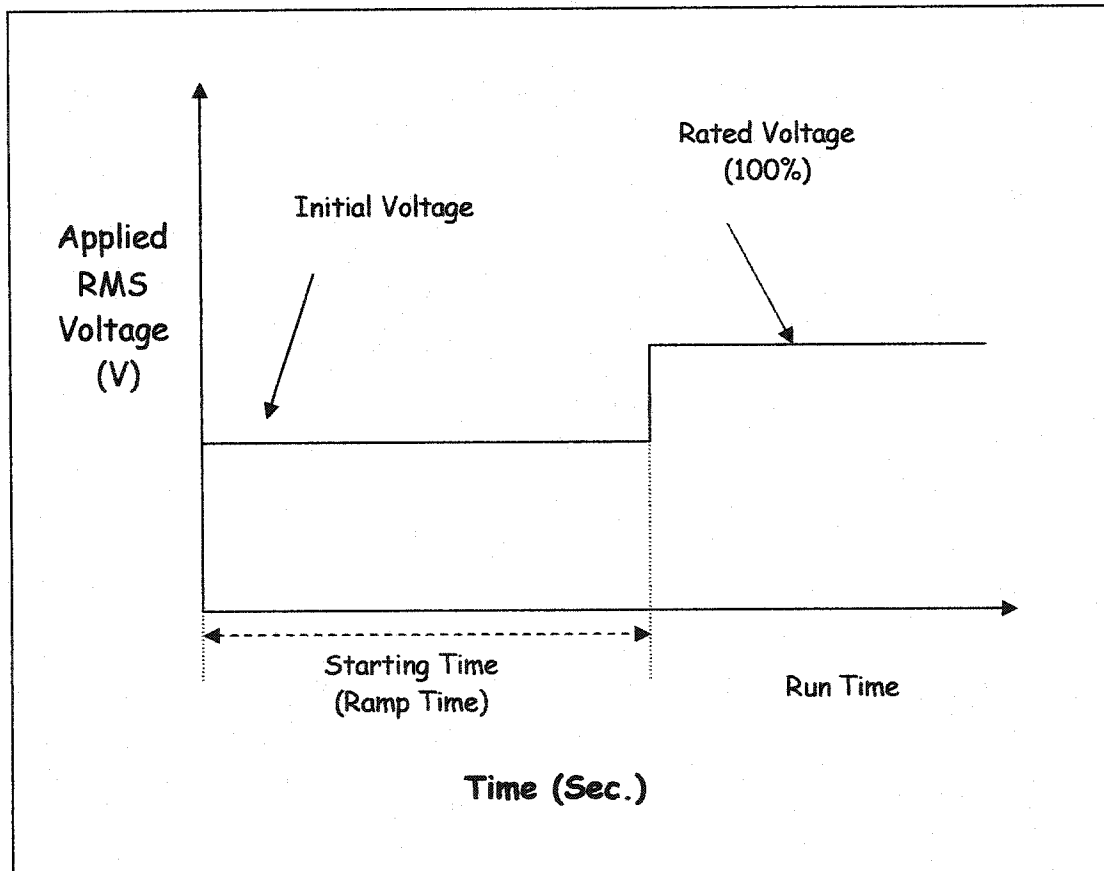
Figure 3.6 : Model B

7. THE THREE PHASE INDUCTION MOTOR MODEL

The induction motor used in the simulation is a 5 Horse Power, three-phase induction one

which normally runs at a rated voltage of 220V and 60HZ rated frequency. The related

numerical data are shown in figure 3.7 within the interface data entry windows. The

electrical part of the induction motor is represented by a fourth-order, state-space model

and the mechanical part by a second-order system.

Figure 3.7 : Data Entry Window of an Induction Motor Model

3.3   SIMULATION RESULTS AND DISCUSSION:

A. DEFINITION:

- **Inrush Current:**

  The current that appear at the starting of an induction motor and it is usually 4 to 5 times the rated value.

- **Voltage dip:**

  It is the sudden drop in the voltage which results from the inrush current.

- **Inrush duration:**

  The time duration starting from the appearance of the inrush current and the voltage dip until both the current and voltage reach to their rated value.

- **Ramp time:**

  The time required for the voltage to reach its rated value.

B. SIMULATION:

The first step in the investigation was to go through the variation of initial voltage V_i starting from 60% of the rated voltage which is the minimum practical voltage applied to the motor to start with fixed ramp time at T_r, which is basically the time needed for the source voltage to reach its rated value. Figure 3.8 and figure 3.9 demonstrate the approach followed in the simulation. We started with the minimum required voltage to start up the three phase induction motor (60% of the rated voltage) then the ramp time T_r was varied to study its effect of widening or narrowing the transient starting voltage dip, inrush current and inrush time duration. Next step was vary to the initial voltage and fixed the ramp time as demonstrated in figure 3.9.
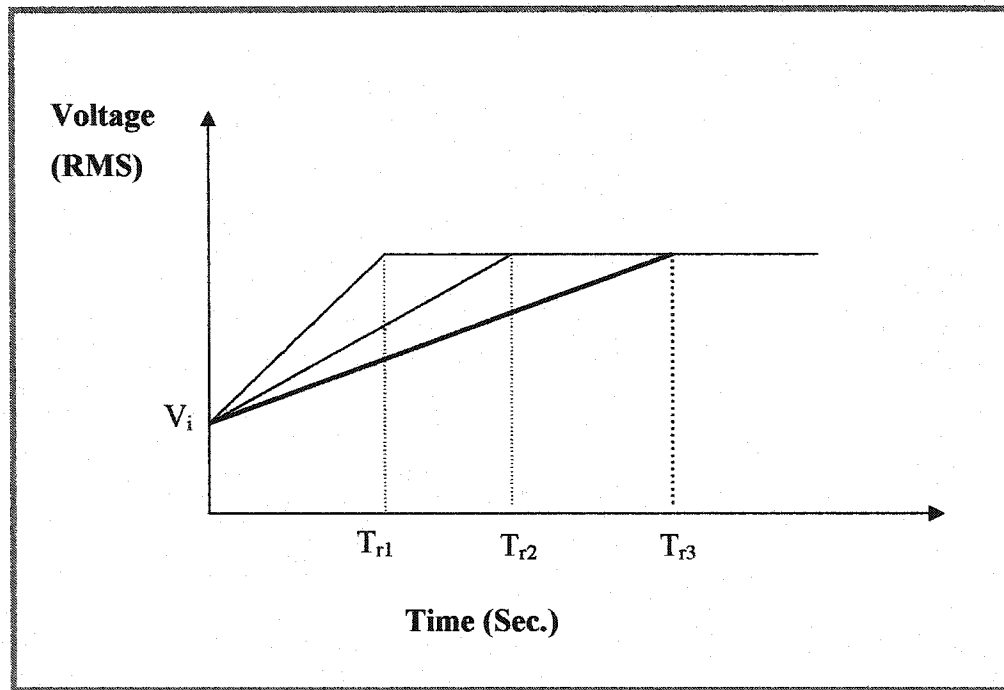
Figure 3.8 Soft starter principles fixed initial voltage and variable ramp time
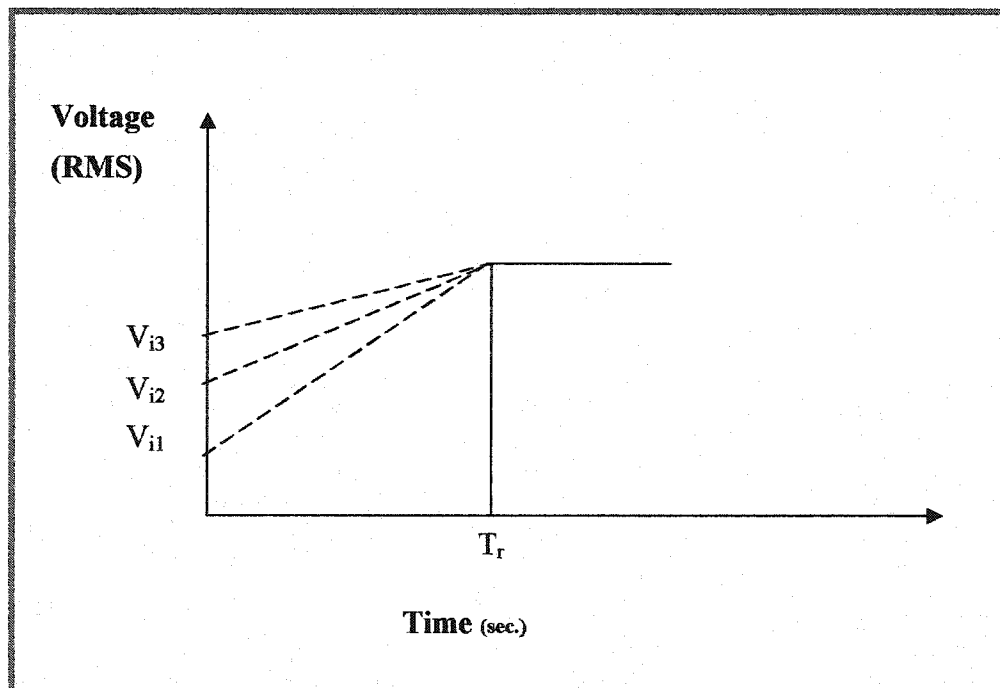
Figure 3.9 : Soft starter principles fixed ramp time and variable initial voltage

1. SIMULATION RESULTS OF MODEL A:

In this model the first two-pulse widths were taken wide enough to secure the required and necessary initial startup voltage. And the subsequent pulse width will increase at every period in a linear manner until it reaches the full rated voltage at a predetermined time or in predetermined cycles. The frequency of these pulses was 120 pulse/sec. or with a rate of 2 pulse/cycle.

### A. 60% of the rated voltage as an initial voltage applied to the Motor

Table 3.1 : Voltage dip, Inrush Current and inrush duration performance at 60% of the rated voltage as an initial voltage with different ramp time of model A

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	11.36	50	0.68
0.05	11.36	50	0.68
0.06	11.36	50	0.68
0.07	11.36	50	0.68
0.08	10.91	48.4	0.6
0.09	10.82	48.3	0.7
0.1	10.77	48	0.68
0.2	10.27	46.5	0.7
0.3	10.14	46.3	0.8
0.4	10.00	46.28	0.82
0.5	10.00	46.2	0.83

Table 3.1 shows that as the ramp time increased the voltage dip and the inrush current decreased while the inrush duration was increased. The best result was achieved at 500 ms

ramp time because at that point the inrush current and the voltage dip were at their minimum and the inrush duration was slightly larger.

B.   70% of the rated voltage as an initial voltage applied to the Motor:

Table 3.2 : Voltage dip, Inrush Current and inrush duration performance at 70% of the rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	10.68	48	0.6
0.05	10.91	48.2	0.6
0.06	10.55	47.94	0.6
0.07	10.55	47.82	0.6
0.08	10.45	47.6	0.6
0.09	10.45	47.5	0.6
0.1	10.45	47.4	0.6
0.2	10.32	46.4	0.65
0.3	10.32	46.4	0.68
0.4	10.00	44.9	0.8
0.5	9.77	43	0.83

The result reflected in table 3.2 were better result in comparison with that in table 3.1, because at 500 ms the inrush current was 43A, which mean 3.2A less than the current in table 3.1. The voltage dip was also reduced slightly. The inrush duration stayed the same in both cases.

C. 80% of the rated voltage as an initial voltage applied to the Motor:

Table 3.3 : Voltage dip, Inrush Current and inrush duration performance at 80% of the rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	10.91	48.2	0.6
0.05	10.91	48.2	0.6
0.06	10.91	48.21	0.6
0.07	10.91	48.22	0.6
0.08	10.91	48.25	0.6
0.09	10.45	47.63	0.6
0.1	10.45	47.7	0.6
0.2	10.00	44.8	0.65
0.3	9.77	44.4	0.7
0.4	9.64	42.1	0.72
0.5	9.45	41.3	0.75

A good result was achieved at 500ms ramp time with an initial voltage of 80% of the rated voltage. The inrush current was reduced by 22% compared to the one without a soft starter and the voltage dip also improved by about 15%. So, this means that the higher the initial voltage the better the result achieved in this model. On the other hand, there was a slight increase in the inrush duration which can be ignored compared to the gain that was achieved on the inrush current and the voltage dip.

D.   90% of the rated voltage as an initial voltage applied to the Motor:

Table 3.4 : Voltage dip, Inrush Current and inrush duration performance at 90% of the
rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	10.45	46.5	0.6
0.05	10.45	46.5	0.6
0.06	10.45	46.5	0.6
0.07	10.45	46.5	0.6
0.08	10.45	46.5	0.6
0.09	10.45	46.4	0.6
0.1	10.45	46.75	0.6
0.3	10.00	42.6	0.62
0.5	9.64	39	0.65
0.7	9.09	37.8	0.68
0.9	7.73	37.5	0.69
1.1	7.73	37.5	0.78
1.3	7.73	37.5	0.78

Since we observed that as the ramp time was increased there was an improvement in the

inrush current and in the voltage dip as well, the ramp time was extended to 1.3 Sec. As a

result of this the best result achieved by this model was at 0.9 ms ramp time and the initial

voltage 90% of the rated voltage. Table 3.4 shows a 30% inrush current reduction and almost 20% voltage dip reduction which are considered as a good improvement

E.   Inrush time duration with different initial voltage and different ramp time:

Table3.5 : Inrush time duration with different initial voltages and with different ramp time at design A model:

Ramp Time	Inrush Duration time at different percentage of the rated voltage (V_r) in Sec.			
	$V_i = 60\% V_r$	$V_i = 70\% V_r$	$V_i = 80\% V_r$	$V_i = 90\% V_r$
0.03	0.68	0.6	0.6	0.6
0.05	0.68	0.6	0.6	0.6
0.06	0.68	0.6	0.6	0.6
0.07	0.68	0.6	0.6	0.6
0.08	0.6	0.6	0.6	0.6
0.09	0.7	0.6	0.6	0.6
0.1	0.68	0.6	0.6	0.6
0.2	0.7	0.65	0.65	0.61
0.3	0.8	0.68	0.7	0.62
0.4	0.82	0.8	0.72	0.63
0.5	0.83	0.83	0.75	0.65

Figure 3.10 : Inrush time duration Vs Voltage Ramp Time at different initial Voltage model A Design

In both table 3.5 and figure 3.10 it was proved that the inrush time duration increased as the ramp time increased. The minimum inrush time was 60ms. However, at that time the values of the inrush current and the voltage dip were not at the minimum. Generally speaking we can also say, that the higher the initial voltage the better the inrush duration time on that model.

F.   Inrush Current and voltage ramp time at different initial voltage with model B design.

Table 3.6 : Inrush Current Vs Voltage Ramp Time at different initial Voltage Type B Design

Ramp Time	$I_{inrsuch}$ at $V_i = 60\% V_r$ (A)	$I_{inrsuch}$ at $V_i = 70\% V_r$ (A)	$I_{inrsuch}$ at $V_i = 80\% V_r$ (A)	$I_{inrsuch}$ at $V_i = 90\% V_r$ (A)
0.03	50	48	48.2	46.5
0.05	50	48.2	48.2	46.5
0.06	50	47.94	48.21	46.5
0.07	50	47.82	48.22	46.5
0.08	48.1	47.6	48.25	46.5
0.09	48.3	47.5	47.63	46.4
0.1	48	47.4	47.7	46.75
0.2	46.5	46.4	44.8	44.5
0.3	46.3	46.4	44.4	42.6
0.4	46.28	44.9	42.1	40.5
0.5	46.2	43	41.3	39.0

Figure 3.11 : Inrush Current Vs Voltage Ramp Time at different initial Voltage

Type A Design

The declining shape of the Inrush current versus the ramp time is clearly presented in

figure 3.11. In addition to that the figure proves that using 90% of the rated value of the

voltage as an initial voltage gives the best result. As we increased the ramp time the better

the result on the inrush current.

G. Voltage dips Percentage at different initial voltage and different ramp time.

Table 3.7 : Voltage dip with different Voltage Ramp Time at different initial Voltage
Type A Design

Voltage Dip at Different percentage of the rated voltage (Vr) as An initial voltage with different ramp time				
Ramp Time	$V_i = 60\%V_r$	$V_i = 70\% V_r$	$V_i = 80\% V_r$	$V_i = 90\% V_r$
0.03	11.36	10.68	10.91	10.45
0.05	11.36	10.91	10.91	10.45
0.06	11.36	10.55	10.91	10.45
0.07	11.36	10.55	10.91	10.45
0.08	10.91	10.45	10.91	10.45
0.09	10.82	10.45	10.45	10.45
0.1	10.77	10.45	10.45	10.45
0.2	10.27	10.32	10.00	10.3
0.3	10.14	10.32	9.77	10.00
0.4	10.00	10.00	9.64	9.8
0.5	10.00	9.77	9.45	9.64
0.7	10	9.76	9.4	9.09
0.9	9.82	9.52	9.1	7.73
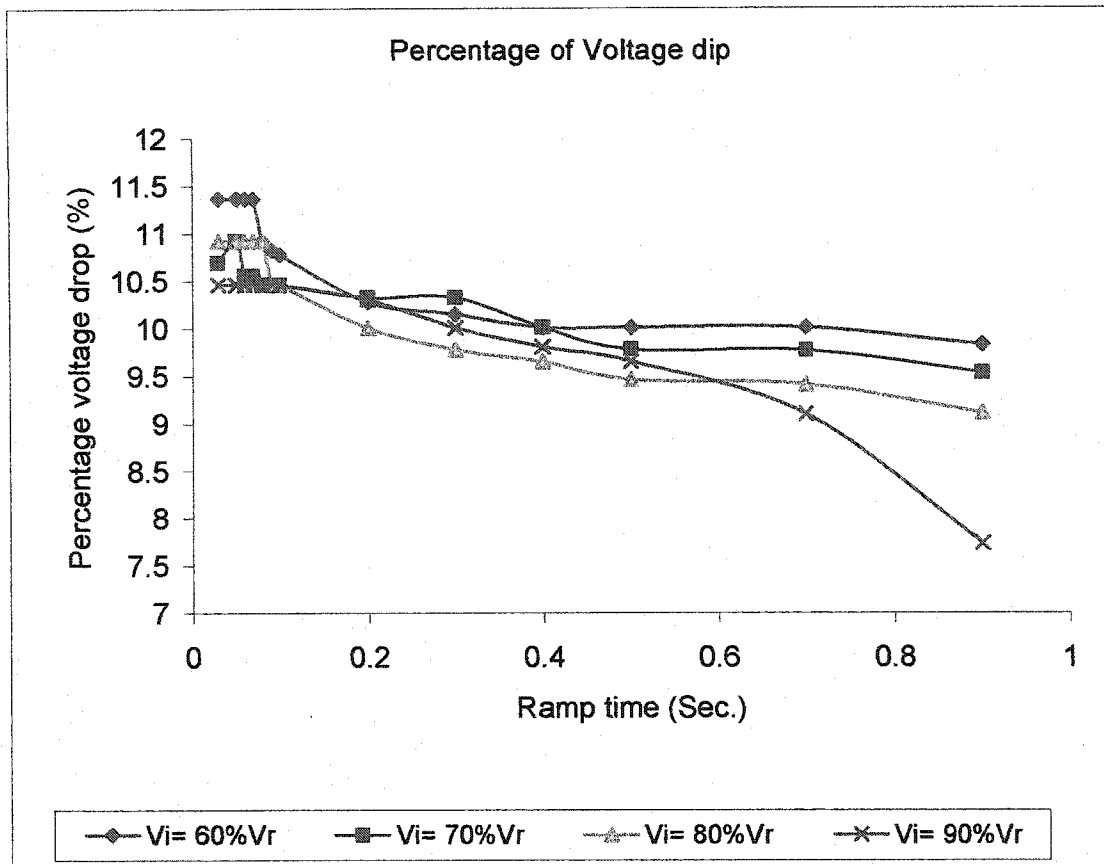
Figure 3.12 : Percentage of the voltage dips Vs Voltage Ramp Time at different initial
Voltage Model A Design

Table 3.7 and in Figure 3.12 show that when we increased the initial voltage and the

ramp time the voltage dip improved. Good voltage dip was obtained at 900 ms ramp time

and at the same time it was the lowest inrush current. This clearly was the best option on

model A.

Torque Pulsation of Model A
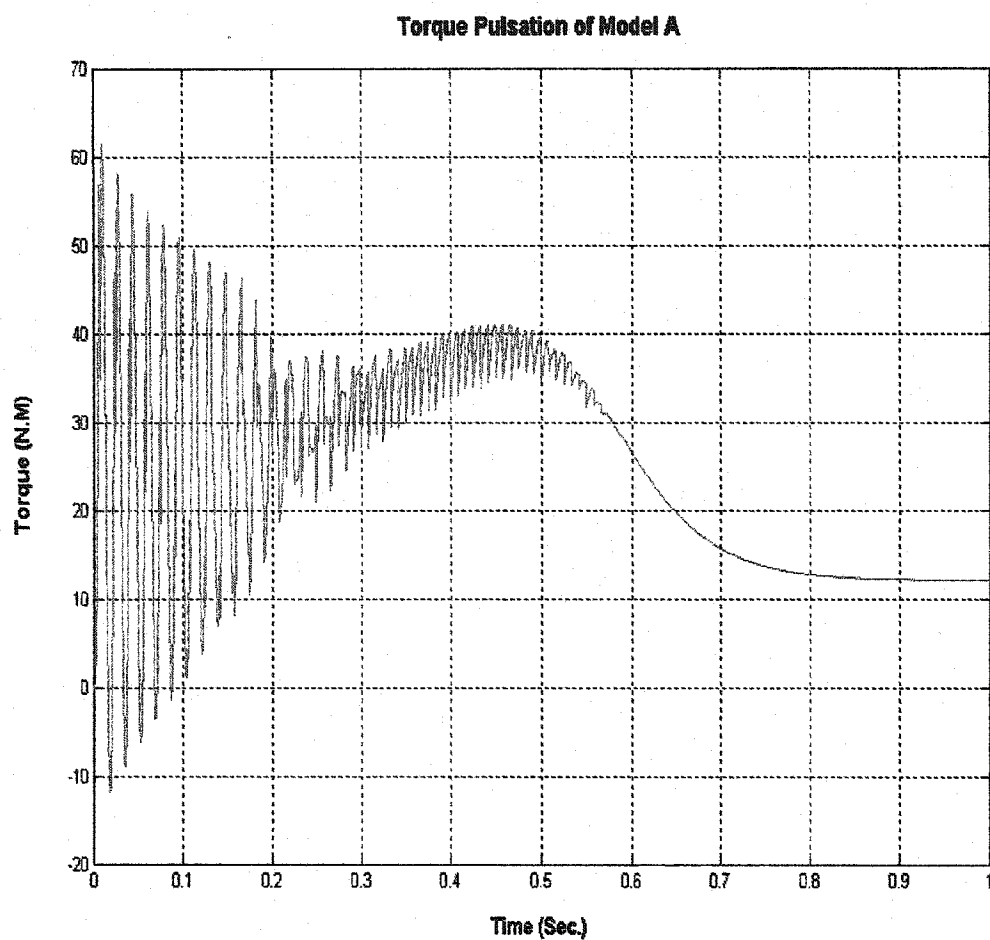
Figure 3.13 : Torque characteristic Model A

2.   DISCUSSION OF PULSE DESIGN A:

The following can be concluded:

a. The voltage dip was improved by about 15% and it kept on improving as we got closer to the rated voltage. The current curves and the voltage curves indicate that as the current increased the voltage increased in almost a linear relationship. This means that if we improve the current peak the voltage dip will improve.

b. As the ramp voltage increased the inrush current decreased. Therefore, the current will be improved by about 30% if we move the ramp time from 30 ms to 500 ms.

c. As the initial starting voltage was increased the results improved. This led us to have shorter inrush times and inrush current. A 90% of an initial voltage better than 80% and 80% better than 70% and so on.

d. There was a linear relationship between ramp time as well as the inrush time period. So, we can say that if we increase the ramp time we will have

  a. Less inrush current

  b. More inrush time period

So, the faster the ramp times the better the result in this design.

e. Adding the soft starter to model A will lead to have good torque pulsation as shown in figure 3.13. This will have less effect on the shaft lifetime in the long-term compared to the one in design A. Therefore, as mechanical stress on the shaft is for a fraction of a second (500ms.) it will not have a negative impact on the life of the motor.

f. It is clear that model A is a good option. Nevertheless, its implementation requires a microprocessor based circuit to fire the Thyristors with adjustable initial voltage as well as adjustable ramp time.

g. The disadvantages of this model will be the high price of implementation and bigger size. This would make it very difficult to install in household air conditioners.

3. SIMULATION RESULT OF MODEL B:

This model applied an entirely different and non-increasing pulse width approach. In this model the initial pulse width was applied every half cycle without any increase for a relatively large number of cycles. The first two pulse widths were taken wide enough to secure the required and necessary initial startup voltage, and then a sudden step function was injected at intermediate times to bring the applied voltage to the rated value.

A. 60% of the rated voltage as an initial voltage applied to the Motor:

Table 3.8 : Voltage dip, Inrush Current and inrush duration performance at 60% of the rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	11.36	50.6	0.68
0.05	11.36	50.4	0.65
0.06	11.36	50.2	0.65
0.07	11.36	50.5	0.68
0.08	10.91	50.25	0.69
0.09	10.82	48.2	0.7
0.1	10.77	50.4	0.7
0.2	10.27	50.6	0.82
0.3	10.14	50.8	0.98
0.4	10.00	51.2	1.1
0.5	10.00	51.4	1.25

Table 3.8 shows a slight improvement in the voltage dip as the ramp time increased. On the other hand there was a small improvement in the inrush current while the inrush duration deteriorated as we increased the ramp time.

B. 70% of the rated voltage as an initial voltage applied to the Motor:

Table 3.9 : Voltage dip, Inrush Current and inrush duration performance at 70% of the rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	11.36	50	0.62
0.05	11.36	50.1	0.63
0.06	11.36	49.75	0.65
0.07	11.36	50.08	0.65
0.08	11.14	49.7	0.65
0.09	11.14	47.5	0.68
0.1	11.27	50.1	0.7
0.2	11.36	50	0.79
0.3	11.36	50.5	0.88
0.4	11.27	50.1	0.99
0.5	11.23	50.2	1.1

As in Table 3.8, table 3.9 shows a slight improvement in the voltage dip as the ramp time increased. On the other hand, their was a slight improvement in the inrush current at 80

ms ramp time but it was not better than the one in table 3.8, while the inrush duration deteriorated as we increased the ramp time. So, the best result obtained here was achieved at 80 ms ramp time.

C.   80% of the rated voltage as an initial voltage applied to the Motor:

Table 3.10 : Voltage dip, Inrush Current and inrush duration performance at 80% of the rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	11.36	49.28	0.61
0.05	11.36	49.25	0.62
0.06	11.23	49.01	0.63
0.07	11.36	49.2	0.65
0.08	11.23	49	0.65
0.09	11.32	49.12	0.65
0.1	11.23	49	0.67
0.2	10.91	48.5	0.72
0.3	10.73	48	0.8
0.4	10.45	47.1	0.88
0.5	10.00	46.2	0.95

In table 3.10 the voltage dip as well as the inrush current show an improvement at 500 ms

ramp time. On the other hand it is noticeable that the inrush duration increased to 0.95 s.

D.   90% of the rated voltage as an initial voltage applied to the Motor:

Table 3.11 : Voltage dip, Inrush Current and inrush duration performance at 90% of the
rated voltage as an initial voltage with different ramp time

Ramp Time (Sec.)	Voltage dip (%)	Maximum Inrush Current (A)	Inrush Duration (Sec.)
0.03	11.36	49.2	0.65
0.05	11.23	48.8	0.64
0.06	11.05	48.4	0.63
0.07	10.91	47.9	0.62
0.08	10.91	47.8	0.61
0.09	10.91	47.6	0.6
0.1	10.68	47.38	0.62
0.3	10.45	43.72	0.7
0.5	9.09	37.5	0.8
0.7	9.09	37.5	0.82
0.9	9.09	37.5	0.84
1.1	9.09	37.5	0.86
1.3	9.09	37.5	0.88

Table 3.11 shows that the best result obtained in this design was at 500 ms ramp time.

Both the inrushes current as well as the voltage dip were at the minimum. This result was

very similar to the best result that was obtained in model A except that the voltage dip here was higher, by about 2%, and the inrush duration also higher by 0.11 Sec.

E. Model B with different initial voltage and with a different ramp times

Table 3.12 : Model B with different initial voltage and with a different ramp times

Ramp Time	Inrush Duration Time at Different Percentage of the Rated Voltage (V_r) in Sec.			
	V_i=60% V_r	V_i=70% V_r	V_i=80% V_r	V_i=90% V_r
0.03	0.68	0.6	0.6	0.6
0.05	0.68	0.6	0.6	0.6
0.06	0.68	0.6	0.6	0.6
0.07	0.68	0.6	0.6	0.6
0.08	0.6	0.6	0.6	0.6
0.09	0.7	0.6	0.6	0.6
0.1	0.68	0.6	0.6	0.6
0.2	0.7	0.65	0.65	0.61
0.3	0.8	0.68	0.7	0.62
0.4	0.82	0.8	0.72	0.63
0.5	0.83	0.83	0.75	0.65

Figure 3.14 : Inrush time duration Vs Voltage Ramp Time at different initial Voltage model B Design

In both table 3.12 and figure 3.14 it is proven beyond any doubt that the inrush time duration increased as the ramp time increased. The minimum inrush time was 60 ms. However, at that time the inrush current and the voltage dip were not at the minimum level. Generally we can also say that the higher the initial voltage, the better the inrush duration time was in that model.

F. Inrush Current and voltage ramp time at different initial voltage in model B

Table 3.13 : Inrush Current Vs Voltage Ramp Time at different initial Voltage Type B Design

Ramp Time	$I_{inrsuch}$ at Vi= 60%Vr (A)	$I_{inrsuch}$ at Vi= 70%Vr (A)	$I_{inrsuch}$ at Vi= 80%Vr (A)	$I_{inrsuch}$ at Vi= 90%Vr (A)
0.03	50	48	48.2	46.5
0.05	50	48.2	48.2	46.5
0.06	50	47.94	48.21	46.5
0.07	50	47.82	48.22	46.5
0.08	48.1	47.6	48.25	46.5
0.09	48.3	47.5	47.63	46.4
0.1	48	47.4	47.7	46.75
0.2	46.5	46.4	44.8	44.5
0.3	46.3	46.4	44.4	42.6
0.4	46.28	44.9	42.1	40.5
0.5	46.2	43	41.3	37.5

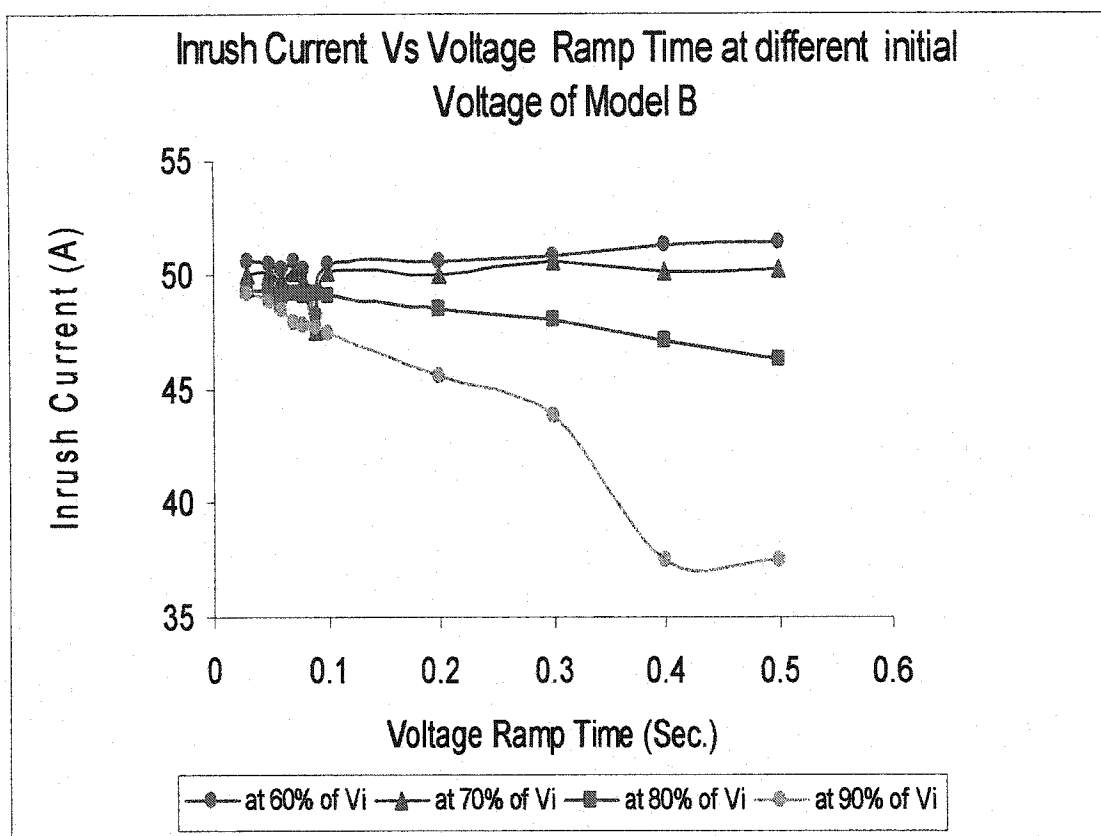Figure 3.15 : Inrush Current Vs Voltage Ramp Time at different initial Voltage Type B Design

As in model A the declined shape of the Inrush current versus the ramp time was at 90% of the rated voltage as shown in figure 3.15. In addition to that in figure 3.15 it is proven that the use of 90% as an initial voltage, gave the best results. So, as we increased the ramp time the better was the result on the inrush current.

G.   Voltage dip percentages at different initial voltages and different ramp times.

Table 3.14 : Voltage dip with different voltage ramp times at different initial voltages
model B Design

Voltage Dip at Different percentage of the rated voltage (V_r) as				
An initial voltage with different ramp time				
Ramp Time	$V_i = 60\% \ V_r$	$V_i = 70\% \ V_r$	$V_i = 80\% \ V_r$	$V_i = 90\% \ V_r$
0.03	11.45	11.36	11.36	11.36
0.05	11.36	11.36	11.36	11.23
0.06	11.36	11.36	11.23	11.05
0.07	11.36	11.36	11.36	10.91
0.08	10.77	11.14	11.23	10.91
0.09	11.36	11.14	11.32	10.91
0.1	11.59	11.27	11.23	10.68
0.2	11.73	11.36	10.91	10.5
0.3	11.82	11.36	10.73	10.45
0.4	11.82	11.27	10.45	9.5
0.5	11.45	11.23	10.00	9.09
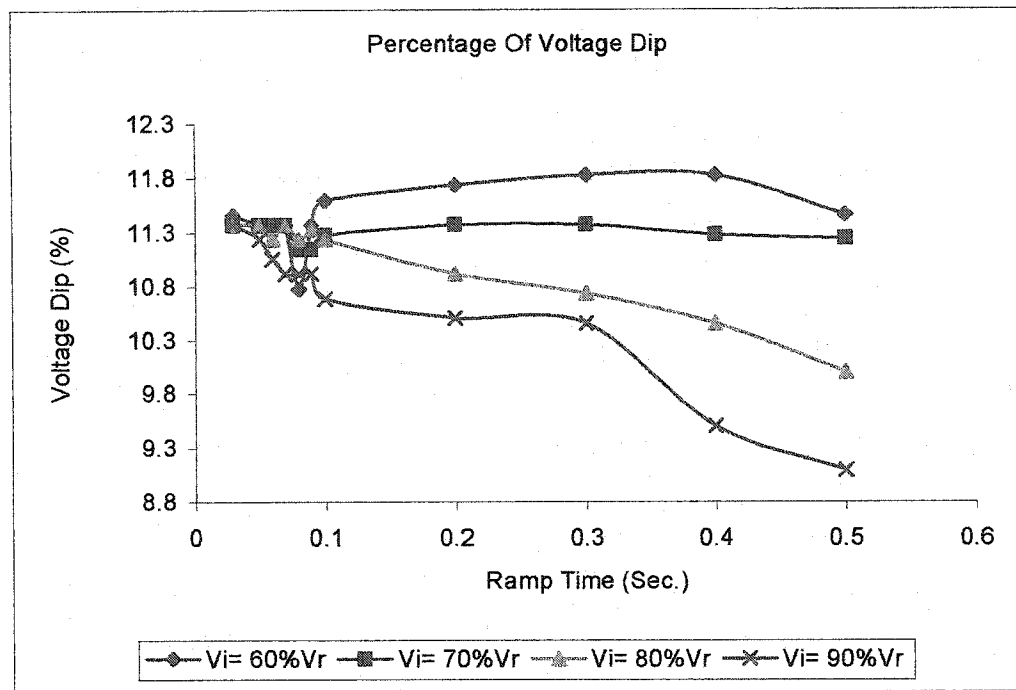
Figure 3.16 : Percentage of the voltage dip Vs Voltage Ramp Time at different initial
Voltage model B Design

In table 3.14 and in Figure 3.16 it is shown that as we increased the initial voltage and the

ramp time the voltage dip improved, and the best voltage dip was obtained at 900 ms

ramp time as well as the lowest inrush current. We obtained the best performance in this

model at this point.

Figure 3.17: Torque Characteristic Model B

Figure 3.18 : Torque Comparison between Models A and B

4. DISCUSSION OF PULSE DESIGN B:

The following conclusions can be drawn:

    a. As in design A, design B showed an improvement in the voltage dip by about 15% and it kept on improving along with the increases in the starting voltage.

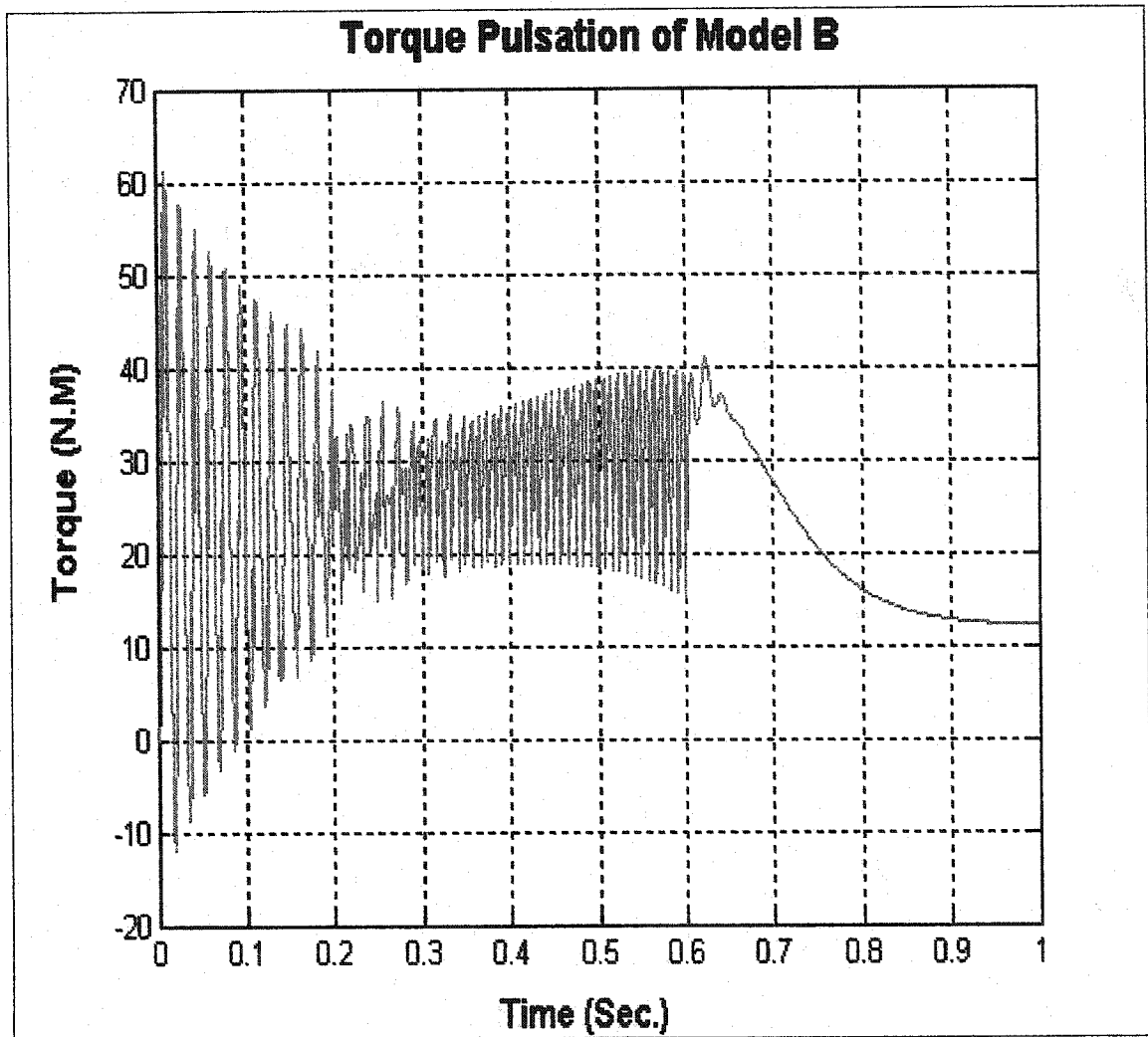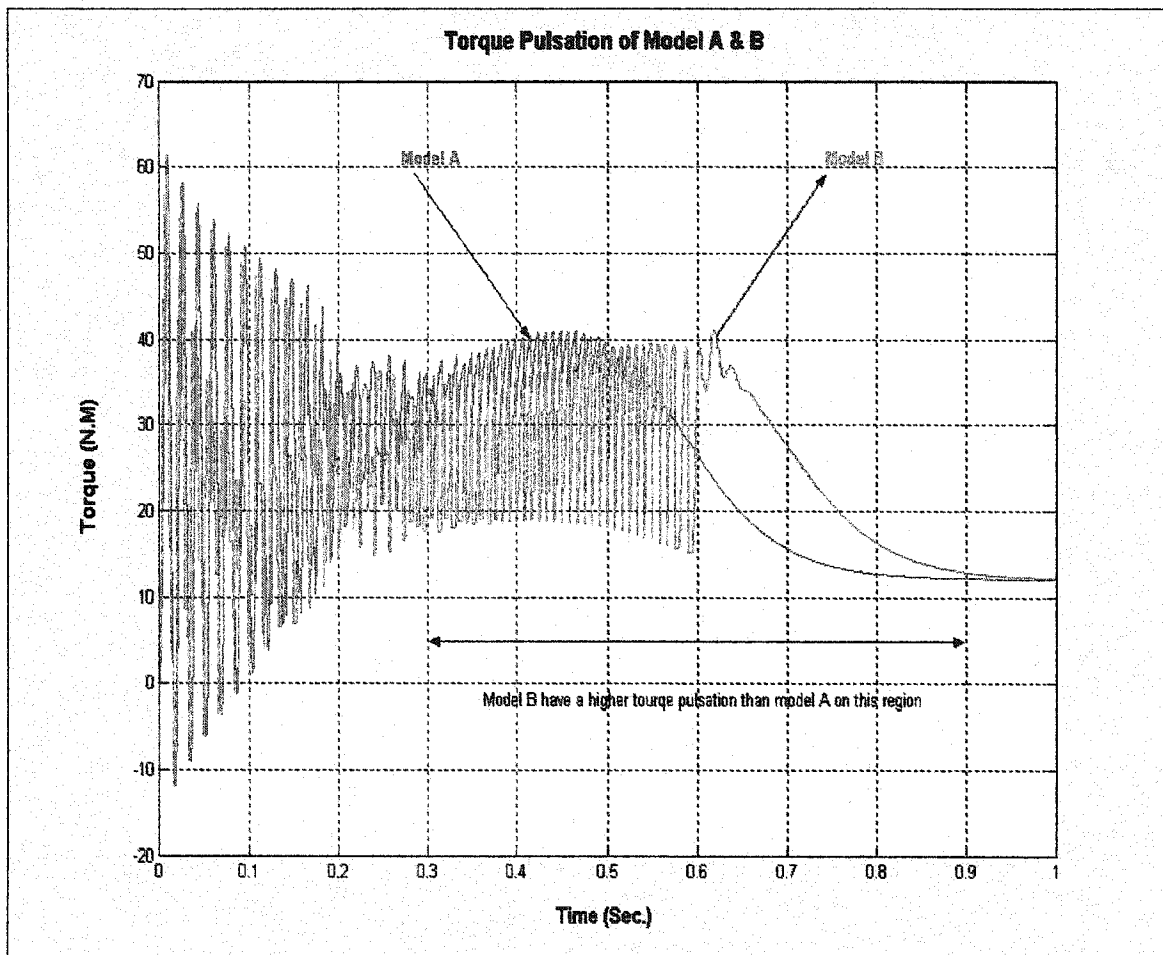   b. As the ramp voltage increased the inrush current decreased. The Inrush current improved by about 30% as we moved the ramp time from 30 ms to 500 ms.

    c. As we increased the initial starting voltage, better results were obtained. We got less inrush current time as well as low inrush current value. This means that starting at 90% of the rated voltage we obtained a better result than starting at a lower level.

    d. There was almost a linear relationship between ramp time and the inrush time period. So, we can safely say that if we increase the ramp time we will have

        1. Less inrush current

        2. More inrush time period

    e. This type of design produced good results in a relatively good torque pulsation but was not better than the one of design A, as shown in the figure 3.18. This will have less effect on the shaft lifetime in the long-term compared to the one in design A. As mechanical stress on the shaft occurs for a fraction of a second (500 ms.), it will not have a negative impact on the life of the motor.

f. The implementation of model B will be less expensive than that of design B and will also be of a smaller size. This type is almost similar to the current limiting resistance practice which is good for the household air conditioners.

CHAPTER 4

4. DISCUSSION OF FILED MEASUREMENTS & EXPERIMENTAL RESULTS

4.1 GENERAL

Four main groups are identified in the refrigeration industries:

4.1. **Consumer Range,** The capacity of this group vary from 1-4 tons

4.2. **Unitary Range,** The capacity of this group vary from 4- 25 tons

4.3. **Modular Unit,** The capacity of this group vary from 20-140 tons

4.4. **Chillers Units,** The capacity of this group start from 25-490 tons

A sample from each was considered for inrush current and voltage dip measurements to demonstrate the importance of the starting energy consumed in each one of them. These samples will cover all the consumers of air conditioners starting with houses and ending at plants, hospitals and shopping malls.

4.2 FIELD MEASUREMENTS

All the measurements were taken through the Leasam Controls' compressor start analyzer model number SSL2, with a baud rate of 38400. This analyzer was specifically designed to check the performance of compressor starting current. The voltage is also monitored simultaneously. The system is factory calibrated to provide an accuracy of 0.5%. The logger is powered by a 9-Volt battery. The measurement was downloaded via a PC. The graphic representation software was with Windows 95/ 98/ NT/2000.

Figure 4.1 shows a sample of the experimental measurement of the inrush current as well as the voltage dip on graphic representation software. This figure will show all identification parameters that may not be clear on the figures.
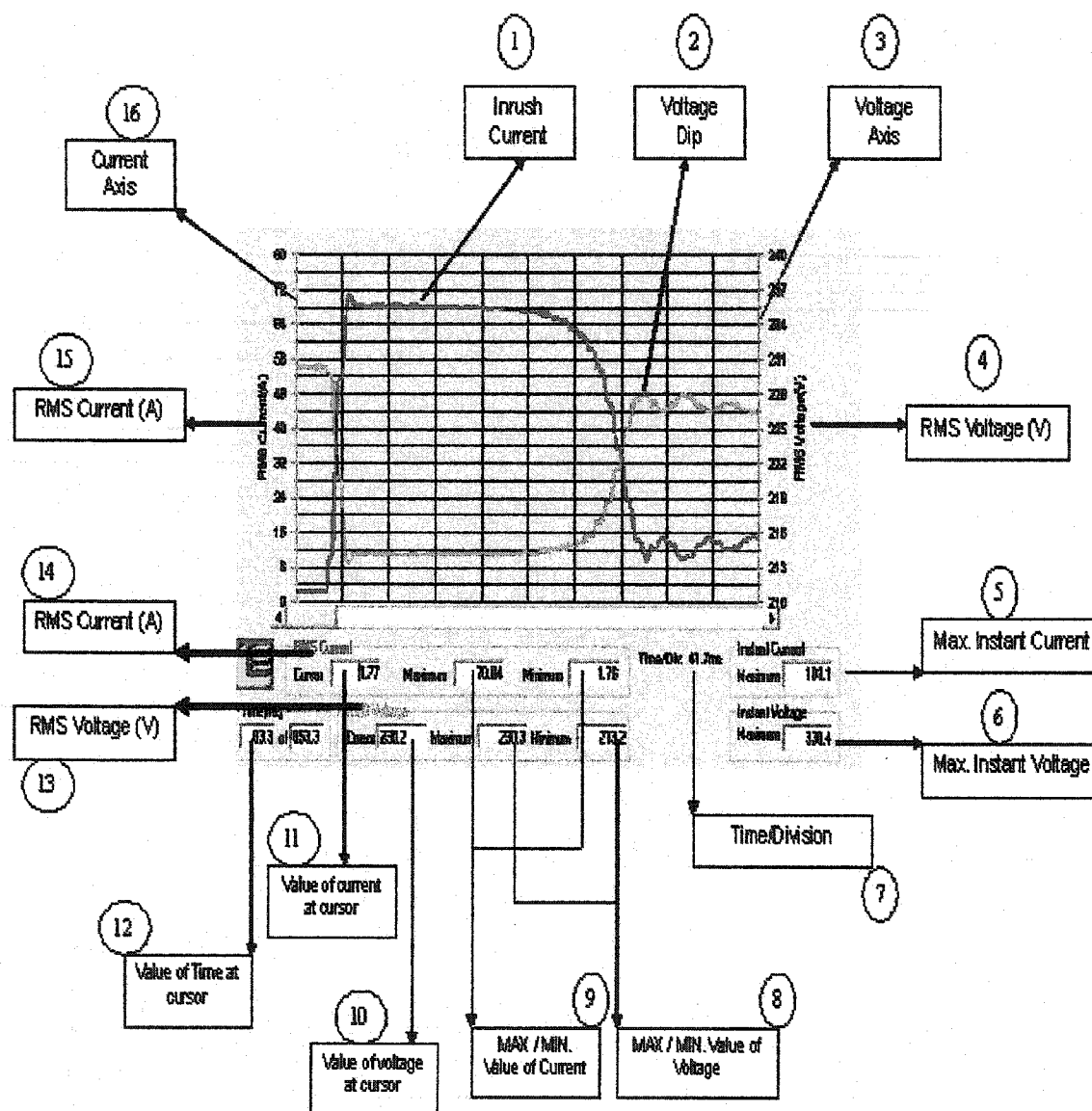

Figure 4.1 : Identification Parameter of graphic representation software

- **IDENTIFICATION OF THE PARAMETERS OF THE GRAPHIC REPRESENTATION SOFTWARE:**

1. Inrush current waveform (RMS Value)

2. Voltage dip waveform (RMS Value)

3. Voltage axis and the scale is adjusted automatically by the software

4. RMS Voltage (V) – Axis Title

5. Maximum Instant Current captured by the logger

6. Maximum Instant Voltage captured by the logger

7. Time Division for the figure, it is fixed to 41.7ms/Div.

8. Maximum and Minimum value of the voltage (RMS values)

9. Maximum and Minimum value of the current (RMS values)

10. RMS voltage value at the cursor pointing place.

11. RMS Current value at the cursor pointing place.

12. Time value at the cursor pointing place.

13. RMS- Voltage (V)

14. RMS- Current (A)

15. RMS Current (A) – Axis Title

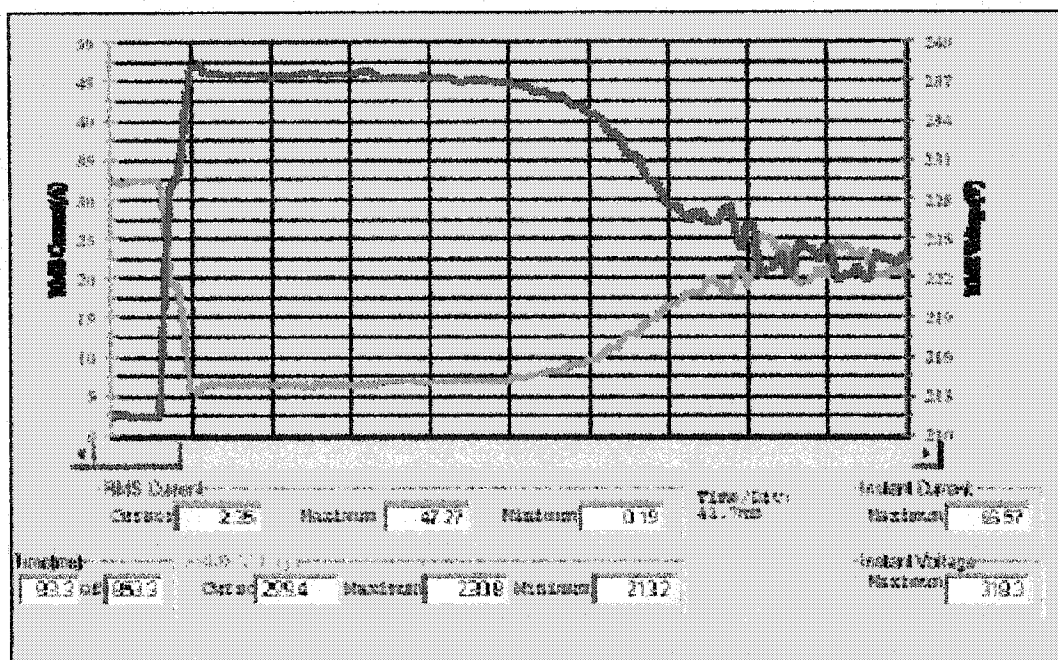16. Voltage axis and, the scale are adjusted automatically by the software

Figure 4.2 : Inrush Current & Voltage Dip of Single Phase Compressor without soft
starter of consumer range

Figure 4.2 shows the performance of one of the most common air conditioners used in the

consumer range in the kingdom of Saudi Arabia. As it is presented in the figure the

maximum RMS inrush current was 42.27A while the instant current was 66.57A .On the

other hand, the minimum voltage dip was 8% of the supply voltage and the inrush

duration took 7.3 time divisions which was equal to about 306 ms. This type of starting

performance occurs several times daily in our houses, offices and shops. The reader can

imagine if two or three of these air conditioners are connected to the same power supply

and started at the same time what could happen to the voltage dip. The voltage dip will

exceed 20% or even more. This type of air conditioner exists everywhere in Saudi Arabia
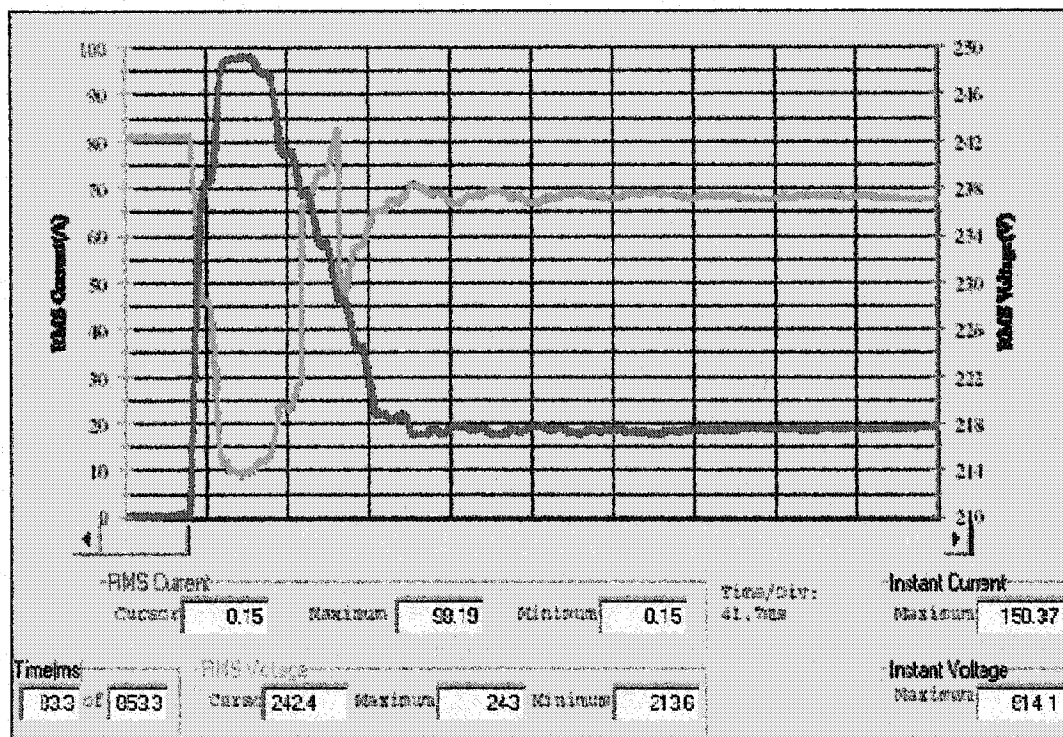
and the world.

Figure 4.3 : Inrush Current & Voltage Dip of Three-Phase Compressor with out soft
starter of unitary products

Figure 4.3 again shows another type of compressor which is mostly used in the
commercial field like in supermarket and shopping centers. The peak current (RMS value)
reached this time was 99.19A, while the current instant recorded by the logger was
150.37A. The voltage dip was also 12.09% which was worse than the consumer type air
conditioner because it has a bigger compressor. However, the inrush duration this time
was less because it is a three phase supply and it was at 105 ms. In this case we have to
oversize the transformer of the sub-station that supplies the shopping centre, since it is
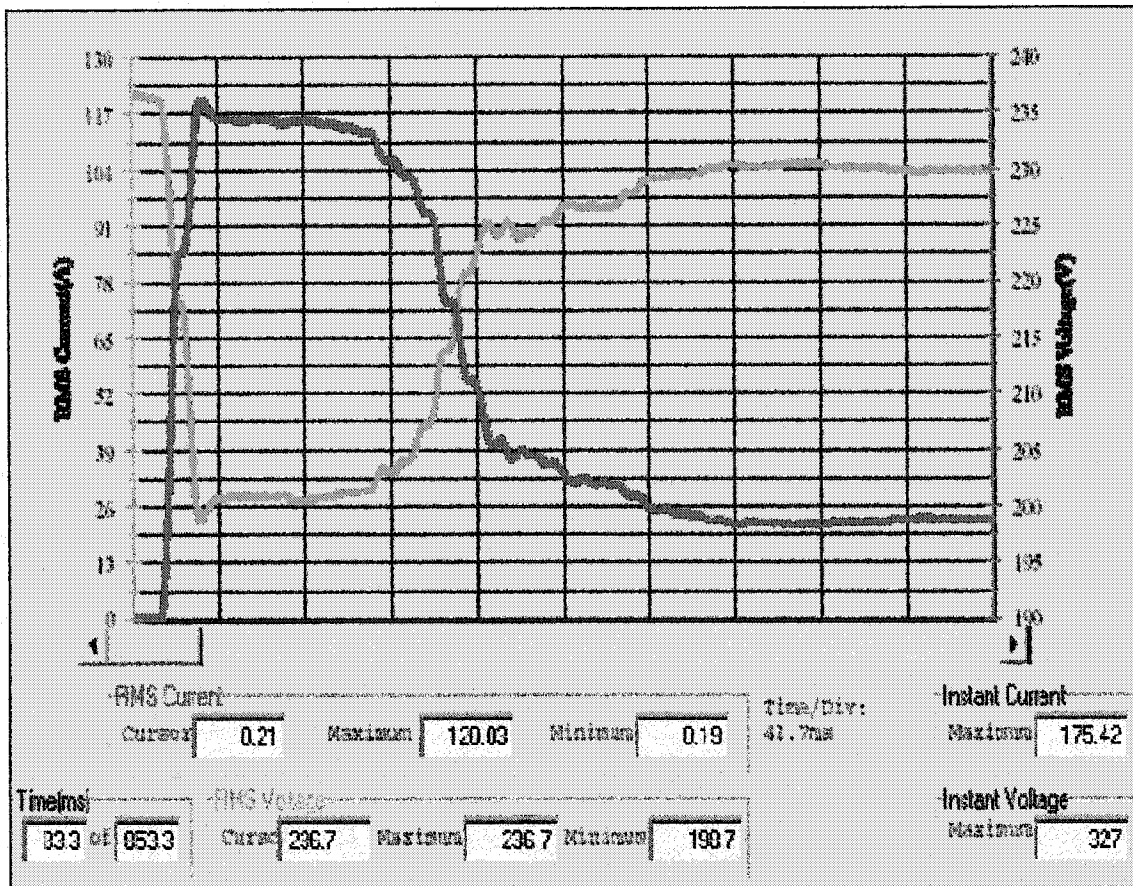equipped with many air conditioners of this type.

Figure 4.4 : Inrush Current & Voltage Dip of Single Phase Compressor with out soft
starter of applied range and small chillers

Finally, the measurement concluded by the compressor type which is normally used in an

applied range and in small chillers. Figure 4.4 shows a 120.03A Inrush current as the

maximum value reached and instant current was 175.42A. In addition to that, the voltage

dips were 16% of the rated voltage. These types of air conditioner exist in shopping malls,

hospitals and party halls. For the big chiller 100 ton and above, the inrush current may

reach 500 A peak RMS in the case of part winding start or to 1210 A if both winding start

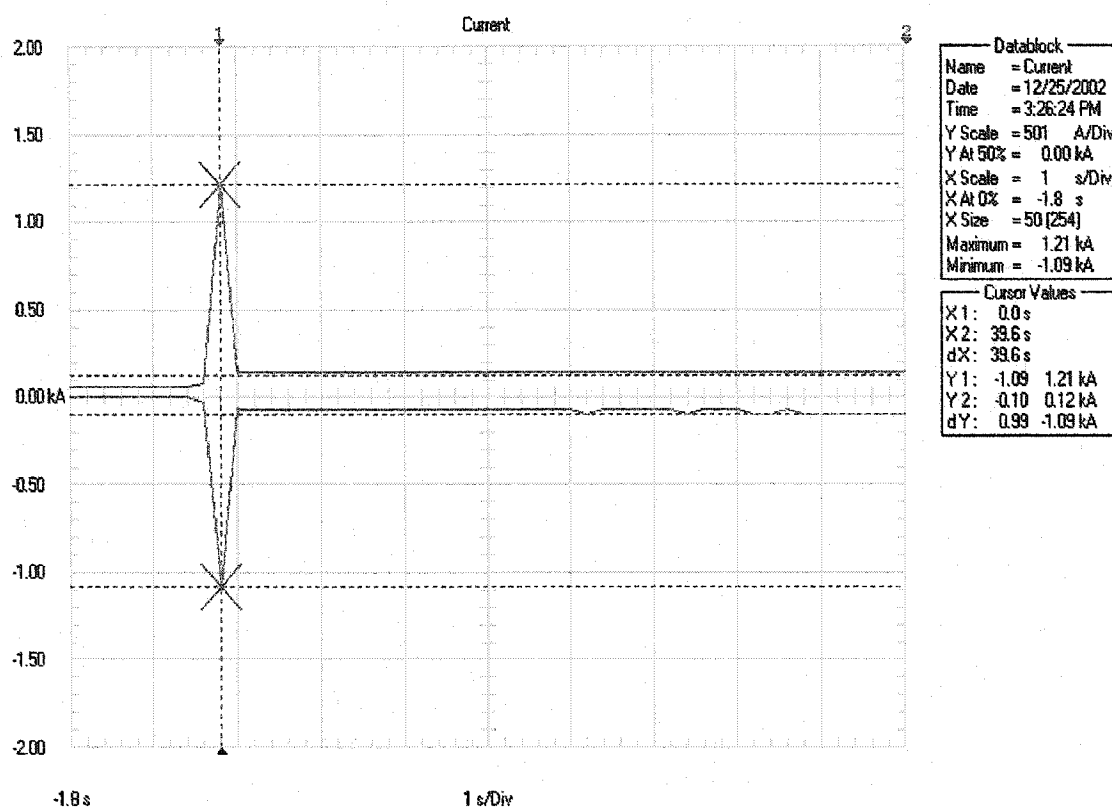simultaneously as shown in figure 40 with a time duration of 300 ms.

Figure 4.5 : Inrush Current of three Phase Compressor with out soft starter of big chiller range

4.3 EXPERIMENTAL SETUP AND MEASUREMENT:

Since model B gave us excellent performance results which was almost similar to the best obtained in model A, it appeared to be the most practical solution. It is also easy to implement and cost effective. The experimental investigation was done to validate the simulation results obtained in model B on one of the most commonly used air conditioner in the consumer range.

Model B is nothing but a reduced voltage applied to the motor for a certain period of time and then a step function is injected to bring the voltage to its rated value. The time of injecting the step function is critical as we shall see later. So, the concept that was followed in the experimental design was to introduce the starting resistance in series with load to apply the required reduce voltage to the motor and then bypass this resistance by the timer built into the programmable logic controller.
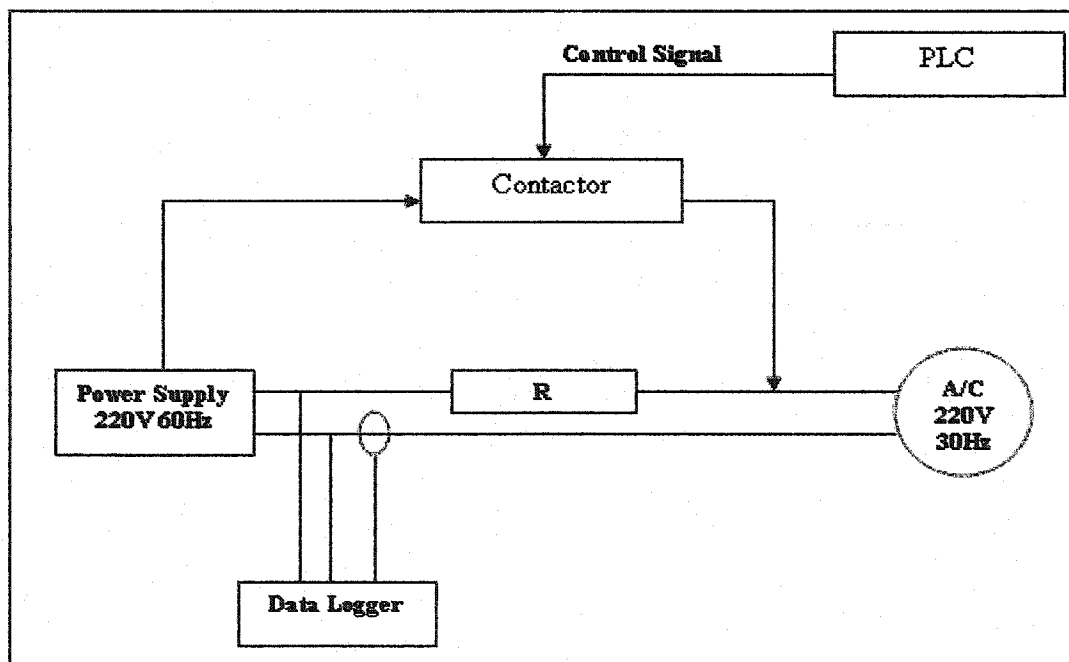

Figure 4.6 : Component of Experimental Setup

Figure 4.6 shows all the elements that were used in the experimental measurement. The following explanation will give a clear description of each component and its function in the circuit.

1. Power supply is taken through an autotransformer, 3-phase 220V, which acts as the main power supply to the system.

2. Data logger is a Leasam Controls' compressor start analyzer, its model number is SSL2 with baud rate 38400. It is similar to the one which was used in the field measurement

3. Power Resistance, 1.4 OHM

4. Air conditioner (A/C), 1.5 ton 220V, Zamil brand.

5. LG Contactor, 25A at 220V contact rating, 24AVC coil voltage (control voltage)

6. Programmable Logic Controller (PLC), Telemecanique brand (Zelio), 24VAC power supply, 12 inputs / 8 outputs model SR1-B201B.

The inrush current of the air conditioners that were used in the experimental measurements was 45.5 while the voltage dip was 12.27% and inrush duration 0.73 sec. It is clearly presented in table 4.1 and figure 4.1 that at step time 0 the resistance was not yet injected to the system. As the step time increased, as indicated in table 4.1, the inrush current and the voltage dip decreased until the best result was achieved at 500ms where the inrush current was 37A, the voltage dip was 10.68% and the inrush duration 0.66sec. Figure 4.6, figure 4.7 and figure 4.8 demonstrate clearly the behavior of the inrush current, the voltage dip and the inrush duration time.

Table 4. 1 : different step time delays and corresponding voltage, Current and inrush time

Step Time (Sec.)	Voltage Dip (%) %	Max. Inrush Current (A) I	Inrush Duration (Sec) T
0	12.27	45.5	0.33
0.25	11.36	43.5	0.33
0.4	10.91	42	0.40
0.5	10.68	36	0.66
0.8	10.45	36	0.66
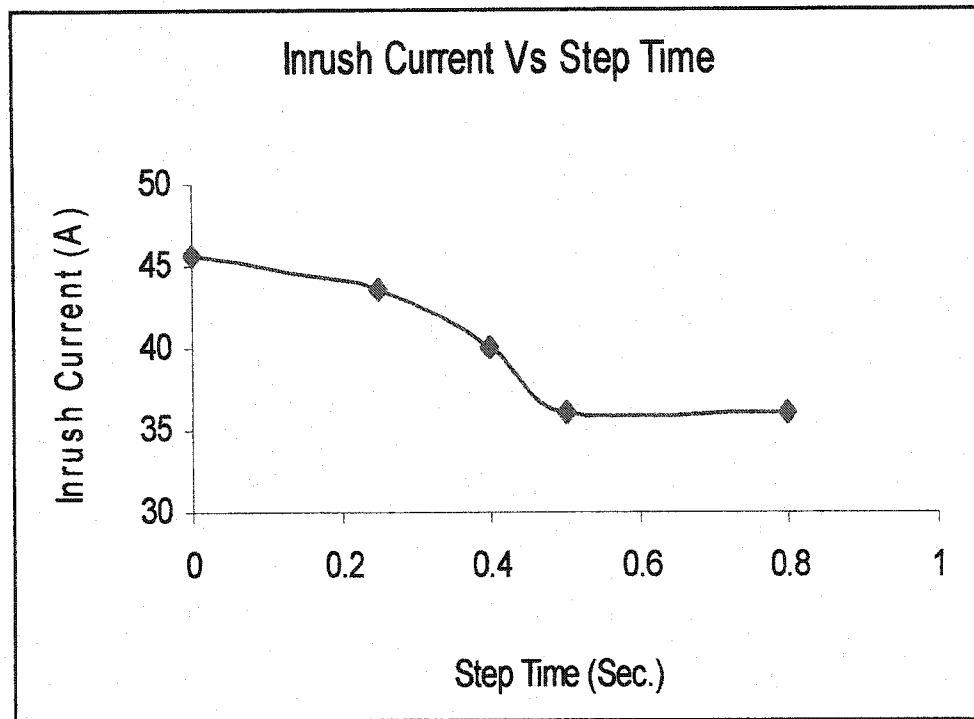
Figure 4.7 : Inrush current Vs. Step time for room air conditioner
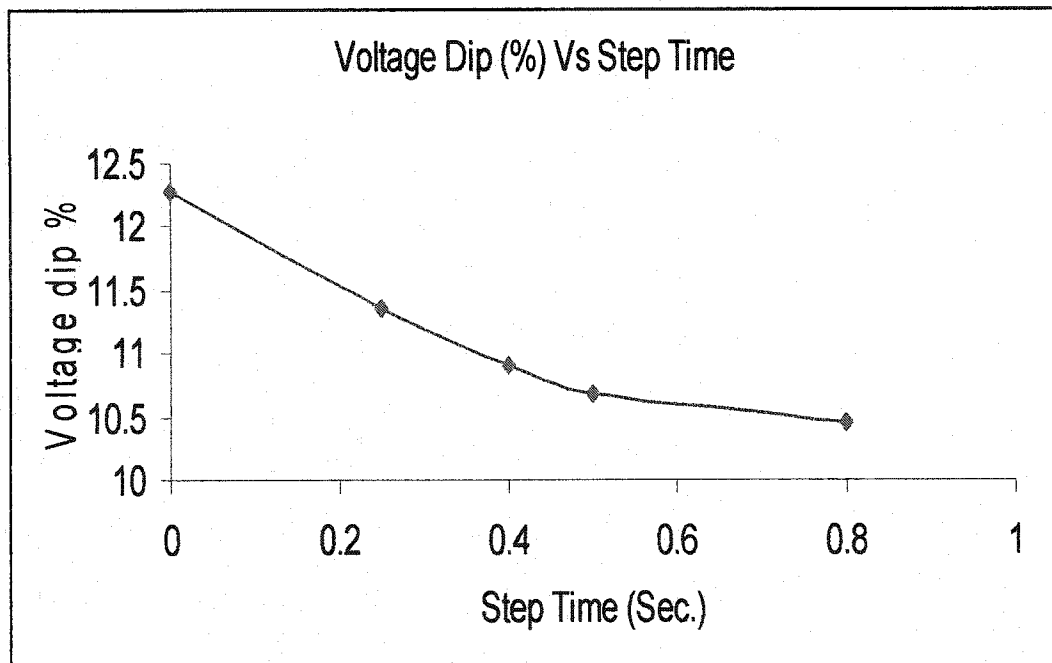

Figure 4.8 : Voltage vs. Step time for room air conditioner
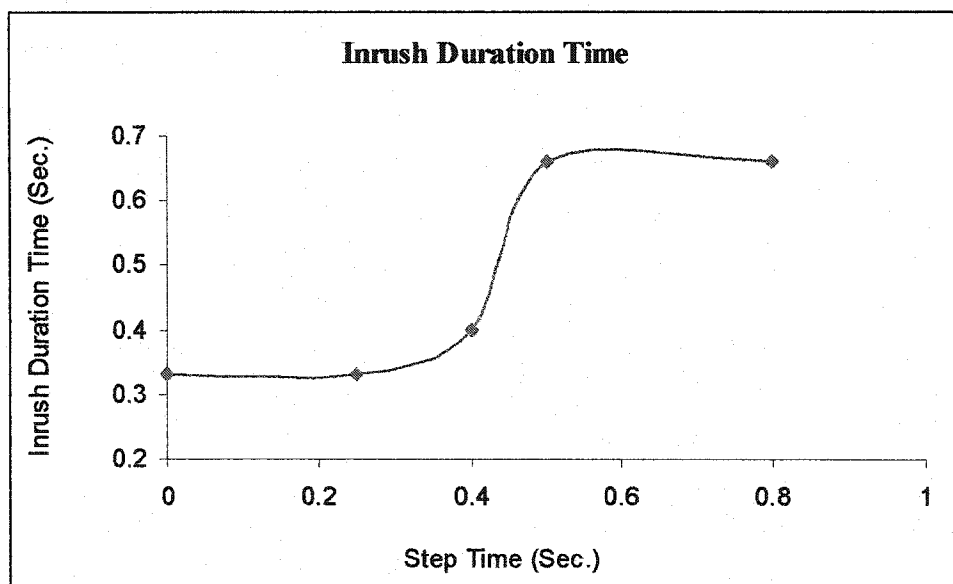
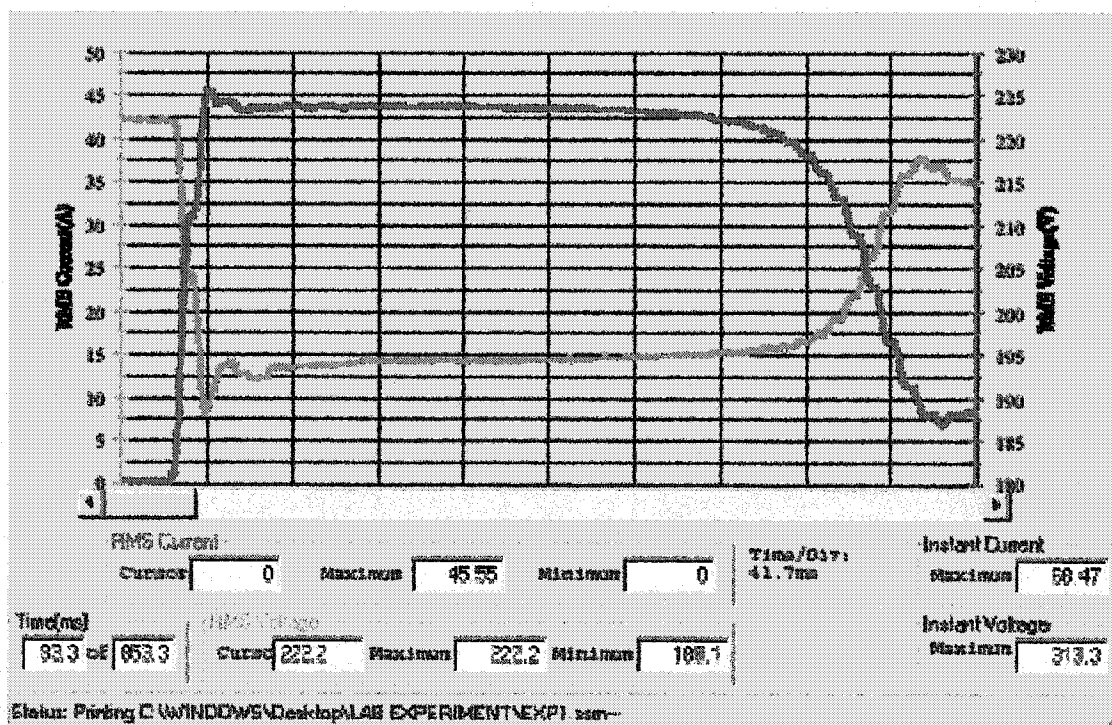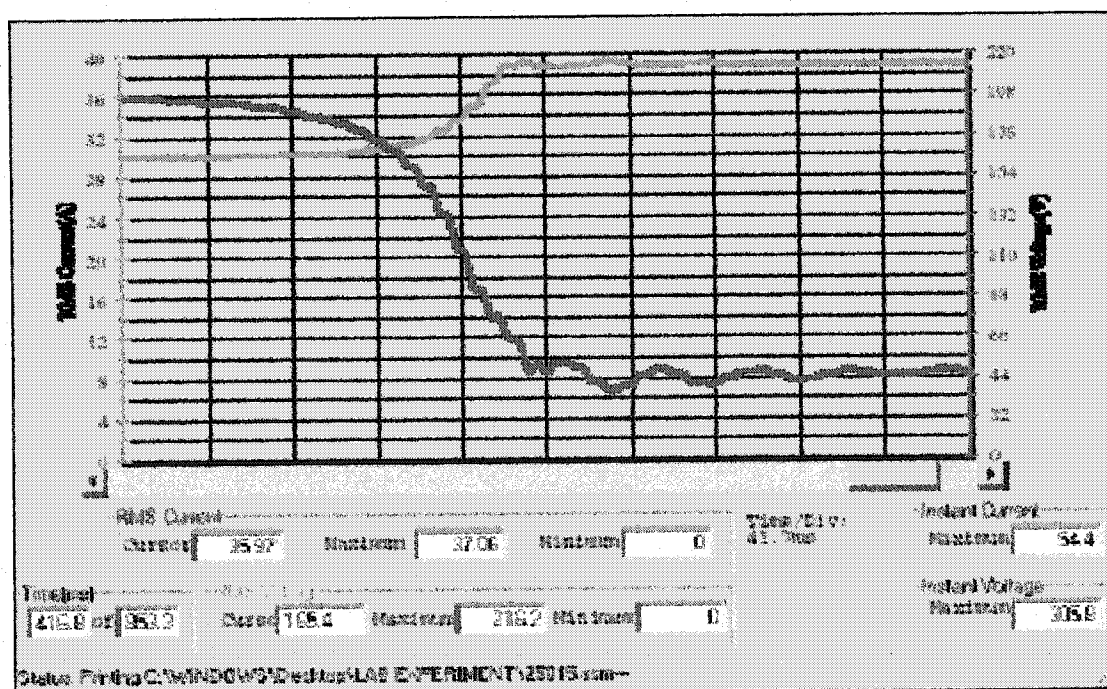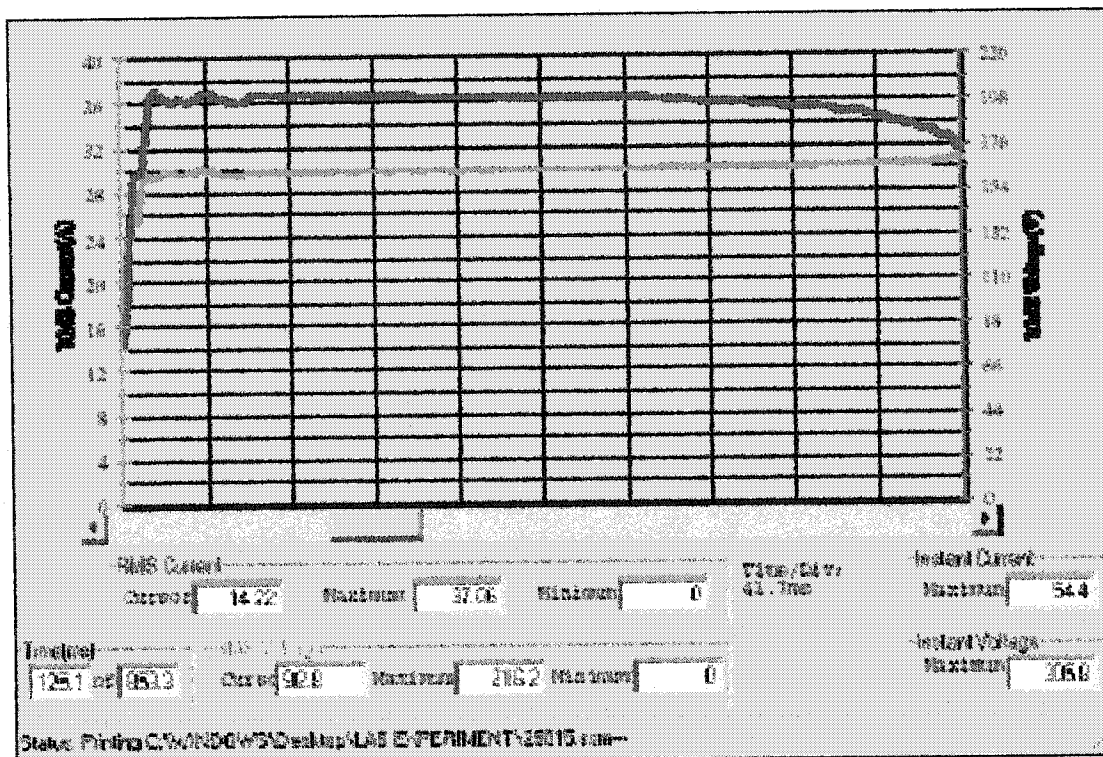Figure 4.9 : Inrush Time Duration vs. Step time

Figure 4.10 : typical Inrush current of the room air conditioner without start resistance

The upper print is continued in the lower print (both are from the same figure).

Figure 4.11 : typical Inrush current of the room air conditioner with start resistance

Figure 4.10 shows the measurement of the experimental result at 500ms step time. The current was reduced from 45.55 to 37.06, which meant a drop of 18.64% and the voltage dip was 10.68. In addition the reduced voltage was 20% less than the rated value. The inrush duration time we can measure by considering both figures, and it was 660 ms.

If we compare these results with the one when the step time was 250 ms, we shall see that it was higher and the peak was still there as it was indicated in figure 4.12. This meant that the selection of the right step time was a critical factor in order to give the motor the required energy to start up. Their will also be a critical time where we have to switch behind. For example, during the switching at 500ms and 800ms excellent results were achieved while at 400ms just before the 500ms the current was worse by 14.28% which proved that the switching time was critical.

In addition to that it was clear that after the addition of a start up resistance, which subjected the system to a reduced voltage at the starting time the instant current up of the system was reduced to 54.4 instead of 68.47 which meant that a reduction by 20.55% in the instant current occurred.

However, one could argue that the inrush duration increased and this may have an effect on the feeder supply, conductor size and insulation. This doubt can be cleared by referring to the National Electric Code (NEC) Standards art 340-10 (Table-310-15). The figure 4.11 below shows the relationship between the current and the ambient temperature and we can see it is almost a linear relationship. It is accepted a 12 AWG wire should conduct a 30A at $30^{O}C$ and as the ambient gets worse we have to de-rate the value as the chart shows.

So, the standard of insulation type starts from 60°C to 90°C. Therefore, any wire conductor has to operate normally at its insulation rated temperature which means that the normal operation of a wire can be 60°C or 75°C or 90°C.

In addition to that, all refrigeration manufacturers are selecting an insulation type of 90°C which is never reached even for a fraction of a second. Therefore, it can be concluded that there will be no effect on the wire insulation by extending the inrush time to 300 ms or more and when comparing the advantages that were achieved, the extension of the inrush time can be ignored. The inrush current can be reduced without any danger to the system.
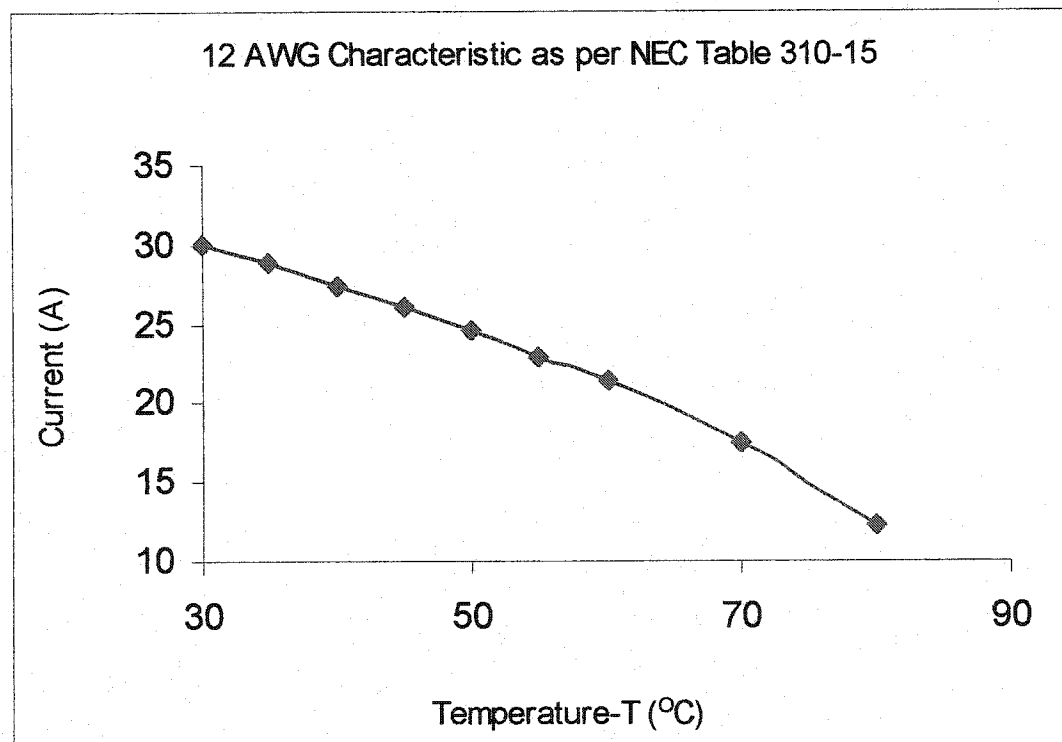
Figure 4.12 : 12 AWG typical Current Vs Ambient temperature characteristics
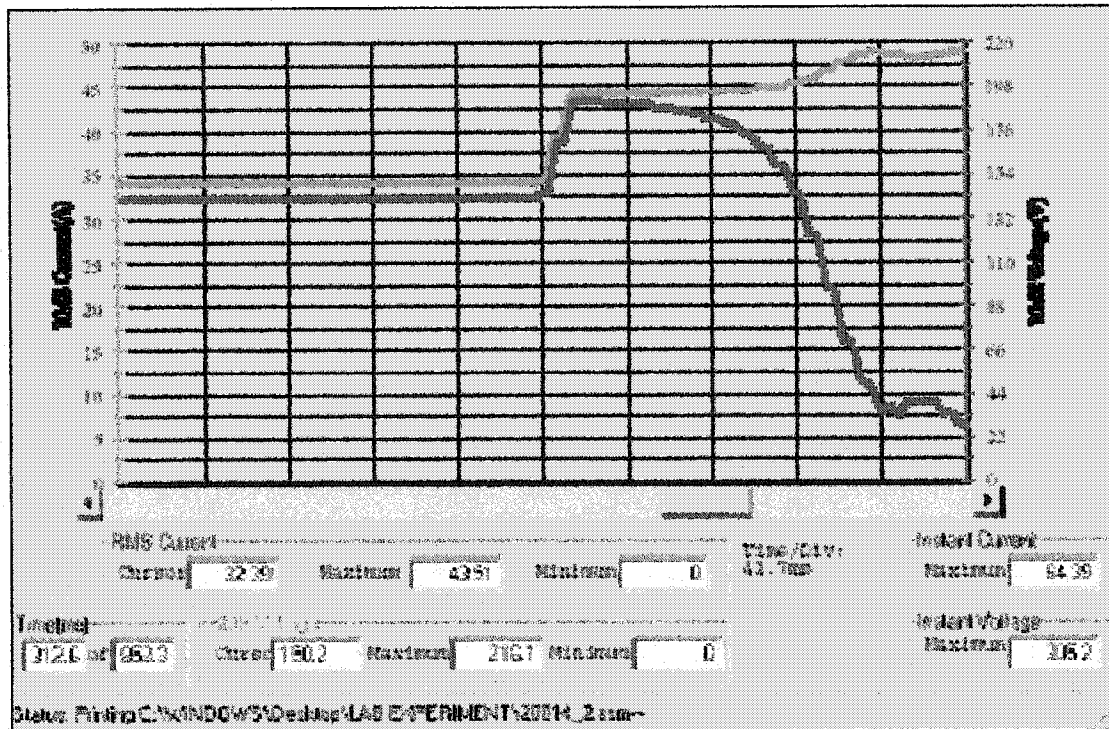
Figure 4.13 : Importance of Switch time

Figure 4.13 explains how critical the switching time is. For example, when we switched at

250 ms on figure 48 the inrush time did not finish its rise or the required energy was not

reached to give the required starting torque and this was why we got a peak current at the

end of the inrush time. Comparing this figure with figure 4.11, indicates that the motor

has already taken its required energy to start up in figure 4.11, while this was not the case

in figure 4.13.

4.4 CONCLUSION OF THE EXPERIMENTAL MEASUREMENTS

The following conclusion can be drawn:

a. The results was similar to design A and the inrush current was improved by about 20% over the regular inrush current.

b. The timing of the step function (to by pass the resistance) was very critical and it had to be after the inrush time had passed or the required energy was already absorbed.

c. This type of design is almost similar to model B and the implementation of this design can be done at a lower cost than any other design. It also, gives us a very good performance. In addition, from a size point of view, it is smaller in size. So, the current limiting resistance is the best practical design and is applicable to the small unit (Consumer level).

d. The disadvantage is mainly the high torque pulsation level which was encountered

CHAPTER 5

5. CONCLUSIONS & RECOMMENDATIONS

5.1 CONCLUSIONS:

A soft starter circuit was designed. In addition to that, two different firing circuits were implemented. These firing circuits were identified as Model A and Model B. Where these models cover several ways of introducing the ramp voltage, model B introduces a constant to the fixed reduced voltage followed by a step increase to reach the rated voltage. We can summarize the different models and their results as follows:

Model A used two-pulse width per period. Both pulses were taken wide enough to secure the required and necessary initial startup voltage. The subsequent pulse widths were increased at every period in a linear manner until it reached the full rated voltage at predetermined ramp times or in a predetermined number of cycles. The frequency of these pulses was 120 pulse/sec. or with rate of 2 pulses/cycle.

An excellent improvement was achieved in model A. The inrush current was reduced by about 30% and the voltage dip was improved by about 15%. The torque pulsation was very good. It was similar to the one without a soft starter. However, the disadvantage of model A lay in the complexity of its implementation. It requires a micro-controller to control the firing circuit which can only be done at a relatively high cost. This relatively high cost and complexity in the design of model A can be justified by its better performance.

Secondly, Model B. This model applies an entirely different and non-increasing pulse width approach. The initial pulse width was applied every half cycle without any increase for relatively large number of cycles. The first two pulse widths were taken wide enough to secure the required and necessary initial startup voltage, and then a sudden step function was injected at an intermediate phase to bring the applied voltage to the rated value.

The performance was closer to that of model A. The inrush current was reduced by about 30% and the voltage dip improved by 15%. The torque pulsation was almost similar to Model A. The implementation of model B does not require a microcontroller. It could simply be implemented by using a bypass resistance at a low cost. As a whole, model B could be a choice when the unit cost is very critical but the performance is certainly compromised.

Model B approach was experimentally investigated and compared with the relevant simulation results. The experimental results were in good agreement with the simulation results. Subsequently model A is recommended for large range of units where its relative cost to the air conditioning unit is acceptable. If produced in a large numbers its production costs will drastically goes down. In that case it could also be integrated with the residential air conditioning unit. So, model A is considered as the best performance option. On the other hand, model B could have a widespread implementation and popularity if the high degree of performance is considered.

5.2 RECOMMENDATION

1. The transient starting energy experimental study might provide useful information in order to further investigate and control the inrush current, the dip in voltage and the inrush duration.

2. Full experimental implementation of model A would be very useful to identify an accurate model for the residential air conditioner which would allow the design of optimal controlling schemes that will minimize the inrush current as well as the voltage dip.

3. Energy conservation investigations could be extended to residential air conditioners via the use of a soft starter, long term voltage control

6. REFERENCES

1. Blaabjerg, F. Pedersen, J.K. Rise, S. Hansen, H.-H. Trzynadlowski, A.M. " *Can Soft Starter Help Save Energy*" IEEE Industry Applications Magazine, Volume 3, Pages 56 - 66 , Sept.-Oct. 1997

2. Electric Power Research Institute "EPRI" Project Summary 2000, www.epri.com/corporate/products-services/project-opps/retail/1001221.pdf

3. A.J.J. Rezek, C.A.D Coelho " *Energy Conservation with use of Soft Starter* " proceeding Harmonics and Quality of Power, Volume 1, Pages 354-359, 1-4 Oct. 2000, Location: Orlando, FL , USA

4. McElveen, R. Toney, M. "*Starting High Inertia Loads*" IEEE Transactions on Industry Applications, Volume: 37, Pages 137 – 144, Jan.-Feb. 2001, Location: Banff, Alta. , Canada

5. Akherraz, M. " *Inrush Current and Speed Regulation of Induction Motor Drives* " Proceedings Electro technical Conference, 6th Mediterranean, Volume 2, On page(s): 1285 - 1288 22-24 May 1991, Location: LJubljana , Slovenia

6. Lukitsch, W.J. "*Soft Starter Vs AC Drivers- Understand the Differences*" IEEE Textile, Fiber and Film Industry Technical Conference, on page(s): 5 pp, 4-6 May 1999. Location: Atlanta, GA , USA

7. Rajendra Prasad, M. Sastry, V.V. "*Rapid Prototyping Tool for a Fuzzy Logic Based Soft-Starter*" Proceedings Power Conversion Conference, volume.2, On page(s): 877 - 880 3-6 Aug. 1997, Location: Nagaoka , Japan

8. Gritter, D. Wang, D. Habetler, T.G. "*Soft starter inside delta motor modeling and its control* "IEEE Industry Applications Conference, volume.2, On page(s): 1137 – 1141, 8-12 Oct. 2000, Location: Rome , Italy

9. Woudstra, J.B., and Deleroi, W. (13-15 July 1988) "*Improved soft starter with thyristor chopper*". Power Electronics and Variable-Speed Drives International Conference, pp.448-451, Location: London , UK

10. Bolognani, S. Zigliotto, M. Unterkofler, K. "*Soft-starting techniques for capacitor-run single-phase induction motors*" IEEE Electrical Machines and Drives conference, On page(s): 41 - 45 , 1-3 Sept. 1997, Location: Cambridge, UK

11. Sastry, V.V. , Prasad, M.R., Sivakumar, T.V. "*Optimal soft starting of voltage-controller-fed IM drive based on voltage across thyristors*" IEEE Transactions on Power Electronics, Volume: 12 On page(s): 1041 - 1051 Nov. 1997.

12.   Kay, J.A. , Paes, R.H. , Seggewiss, J.G. ,Ellis, R.G. *"Methods for the control of large medium-voltage motors: application considerations and guidelines"* IEEE Transactions on Industry On page(s): 1688 - 1696 Volume: 36, Nov.-Dec. 2000, San Diego, CA , USA.

13.   REO UK LTD- "Soft Starter Units for 3-Phase Asynchronous Motor" Technical Manual, www.reo.co.uk

14.   "Electronic Soft starter and their application" internet site.

15.   Group Schneider Co. "Practical aspects of industrial control technology" 1998

16.   M. H. Rashid "Power Electronics Circuit Devices and Application" Second Edition 1993

Vita

- Abdullah Saeed Al-Amoudi was born in Taif, Saudi Arabia in 1975
- Receive the bachelor of Electric Engineering degree from king fahd University of petroleum and minerals Saudi Arabia Dhahran
- Since graduation till 2002 he has been with Al-Zamil Air conditioner factory in Dammam as an Electrical Engineer in R&D Department (Automation and control Section)
- Since 2002 till present he is working with Amiantit Group in Dammam as an Electrical section head (Engineering Department).
- During his industrial experience he has work in several different fields such as drives control, PLC system Engineering, design of power system distribution network (medium voltage) and power quality improvement.