

56613

**A THYRISTORIZED INDUCTION MOTOR SOFTSTARTER:
ANALYSIS AND PERFORMANCE OPTIMIZATION
BY A HYBRID MODEL**

**A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY**

BY

CÜNEYT BARLAK

**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
IN THE DEPARTMENT OF
ELECTRICAL AND ELECTRONICS ENGINEERING**

SEPTEMBER 1996

Approval of the Graduate School of Natural and Applied Sciences



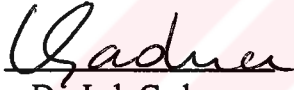
Prof. Dr. Tayfur Öztürk
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.



Prof. Dr. Fatih Canatan
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.



Dr. Işık Çadırcı
Co-Supervisor



Prof. Dr. Muammer Ermiş
Supervisor

Examining Committee Members

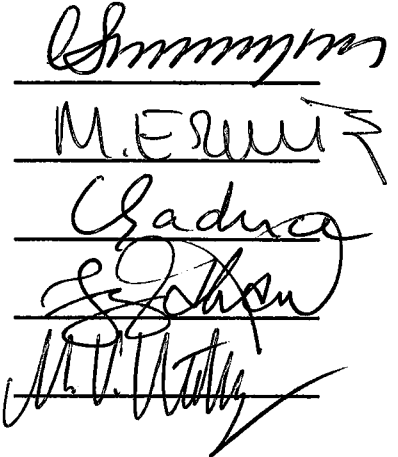
Prof. Dr. Ahmet Rumeli

Prof. Dr. Muammer Ermiş

Dr. Işık Çadırcı

M.S. Erbil Nalçacı

M.S. Volkan Utalay



ABSTRACT

A THYRISTORIZED INDUCTION MOTOR SOFTSTARTER: ANALYSIS AND PERFORMANCE OPTIMIZATION BY A HYBRID MODEL

Barlak, Cüneyt

M.S., Department of Electrical and Electronics Engineering

Supervisor: Prof. Dr. Muammer Ermiş

Co-Supervisor: Dr. Işık Çadircı

September 1996, 168 pages

In this thesis, starting performance of a thyristorized voltage controlled, squirrel-cage induction motor softstarter has been investigated and optimized.

Transient performance analysis of the softstarter has been made by using a hybrid induction machine model which takes into account of disconnected, two-phase and three-phase operational modes of the machine.

A new control strategy has been proposed both to limit the starting current at a desirable level to avoid high current peaks causing fluctuations in the supply voltage and to minimize the starting torque pulsations causing mechanical stress on the motor shaft. Computer simulation results which compare different softstarter control strategies are also given.

Keywords: Softstarter, Hybrid Model, Induction Motor, Optimum Firing Strategy.

ÖZ

TRİSTÖRLÜ BİR ENDÜKSİYON MOTOR YUMUŞAK YOLVERİCİSİ: HİBRİD MODEL İLE ANALİZ VE PERFORMANS OPTİMİZASYONU

Barlak, Cüneyt

Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Muammer Ermiş

Ortak Tez Yöneticisi: Dr. Işık Çadircı

Eylül 1996, 168 sayfa

Bu tezde tristörlü voltaj kontrollü bir sincap-kafesli endüksiyon motor yumuşak yol vericisinin kalkış performansı incelenmiş ve optimize edilmiştir.

Yumuşak yol vericisinin geçici durum analizi, makinanın bağlantısız, iki-faz ve üç-faz çalışma modlarını dikkate alan bir hibrid endüksiyon makina modeli kullanılarak yapılmıştır.

Hem şebeke voltajındaki dalgalanmalara neden olan yüksek akımları önlemek için kalkış akımını istenilen seviyede sınırlandırmak ve hem de motor shaftında mekaniksel gerilmeye yol açan kalkış tork darbelerini minimuma indirmek için yeni bir kontrol stratejisi önerilmiştir. Farklı kontrol stratejilerini karşılaştıran bilgisayar simülasyon sonuçları da ayrıca verilmiştir.

Anahtar Kelimeler: Yumuşak-Yolvericisi, Hibrid Model, Optimum Ateşleme Stratejisi



To My Family

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Prof. Dr. Muammer Ermiř and Dr. Iřık adırcı for their patient supervision, guidance and suggestions that made this design possible.

Special thanks to Sertan Varma, who works in T B TAK Bilten, for his helps and suggestions.



TABLE OF CONTENTS

ABSTRACT	iii
ÖZ	iv
ACKNOWLEDGMENTS	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	xi
LIST OF FIGURES	xii
CHAPTER	
1. INTRODUCTION	1
1.1 General	1
1.2 Conventional Starting Methods for Medium Voltage Induction Motors	3
1.2.1 Line starting of squirrel-cage induction motors	3
1.2.2 Reduced voltage, autotransformer starting	4
1.2.3 Resistance starting	4
1.2.4 Wye-delta starting	5
1.2.5 Wound-rotor motor starting	6
1.2.6 Disadvantages of conventional starting methods ..	6
1.3 Control of Squirrel-cage Motors with Adjustable-Frequency Softstarter	7
1.4 Control of Squirrel-cage Motors with Voltage Controlled Softstarter	8

1.4.1	Review of commercial systems	13
1.4.2	Control strategies	17
1.4.2.1	Voltage ramp control	17
1.4.2.2	Current ramp control	19
1.4.2.3	Speed control	20
1.5	Scope of the Thesis	20
2.	SYSTEM DESCRIPTION AND PROBLEM DEFINITION ...	22
2.1	A Review of Voltage Controllers	22
2.2	Voltage Controller Treated in the Thesis	25
2.2.1	Three-phase mode	28
2.2.2	Two-phase mode	30
2.2.3	Disconnected mode	30
2.3	Problem Definition	31
2.4	Inputs and Outputs of the System	31
3.	MATHEMATICAL MODEL OF THE SYSTEM	32
3.1	Mathematical Model of the Operational Modes	35
3.1.1	Three-phase model (Mode 0)	35
3.1.2	Two-phase model	38
3.1.2.1	Mode 1	38
3.1.2.2	Mode 2	38
3.1.2.3	Mode 3	38
3.1.3	Disconnected model (Mode 4)	38
3.2	Solution Method	40

3.3 Transition Between Operational Modes	41
3.4 Machine Parameters	47
3.4.1 Sensitivity analysis with respect to changes in motor parameters	48
3.4.1.1 Variation of the leakage reactance with respect to the current variation	48
3.4.1.2 Results of the experiment	49
3.4.1.3 Simulation results	51
3.4.1.4 Effects of the variation of the magnetizing reactance on electromagnetic torque and line currents	52
3.4.1.5 Effects of the variation of the motor resistance on electromagnetic torque and line currents	52
3.4.2 Results of the sensitivity analysis	53
4. RESULTS	55
4.1 Minimization of the Torque Pulsations	55
4.1.1 The triggering strategy in the case of continuous motor current	58
4.1.2 The triggering startegy if the line current is discontinuous and the triggering angle α is less than the power factor angle at unity slip	63
4.1.3 The triggering startegy if the triggering angle α is greater than the power factor angle at unity slip	73
4.2 Limiting the Starting Current	80
5. CONCLUSIONS	108
REFERENCES	112

APPENDICES

A. COMPUTER PROGRAM	115
A.1 About the Computer Program	115
A.1.1 Subroutine ARB	115
A.1.2 Subroutine RGKS	116
A.1.3 Subroutine FCT	118
A.1.4 Subroutine FLWCRT	119
A.1.5 Subroutine OUTP	119
A.2 Calculation of the Simulation Data	119
A.3 Computer Program Written in Fortran Computer Language	121
A.3.1 The first program	121
A.3.2 The second program	142
B. TRANSFORMATION MATRICES	166
C. MOTOR PARAMETERS AND SPECIFICATIONS	167
D. LOAD TORQUES OF THE MOTORS USED IN THE THESIS	168

LIST OF TABLES

TABLE

3.1	Transition between operational modes when the initial operational mode is Mode 0	42
3.2	Transition between operational modes when the initial operational mode is Mode 1	43
3.3	Transition between operational modes when the initial operational mode is Mode 2	44
3.4	Transition between operational modes when the initial operational mode is Mode 3	45
3.5	Transition between operational modes when the initial operational mode is Mode 4	46
3.6	Experimental results	50
3.7	Torque and current variation with respect to the leakage reactance	51
3.8	Torque and current variation with respect to the magnetizing reactance	52
3.9	Torque and current variation with respect to the motor resistance	53
4.1	β_2 and β_3 angles with respect to α angles for motor-2	67
4.2	β_2 and β_3 angles with respect to α angles for motor-2	75

LIST OF FIGURES

FIGURES

1.1 Adjustable-frequency softstarter	8
1.2 Voltage-controlled softstarter	9
1.3 Voltage controller used for frequent reversal of induction motors	9
1.4 Starting with voltage ramp	14
1.5 Starting with voltage limitation	14
1.6 Starting with voltage ramp and voltage limitation	15
1.7 Starting with voltage ramp and current limitation	15
1.8 Starting with adjustable starting torque ,voltage ramp and current limitation	15
1.9 Starting with adjustable starting torque and voltage limitation	16
1.10 Soft stop types	16
1.11 Motor speed response which is dependent on load and independent of voltage ramp with light and heavy loads	18
1.12 Voltage ramp	19
2.1 Possible connections for voltage controllers	23
2.2 Another possible connection for voltage controllers	24
2.3 Voltage controller used in the thesis	26
2.4 Supply and motor phase voltages	28
2.5 Three-phase operation	29
2.6 Two-phase operation	29
2.7 Operation in disconnected mode	30

2.8	Inputs and outputs of the system	31
3.1	Representation diagram of three-phase induction machine	33
3.2	Approximate equivalent circuit for locked rotor test	48
3.3	Connection diagram for the experiment	49
3.4	I-X curve obtained from the experiment	51
4.1	a) Electromagnetic torque vs. time, b) phase-A current vs. time with simultaneous switching of motor phases to the supply for motor-2	57
4.2	Firing instants of the thyristors with nonsimultaneous starting to minimize torque pulsations if the line current is continuous	59
4.3	a) Electromagnetic torque vs. time, b) phase-A current vs. time with nonsimultaneous switching of motor phases to the supply and with minimized torque pulsations for motor-2 when $\alpha=30^\circ$	60
4.4	a) Electromagnetic torque vs. time, b) phase-A current vs. time with nonsimultaneous switching of motor phases to the supply and with minimized torque pulsations for motor-2 when $\alpha=60^\circ$	61
4.5	a) Electromagnetic torque vs. time, b) phase-A current vs. time with nonsimultaneous switching of motor phases to the supply and with minimized torque pulsations for motor-1 when $\alpha=60^\circ$	62
4.6	a) Starting, b) transient and c) steady-state current vs. time which are the expanded types of the phase-A current of motor-2 obtained by using the β_2 function and assuming $\beta_3=90^\circ$ as described in subsection 4.1.2 when $\alpha=72^\circ$	64
4.7	a) Starting, b) transient and c) steady-state current vs. time which are the expanded types of the phase-B current of motor-2 obtained by using the β_2 function and assuming $\beta_3=90^\circ$ as described in subsection 4.1.2 when $\alpha=72^\circ$	65
4.8	a) Starting, b) transient and c) steady-state current vs. time which are the expanded types of the phase-C current of motor-2 obtained by using the β_2 function and assuming	

$\beta_3=90^\circ$ as described in subsection 4.1.2 when $\alpha=72^\circ$	66
4.9 Firing instants of the thyristors with nonsimultaneous starting to minimize torque pulsations if the triggering angle α is less than the power factor angle when slip=1 and the line current is discontinuous in the first few periods of starting	68
4.10 Electromagnetic torque vs. time obtained by using the firing strategy mentioned in subsection 4.1.1 for motor-2 when a) $\alpha=68^\circ$ and b) $\alpha=72^\circ$	69
4.11 Electromagnetic torque vs. time obtained by using the β_2 and β_3 values given in table 4.1 for motor-2 when a) $\alpha=68^\circ$ and b) $\alpha=72^\circ$	70
4.12 Electromagnetic torque vs. time obtained by using the β_2 function and assuming $\beta_3=90^\circ$ for motor-2 when a) $\alpha=68^\circ$ and b) $\alpha=72^\circ$	71
4.13 a) Electromagnetic torque vs. time, b) current vs. time obtained by using the β_2 function and assuming $\beta_3=90^\circ$ for motor-1 when $\alpha=72^\circ$	72
4.14 a) Starting, b)transient and c) steady-state current vs. time simulations, which are expanded types of figure 4.16, obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-2 when $\alpha=80^\circ$	74
4.15 Firing instants of the thyristors with nonsimultaneous starting to minimize torque pulsations if the triggering angle α is greater than the power factor angle at slip=1	76
4.16 a) Electromagnetic torque vs. time, b) phase-A current vs. time obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-2 when $\alpha=80^\circ$	77
4.17 a) Electromagnetic torque vs. time, b) phase-A current vs. time obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-2 when $\alpha=100^\circ$	78

4.18 a) Electromagnetic torque vs. time, b) phase-A current vs. time obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-1 when $\alpha=80^\circ$	79
4.19 Ramp triggering function	81
4.20 Cosine triggering function	82
4.21 The starting current limiting method proposed in this thesis	83
4.22 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 obtained by using the method in subsection 4.1.1 to minimize torque pulsations when $\alpha=0^\circ$	86
4.23 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=0.5s$	87
4.24 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=0.5s$	88
4.25 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$	89
4.26 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$	90
4.27 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=3.69s$	91
4.28 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=3.69s$	92

4.29 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=4s$	93
4.30 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=4s$	94
4.31 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with using the method in subsection 4.1.3 to minimize torque pulsations when $\alpha=100^\circ$	96
4.32 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with the method used in the thesis. Here $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.6*I_{NOMINAL}$	97
4.33 Current vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5*I_{NOMINAL}$	99
4.34 Electromagnetic torque vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5*I_{NOMINAL}$	99
4.35 Triggering function vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5*I_{NOMINAL}$	100
4.36 Rotor speed vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5*I_{NOMINAL}$	100

4.37 Current vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3*I_{NOMINAL}$	101
4.38 Electromagnetic torque vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3*I_{NOMINAL}$	101
4.39 Triggering function vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3*I_{NOMINAL}$	102
4.40 Rotor speed vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3*I_{NOMINAL}$	102
4.41 Current vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4*I_{NOMINAL}$	103
4.42 Electromagnetic torque vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4*I_{NOMINAL}$	103
4.43 Triggering function vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4*I_{NOMINAL}$	104

4.44 Rotor speed vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4*I_{NOMINAL}$	104
4.45 Current vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$	105
4.46 Electromagnetic torque vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$	105
4.47 Triggering function vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$	106
4.48 Rotor speed vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$	106

CHAPTER 1

INTRODUCTION

1.1 General

Alternating current has a property that allows it to be transported over long distances by wire more efficiently than direct current. Because of this property, most modern power-generating systems produce ac power. Consequently, the majority of motors used throughout industry are designed to use ac power [1].

There are other advantages of ac motors besides the wide availability of ac power. In general ac motors of the same horsepower rating are smaller and, therefore less expensive than dc motors. Induction motors do not use brushes and commutators. Thus, they are less prone to mechanical wear and sparking. This feature decreases maintenance requirements. Ac motors are well suited to constant-speed applications; several ac motors can be made to run in synchronization at the same speed. Industry uses ac motors in a wide variety of shapes, sizes, and power ratings [1].

Ac motors may be classified in several different ways. For instance, they may be classified according to their power rating as fractional- or integral-horsepower machines. As the name suggests, a fractional-horsepower motor has a rating under 1hp and an integral-horsepower motor has a rating above 1hp. Large-apparatus ac motors are usually found in sizes from 200 to 100,000 hp. The number of phases (usually one or three) applied to the stator windings is another basis for classification. Single phase motors are found in domestic, business, farm, and small-industry applications. Three-phase power is generally used in heavy industry [1].

The induction motor is the most common of all motors but it is seldom used as a generator because its performance characteristics as a generator are unsatisfactory for most applications. The induction machine may also be used as a frequency changer [2].

The rotor may be one of the two types. A wound rotor carries a polyphase winding similar to and wound for the same number of poles as the stator. The terminals of the rotor winding are connected to insulated slip rings mounted on the shaft. Carbon brushes bearing on these rings make the rotor terminals available external to the motor. The squirrel-cage rotor is the second type. It has a winding consisting of conducting bars embedded in slots in the rotor iron and short-circuited at each end by conducting end rings. The extreme simplicity and ruggedness of the squirrel-cage instructions are outstanding advantages of the induction motor [2].

The construction of the squirrel-cage induction motor is relatively simple compared to other machines, but speed control of it requires some kind of drives. Although its energy efficiency is good at full speed and full load, at standstill it has a low impedance. To ensure efficient employment of energy, careful consideration should be given to the method of starting [3].

There are two kinds of softstarting methods for squirrel-cage induction motors: Frequency controlled or voltage controlled. Frequency control is used when the control is done in a wide speed range, but this kind of softstarting is more expensive than the second type called voltage-controlled softstarting which is economical.

In this thesis, voltage-controlled softstarters are investigated, suitable firing conditions for minimizing torque pulsations and limiting the starting current are found and related computer simulation results are given.

First, hybrid model of an induction motor has been set up and state-space representation of the system used to get the computer simulations has been obtained. The motor has become ready to run after the transition between operational modes has been organized. To optimize starting performance,

minimization of torque pulsations is necessary. Minimization of torque pulsations has been investigated in three parts and three different triggering strategies have been found as described in section 4.1. To limit the starting current which is necessary for softstarting, a triggering strategy has been developed as given in section 4.2. These triggering strategies mentioned in section 4.1 and section 4.2 have been tried on two different induction motors and good simulation results given in chapter 4 have been obtained. One of the motors is small-sized induction motor and the other is medium-sized induction motor and their parameters are given in appendix C. To solve the differential equations, a fourth-order Runge-Kutta method has been used in the computer program. More information about this method and the computer program is given in appendix A.

1.2 Conventional Starting Methods for Medium Voltage Induction Motors

1.2.1 Line starting of squirrel-cage motors [4]

The simplest way to start a squirrel-cage induction motor is merely to connect it to the line. Under these circumstances the motor will usually draw from five to seven times full-load current and develop a torque of 150 to 250 per cent of full-load torque.

One objection to this type of starting especially for medium voltage induction motors is that the motor takes a very large current from the line for a short time period. This large current is likely to cause fluctuations in power supply voltage which may be objectionable.

In modern installations, it is customary to use a push-button-operated magnetic switch or contactor to connect the motor to the line. This kind of device is usually arranged to open the circuit in case of current or voltage failure.

In some cases direct-on-line starting may be injurious to the connected machinery on account of the very rapid acceleration and the high torque

developed. For example, if a motor is belted to its load, it may be that the large torque developed may cause the belt to slip, causing excessive wear. In such cases it is obviously desirably to use a starter to reduce the torque developed.

1.2.2 Reduced voltage, autotransformer starting [4]

An autostarter, or compensator, consists of an autotransformer and the necessary switches. In a 3-phase autostarter the transformer ordinarily has 3 legs with 1 winding on each of the legs and the 3 windings connected in wye. A reduced voltage is applied to the motor with the starting connection. When the motor has reached about 80 per cent of nominal speed, the connections are changed so that the transformers are deenergized and the motor is connected to full line voltage. The switch which makes these changes may be air-break or may be immersed in oil so as to reduce sparking. In manually operated starters, provision is made so that the operator must first throw the handle to the starting position and later throw it quickly to the running position.

In addition to making the changes of connections as described above the compensator is usually provided with automatic no-voltage and overload protection. Usually both of these have delayed actions so that momentary interruption of the voltage or momentary overload will not disconnect the motor from the line.

Most compensators are provided with three sets of taps so as to apply approximately 80, 65, or 50 per cent of line voltage to the motor. The lowest taps which will give satisfactory starting are ordinarily used.

1.2.3 Resistance starting [4]

Frequently a resistance starter is used instead of an autostarter to obtain reduced voltage starting. Starting resistors are connected on each phase with

series/parallel contacts. To start, the series contacts are closed to connect the three resistors. When the motor has accelerated, closing of parallel contacts on the resistors will short out the starting resistors and the motor then operates at full line voltage. If desirable, these resistances can be cut out gradually, or they can be cut one after the other, thus making the starting somewhat smoother. Even without these refinements the starting will be somewhat smoother than with autotransformer starting.

1.2.4 Wye-Delta starting [4]

In the case of some motors, it is possible to use a starting switch which connects the motor in wye for starting and in delta for running. This reduces the voltage applied over each phase by a factor $1/\sqrt{3}$, and so the torque developed is one-third of that which would be developed if the motor were connected in delta. Since the current in each phase is reduced by a ratio of $1/\sqrt{3}$, and since these are connected in wye rather than in delta, the line current is reduced to one-third. Hence, when the motor is connected in wye, it takes one-third as much starting current and develops one-third as much torque.

It may be considered that it is an ideal method of starting a motor, because no autotransformer or resistors are required; however, the method has several disadvantages which restrict its use. It is not usually desirable to wind small motors in delta, because this requires coils wound with more turns of finer wire. Also, it is necessary to bring out 6 leads instead of 3. Moreover the method is inflexible since it is possible to get only one value of starting torque, and one-third torque is insufficient for many applications. With autotransformer or resistance starting, the torque can be adjusted in accordance with the requirements of the drive. This method of starting is therefore used infrequently in applications where only a small starting torque is required.

1.2.5 Wound-rotor motor starting [4]

Wound-rotor motors are practically always started with full line voltage applied to the stator. The value of starting current is controlled by inserting resistors into the rotor. The resistors are usually connected in wye, and provision is made for cutting out the resistances in several steps as the motor comes up to speed. The controller or starter may take the form of an ordinary manual dc starting box, except that there will be three sets of contacts. The control panel includes a line contactor for connecting the stator to the line, also an overload relay. In the case of larger size motors a drum controller is used to carry the contacts and cut out the various sections of the resistances or, the resistance steps may be cut out by magnetic contactors similar to the type used to connect the stator to the line. Also in the case of very large motors, water rheostats have been employed with success.

When starting current is reduced by the use of secondary resistance in this manner, the starting torque per ampere, or starting efficiency is increased owing to improvement of motor power factor. The improvement is so pronounced that increased motor resistance may not only decrease the starting current but at the same time produce more starting torque. When primary resistance or a autostarter is used to reduce starting current however, the starting efficiency is reduced.

1.2.6 Disadvantages of conventional starting methods [3]

There are two main disadvantages with the above-mentioned methods of motor starting; first, the high current peaks, particularly those associated with wye-delta and autotransformer starting. When these current peaks occur, the supply system should be able to withstand them without any noticeable decrease in voltage. For that reason, many electricity supply authorities limit direct-on-line started motors to a maximum of around 5.5 kW.

In 'island' installations where power is generated on site and there is no connection to a main power supply (a typical example being an offshore or desert-location oil or gas production installation) voltage regulation may be a serious problem. Such sites are extensively equipped with induction motors. Starting of the very big motors has to be coordinated with generator availability. This is not usually a problem, given that procedures are effective and observed. The diverse duty-cycles of the many medium-sized and smaller motors may, however, be capable of causing unpredictable system-voltage regulation, all such motors commonly being direct-on-line started.

The second problem is that of mechanical shock due to the sudden torque stresses, caused by the current surges, that have to be observed by gearboxes, belts, drive shafts and driven equipment. Such stresses inevitably tend to reduce the serviceable life of these components.

Difficulties can also be experienced with particular types of loads such as cranes, where load oscillation can be started by the initial shock. Similarly, shock waves can be transmitted along hydraulic pipework, weakening joints in pumping systems. In conveyor systems, loads may be displaced or damaged on start-up. What is needed is therefore a system that increases the voltage smoothly, so eliminating transient current and torque surges.

1.3 Control of Squirrel-cage Motors with Adjustable-Frequency

Softstarter [2]

The synchronous speed of induction motors is directly proportional to the applied frequency. Speed control of these motors is obtained by supplying electrical power to the stator from an adjustable-frequency, solid-state control unit. The induction motor will follow the frequency within the slip frequency. Expensiveness is the major disadvantage of this kind of softstarting systems with respect to voltage controlled softstarters.

The adjustable-frequency power is generated by a thyristor circuit called an inverter. To form a set of three-phase voltage waves in an inverter, six thyristors or transistors are connected in a bridge configuration to a dc bus. By switching the semiconductor switches in a prescribed sequence, a rectangular or stepped approximation to a set of three-phase sine waves is formed at the ac terminals of the bridge. By speeding up or slowing down the switching rate, the frequency and motor speed are controlled. As a result of this, softstarting is performed.

A typical drive system consists of a rectifier to convert power from ac supply line to dc form, an inverter to form the adjustable-frequency ac from the dc bus, an induction motor, and a control system to set the frequency, adjust the motor voltage, and insure that the maximum torque of the motor is not exceeded during speed changes. A block diagram of a adjustable-frequency softstarter is shown in figure 1.1.

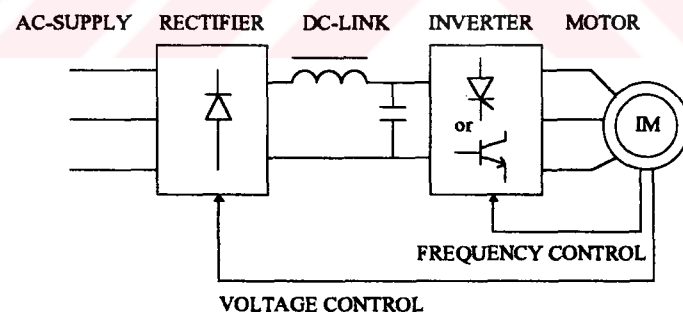


Figure 1.1 Adjustable-frequency softstarter.

1.4 Control of Squirrel-cage Motors with Voltage Controlled Softstarter

This type of softstarting is used when the supply system may not withstand high current peaks and mechanical shock due to sudden torque

stresses during starting of a large induction motor and when speed control is required for small motors in a limited shaft speed range. A block diagram of a voltage controlled softstarter is shown in figure 1.2.

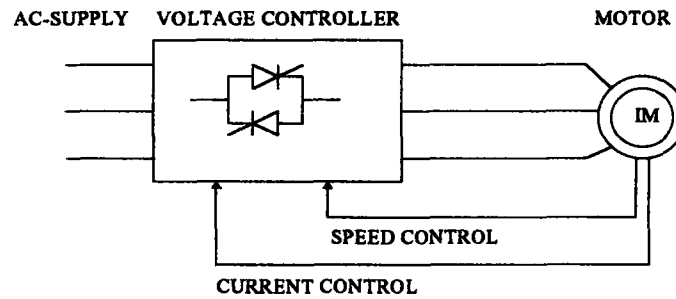


Figure 1.2 Voltage-controlled softstarter.

Another application of such systems is the frequent reversal of the induction motor which requires additional power semiconductors shown in figure 1.3.

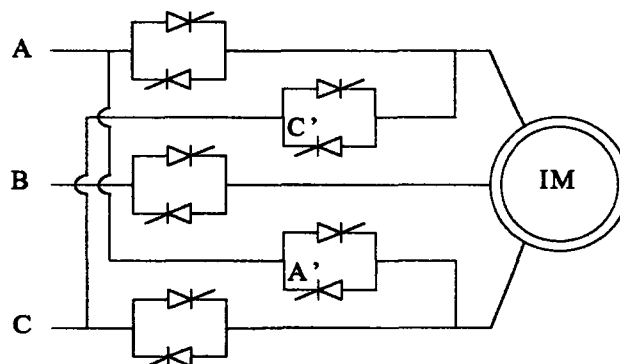


Figure 1.3 Voltage controller used for frequent reversal of induction motors.

Voltage control is achieved by the use of a voltage controller which consists of a power circuit containing six thyristors arranged in anti-parallel pairs on each phase, and a control circuit which determines the firing instants of the thyristors. This control circuit gives firing pulses to the gates of the thyristors. Firing pulses are reduced during a time period and as a result voltage applied to the motor terminals is smoothly increased. Because the voltage across the motor windings ramps up smoothly, the rapid increase of the phase currents are avoided and current limiting is performed. However, this method is not suitable to minimize the pulsations in torque. In order to minimize the torque pulsations, triggering instants of the thyristors in each of the three phases should be set a predetermined value at the first period of the starting. The starting torque is directly proportional to the square of the applied voltage. Depending on the load requirements, starting torque can be obtained by adjusting the firing instants of the thyristors to a value at which the required starting voltage is obtained.

Numerous papers have been written on the subject of performance of three-phase induction motors fed from a thyristor voltage controller. While some of the papers are about steady-state performance, some of them discuss the transient analysis of the induction motors, but only a few of them describes about soft starting.

In literature; The steady state performance of three-phase induction motors is analyzed in terms of phase variables rather than d-q axis variables. A closed form solution is obtained. Truncation, iteration or integration is not required in the solution process [5].

Representation of a nonsinusoidally supplied induction motor as a back emf in series with a series RL circuit has been developed and steady-state performance evaluation of the motor-controller system can be conveniently achieved by the developed model. Also, it is shown that the effect of the back emf on the system performance is significant especially at high operating speeds [6].

Controlled starting of induction motors is discussed and a method for ac control is proposed. According to this method, there is a system that matches an induction motor with a starter that ramps the starting current up from the zero level, while still ensuring a proper start for the driven load. A feedback loop measuring kVA controls the amount of power being supplied to the motor during starting cycle [7].

Among all the reduced-voltage starter types, the solid state reduced voltage starter provides the smallest acceleration for a squirrel-cage induction motor [8]. In addition, there is adjustability of the current and torque while starting. One of the limitations of the solid-state starter is that for loads which take a long time to accelerate, higher capacity SCR's and special overload may be necessary. Another limitation is the heat given off by the SCR's when they are conducting. This heating effect may be avoided after starting if a shorting contactor is used. Considerations must also be given to harmonics during times when the SCR's are not in full conduction.

A general method of analysis of the transient performance of SCR-controlled three-phase induction motors has been presented [9]. The method utilizes the instantaneous symmetrical components transformation, with all electrical variables referred to stationary stator frame. The distinct advantages of the model over the phase-variable model have been highlighted. In-line switching constraints are incorporated and simulation of all operating modes is accomplished without reference to rotor position.

A method of solution by digital simulation using phase variables has been developed for transient analysis of three-phase SCR-controlled induction motors [10]. This method enables transient current, speed and electromagnetic torque patterns to be predicted for run-up conditions and conditions of operating mode transition for constant triggering angle during starting.

The results in reference [11] show that transient over synchronous speed operation and negative transient torques during acceleration can be explained by the instantaneous speed variations of the rotating airgap field.

The assumption, that the transient mains-frequency torque is due to mainly to the transient asymmetrical flux produced by the transient magnetizing current is confirmed by the experimental results[12]. It is seen from the results that this transient flux also produces a transient negative torque owing to the generation of the transient speed-frequency currents.

The switching of a three-phase induction machine can be achieved without the transient problems associated with high currents. Utilizing a dynamic function for the triggering angle of the voltage controlled thyristors proves to be a simple and effective way to improve transient performance. By employing the proper triggering function, the rate at which the main flux builds up is decreased, and transient torque is smoothed. Defining a value for the maximum required transient current is possible by choosing the starting angle of the triggering function [13]. Only a cosine function is used to minimize torque pulsations during the starting time. Its frequency is determined depending on the slip of the motor.

Solid-state ac motor starters using switched power semiconductors are being used increasingly to replace electromagnetic line starters and reduced voltage starters because of their soft start capability and other advantages. In reference [14], the operation, theory, options, and rating practices of these devices are considered as well as where and how they are being or can be used in the pulp and paper industry.

In this thesis, transient performance of induction motors is investigated using a voltage controlled softstarter. Three different triggering strategies are presented to minimize torque pulsations depending on the triggering angle α . During the study on this thesis it has been seen that torque pulsations depends on the triggering instants of the thyristors at the first period of the starting. These strategies calculate the firing instants of the thyristors for the first period. Also a firing strategy is developed to limit the current to a prespecified value. In this strategy, firing angles of the thyristors are calculated depending on the value of the line current. If the current is below the limit value, a cosine triggering

function whose frequency is constant is used to decrease the triggering angles of the thyristors. Otherwise, triggering angles are kept constant until the line current decrease below the limit value.

1.4.1 Review of commercial systems

During the preparation of the thesis two kinds of commercially used softstarters are investigated. One of them is Siemens product called Sikostart 3RW22. Current limit at start is 2-6 times the rated current and depending on the current limit the maximum starting time varies between 2 and 200 seconds. Different kinds of starting methods are available for different load and working conditions. These are as follows: starting with voltage ramp shown in figure 1.4; starting with voltage limitation shown in figure 1.5; starting with voltage ramp and voltage limitation shown in figure 1.6; starting with voltage ramp and current limitation shown in figure 1.7; starting with adjustable starting torque, voltage ramp and current limitation shown in figure 1.8 and finally starting with adjustable starting torque and voltage limitation shown in figure 1.9. There are also two kinds of softstop. One of them is for pumps and cranes and the other is for systems with high inertia as shown in figure 1.10. Symbols in the figures are as follows :

- U : Motor terminal voltage;
- U_s : Starting voltage;
- U_B : Limiting voltage;
- U_L : Adjustable starting voltage;
- U_N : Nominal voltage;
- I : Motor current
- I_A : Starting current at direct-on-line starting;
- I_s : Starting current;
- I_B : Limiting current;

I_N : Nominal current;

t : time

t_L : Adjustable starting time;

t_R : Ramp time;

t_B : Limiting time;

n : speed.

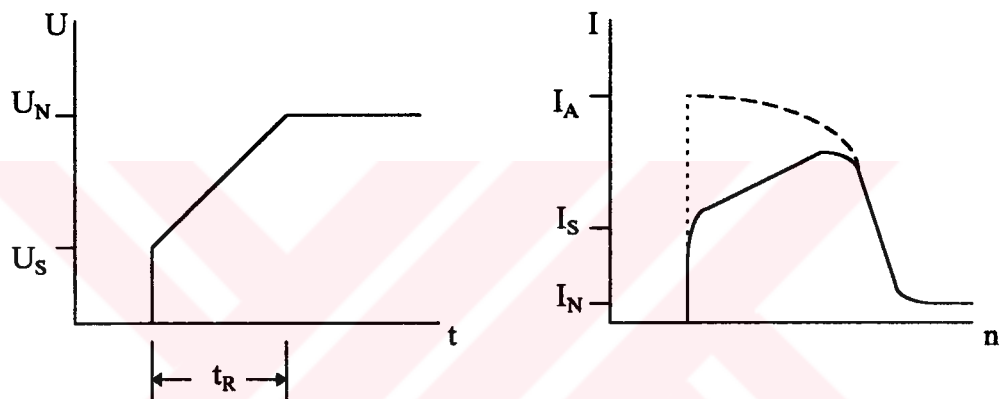


Figure 1.4 Starting with voltage ramp.

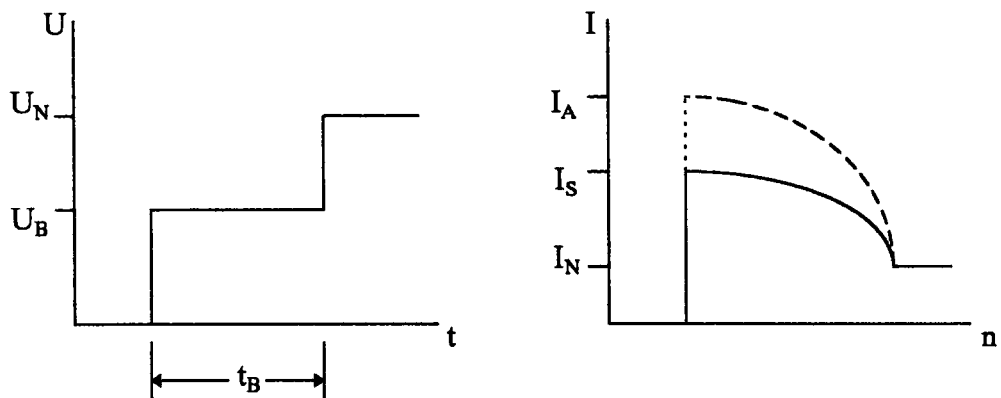


Figure 1.5 Starting with voltage limitation.

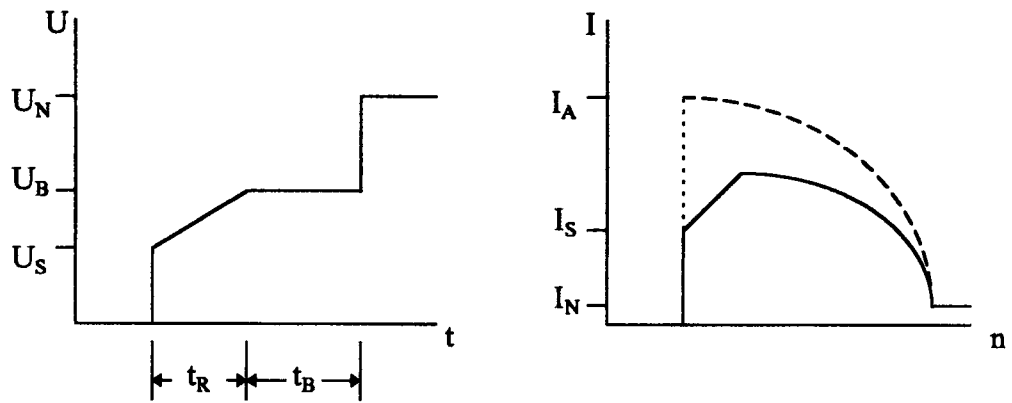


Figure 1.6 Starting with voltage ramp and voltage limitation.

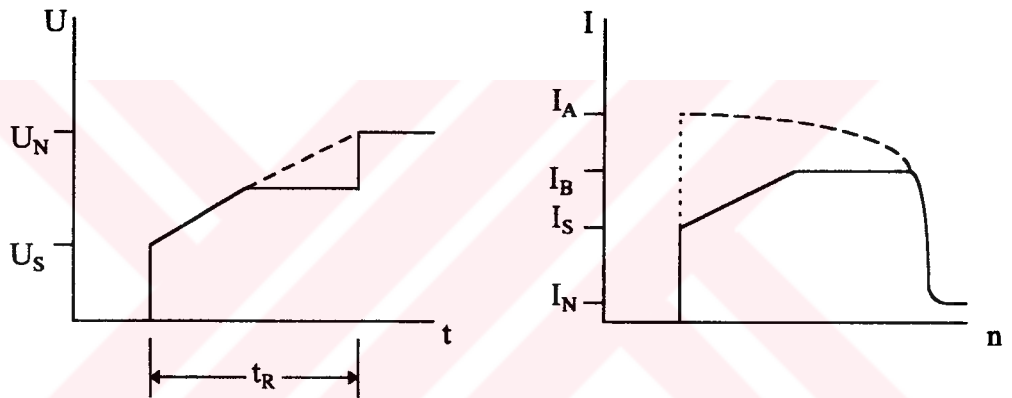


Figure 1.7 Starting with voltage ramp and current limitation.

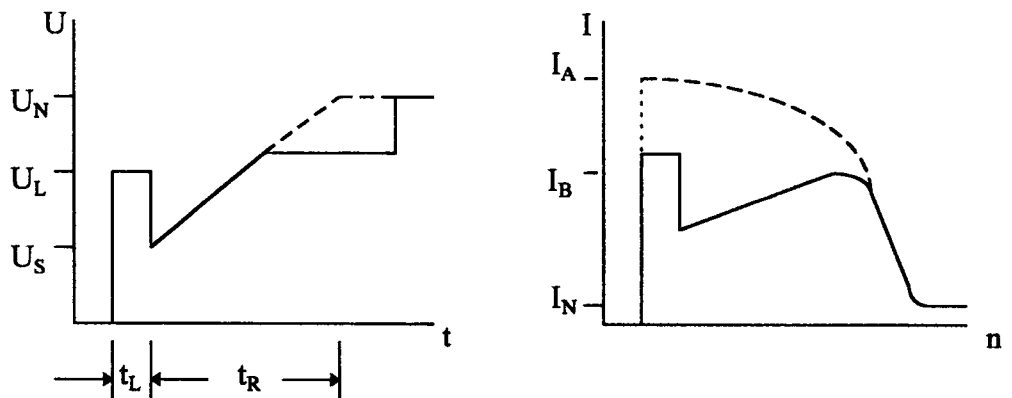


Figure 1.8 Starting with adjustable starting torque, voltage ramp and current limitation.

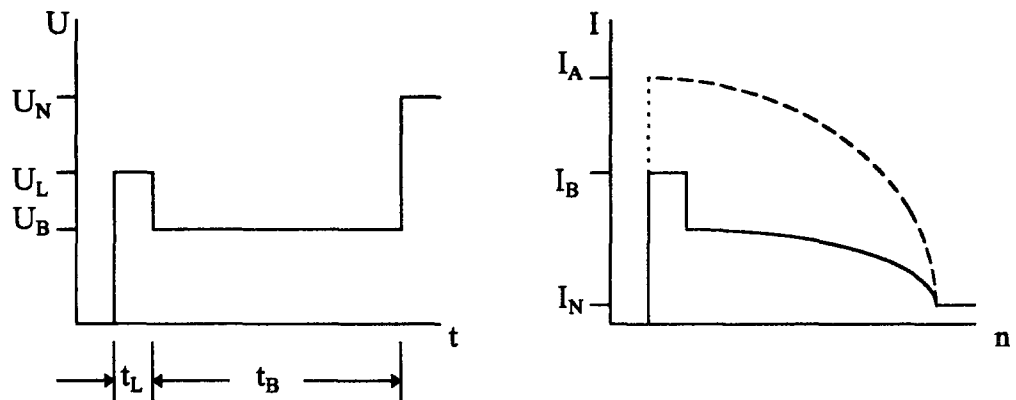


Figure 1.9 Starting with adjustable starting torque and voltage limitation.

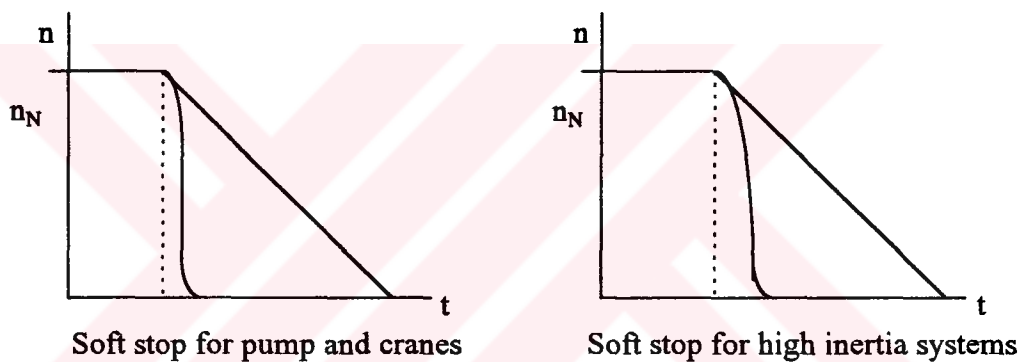


Figure 1.10 Soft stop types.

The second type softstarter is ABB product called Softstart. For this softstarter, only one kind of control strategy is used. During the starting time voltage increases following a ramp. The time up voltage can be set between 0.5 and 60 seconds and current limit at start is 2-5 times the rated current. Softstart also has a soft stop function with adjustable ramp time between 0.5 and 240 seconds.

1.4.2 Control strategies

There are various types of control strategies used in softstarters. Each strategy has been developed to satisfy different load conditions and different working conditions, but all of them carry the main properties of softstarting.

1.4.2.1 Voltage ramp control [3]

When used in voltage ramp control, the time taken for the voltage across the motor windings to reach that of the supply voltage is set by the ramp input on the control circuit. The ramp time is adjustable from the lowest value to the highest point. There is, however, one problem with ramping the motor voltage up from zero volts to the maximum supply voltage, which arises from the fact that many mechanical systems require a breakaway torque, below which the rotor of the motor remains stalled by the load: until the voltage has increased sufficiently to cause enough current to flow to overcome this breakaway torque the motor will remain at standstill. This therefore wastes power and causes overheating.

The problem can be solved by setting the control circuit to deliver the required initial voltage by suitably advancing the thyristors initially. This voltage level is usually adjustable between 0 to 50% of the supply voltage, and is referred to as pedestal voltage as shown in figure 1.12.

It should be noted that the ramp time is the time taken for the voltage across the motor windings to reach maximum, not the time taken for the motor to get up to speed. If the motor is lightly loaded it can reach full speed long before the motor voltage has reached its maximum value. Similarly, if the motor is heavily loaded, its voltage can reach maximum before the motor reaches full speed. These situations are shown in figure 1.11.

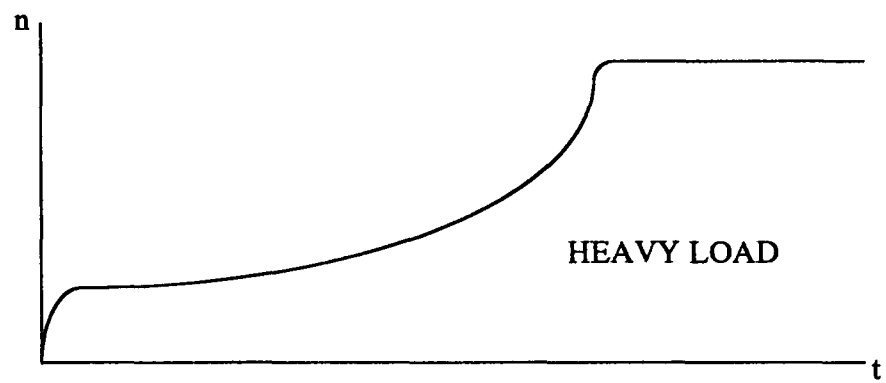
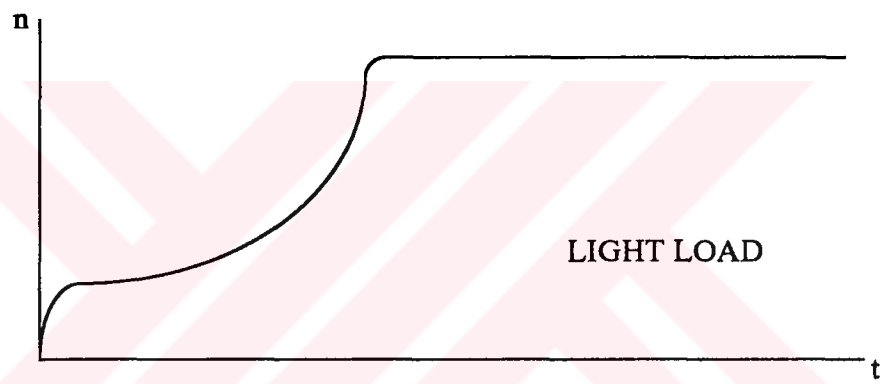
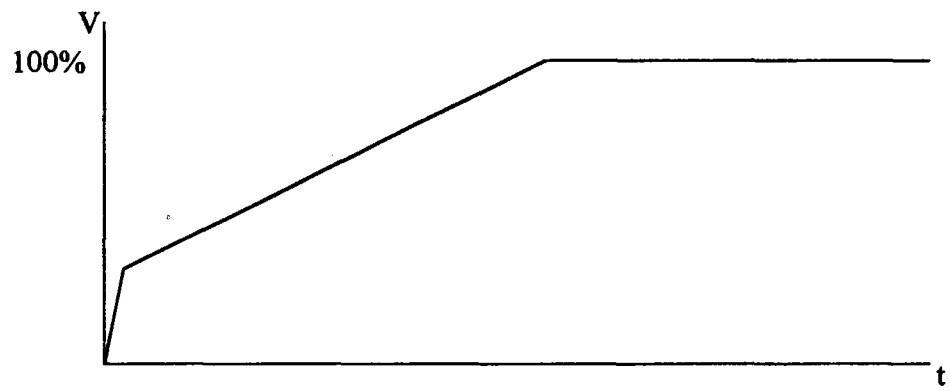


Figure 1.11 Motor speed response which is dependent on load and independent of voltage ramp with light and heavy loads.

Also, the ramp time set on the control circuit will automatically be extended if the motor starting current rises above the current-limit level on the control circuit.

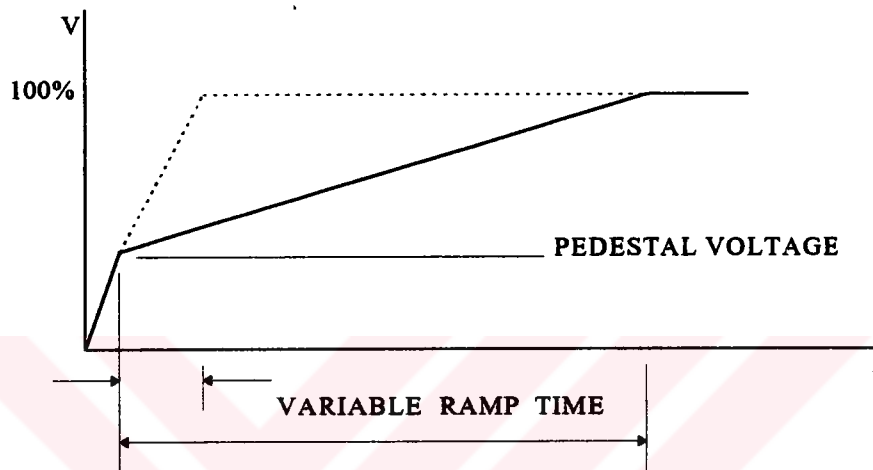


Figure 1.12 Voltage ramp.

1.4.2.2 Current ramp control [3]

This mode of operation is very similar to that of the voltage ramp mode, except that current instead of voltage is increased gradually over a period of time. This is done by taking the output of the ramp circuit and using it to control the current limit function.

Under current-ramp control, the current limit in the control circuit takes full control of the thyristor firing angles, allowing them to advance to a point where the motor current reaches the current-limit set point. The phase angle will then be held at this point until the current starts to drop, so allowing the thyristors to advance again.

This mode of control has application when the motor needs to be accelerated in the shortest possible time whilst limiting the current to a preset value because of supply restrictions or the other reasons. The actual acceleration rate of the motor will depend on how heavily it is loaded: the lighter the load, the faster the acceleration.

1.4.2.3 Speed control [3]

To use a softstarter in speed control it is necessary to fit a tachogenerator to the motor shaft to provide a speed feedback to a control loop to maintain a linear rate of change of speed during the motor starting. Also, by controlling the input to the ramp circuit, the motor can be made to run continuously at any speed between standstill and full speed. Only fan or centrifugal pump load, or other loads with exponential characteristics, are suitable for this type of control and it is essential to ensure that the motor has adequate cooling to handle the additional heating losses caused by running at high slip.

1.5 Scope of the Thesis

In this thesis, voltage controlled softstarting method is investigated for an adequate starting of induction motors and minimization of torque pulsations and current limitation is performed theoretically.

In chapter 1, conventional starting methods and their disadvantages are described. Softstarting methods and their applications in commercial systems are also given in this chapter.

In chapter 2, a review of voltage controllers is given. Possible configurations of voltage controllers are shown. Their operational principles, advantages and disadvantages are explained. The voltage controller used in the thesis, its work and usage are also described in this chapter.

Mathematical hybrid model of induction motors and state-space equations for every operational modes are given in chapter 3. How the operational modes change from one mode to another one is explained. Sensitivity analysis with respect to changes in motor parameters are also given in this chapter.

In chapter 4, optimum firing instants of thyristors to minimize torque pulsations and firing function to limit the starting current are described and simulation results are presented.

In chapter 5, general conclusions and proposals for further work are given.



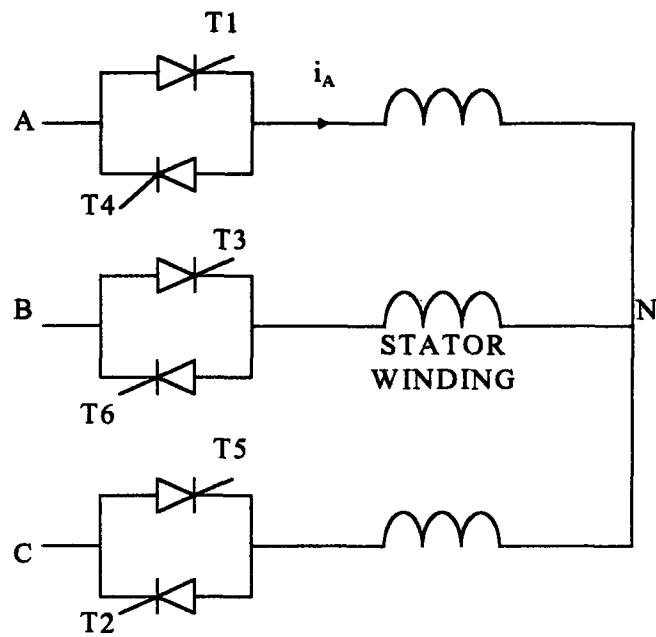
CHAPTER 2

SYSTEM DESCRIPTION AND PROBLEM DEFINITION

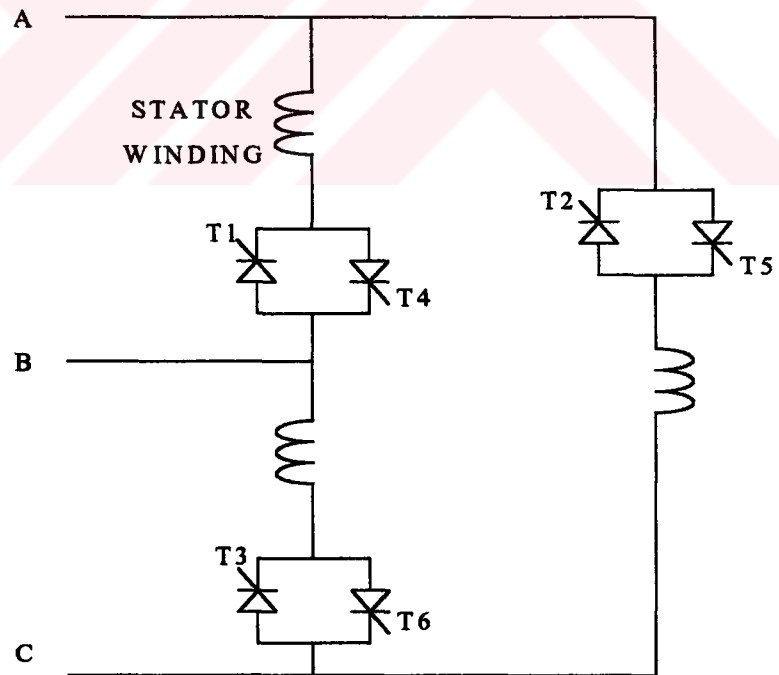
2.1 A Review of Voltage Controllers

Figure 2.1 shows two commonly used 3-phase ac voltage controller circuits for wye and delta connected induction motor stator windings. Connection D_1 can also be used with a delta connected stator. Motor losses increase with a delta connection, because a third harmonic current may circulate. Each thyristor pair of circuit D_1 carries the line current, whereas each thyristor pair of circuit D_2 carries only the phase current. Thus in D_2 the thyristor current rating is reduced by a factor of $\sqrt{3}$. Under normal operation, the maximum voltage to which the thyristors of circuit D_1 are subjected is $(\sqrt{3}/2)$ times smaller than that of the thyristors of circuit D_2 . However, under abnormal conditions, the maximum voltage is the same (that is, equal to the line voltage). Such an abnormal condition can arise if thyristors in one of the phases are conductive by device failure or misfiring, when all phases are intended to be off. Since such abnormal can always arise, the thyristor voltage rating is chosen to be higher than the peak of the line voltage. Thus voltage controller D_2 would cost less than circuit D_1 . However, circuit D_2 can be used only when the machine is delta connected and both ends of the phase windings are available. This situation may not exist in many commercial available motors.

A cheaper controller can be obtained by replacing one thyristor in each phase of circuit D_1 by a diode. This approach introduces even harmonics. The predominant harmonic is the second, compared to the fifth and third for the circuits D_1 and D_2 , respectively. The presence of the low-frequency second harmonic increases the losses considerably, particularly at low motor speeds.



Circuit D1.



Circuit D2

Figure 2.1 Possible connections for voltage controllers.

Asymmetrical circuits are obtained by removing one or two antiparallel thyristor pairs from circuit D_1 and connecting corresponding motor phases directly to the source as shown in figure 2.2. These asymmetrical circuits cause asymmetrical operation of the induction motor and increase harmonics.

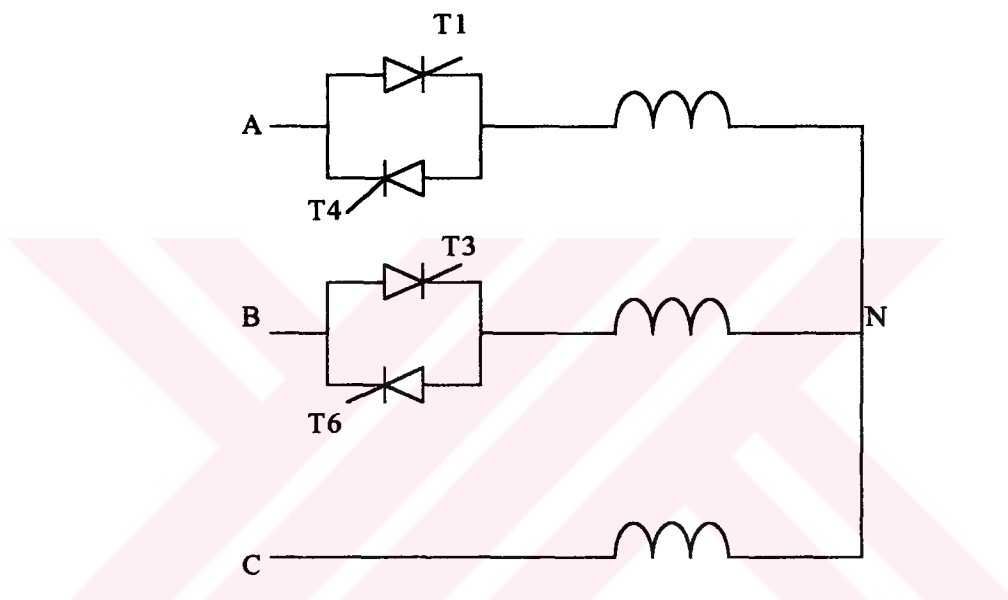


Figure 2.2 Another possible connection for voltage controllers.

The asymmetrical operation and the large harmonic content substantially derate the motor. The torque capability, which is already low at low speeds, is greatly reduced. Hence these asymmetrical circuits as in figure 2.2 are not used in softstarters but only in static switches or direct-on starters.

The thyristors of the controllers of figure 2.1 are fired in the sequence of their numbers with a phase difference of 60° . For circuit D_1 , the firing angle α

is measured from the zero crossing of the phase voltage V_{AN} . For the circuit D_2 , the firing angle is measured from the zero crossing of the line voltage V_{AB} .

For the firing angle $\alpha \leq \varnothing$, the motor terminal voltage remains constant and nearly equal to the supply voltage. Here,

$$\varnothing = \tan^{-1}(X_{in} / R_{in}) \quad (2.1)$$

where $(R_{in} + jX_{in})$ is the input impedance of the induction motor. Both motor voltage and current are sinusoidal. For higher values of α , the current flows discontinuously and the motor voltage decreases with an increase in α . The zero motor voltage and current are reached at $\alpha=150^\circ$ and $\alpha=180^\circ$ for the circuits D_1 and D_2 respectively. Because of the discontinuous conduction and dependence of R_{in} and X_{in} on motor slip s , the analysis of the induction motor fed by an ac voltage controller becomes complicated.

2.2 Voltage Controller Treated in the Thesis

Since the motors which are used in the research are wye-connected, the voltage controller shown in figure 2.3 is used in the thesis. Motor parameters are as given in appendix C. As shown in figure 2.3 motor terminals A, B and C are connected to the supply terminals R, S, and T respectively. There are back-to-back connected thyristors in each phase which are used to control the motor terminal voltage. The thyristors are assumed to be ideal.

Triggering sequence of the thyristors is T1, T2, T3, T4, T5 and T6. Triggering angle of each thyristor is determined from the zero crossing point of the phase voltage, to which the thyristor is connected, to the point where the thyristor must be triggered. At steady state triggering angle may be between 0 and 150 degrees because all the thyristors are assumed to have the same triggering angle. Before 0 and after 150 degrees the voltage on a thyristor becomes negative and the thyristor can not be active even if the firing pulse is received. At the transient state of operation according to the firing strategy proposed in this thesis, the triggering angle of the thyristors decreases from the

initial triggering angle to the final value determined by a special firing function. Initial value should be between 150 degrees and power factor angle. Above 150 degrees thyristors can not be active because of the negative voltage on them and below the power factor angle motor terminal voltage becomes continuous and the starting becomes direct-on starting which is not desired. The final value of the triggering function should not be less than 0 to operate the thyristors.

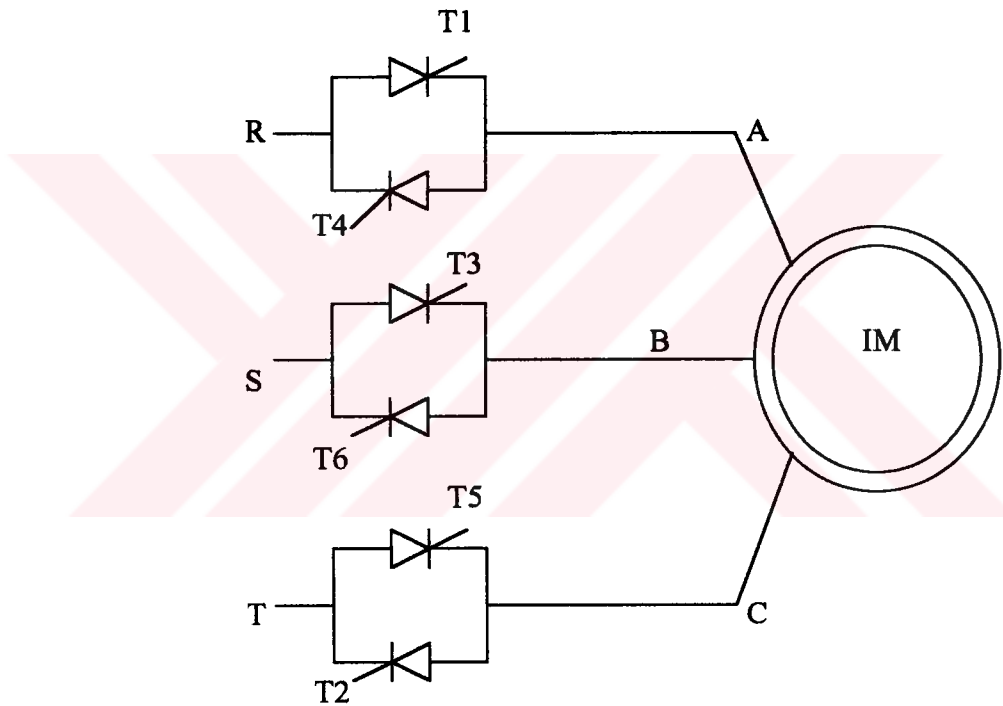


Figure 2.3 Voltage controller used in the thesis.

It is assumed that at the beginning of the operation, the thyristor T1 is ready to be active. The operation begins when the thyristor T2 is fired. At that instant the motor terminals A and C are connected to the supply terminals R and T respectively and the motor begins to operate in two phase mode. If the

thyristor T3 is triggered before the thyristor T1 is ceased, all three terminals of the motor is connected to the supply terminals and three phase mode operation begins. If the thyristor T3 is not fired when the thyristor T1 turns off, only the motor terminal C remains connected to the supply, but this does not allow the current flow to be continued in any one phase and the operation enters a new state which is called disconnected mode. The operation stays at this state until the thyristor T3 is fired and then the state changes to another two phase mode. After the thyristor T3 fired if the motor operates in three phase mode, the thyristor T4 is fired only after the thyristor T1 is turned off but if the motor operates in two phase mode and the thyristor T3 is fired before the thyristor T2 reverts to its blocking mode, then the motor begins to operate in three phase mode or if the motor operates in two phase mode and it is fired after the thyristor T2 is turned off, then the operation state switches from disconnected mode to the third type of two phase mode.

Motor phase voltage shown in figure 2.4 is controlled by the triggering angles of the thyristors and phase-A effective voltage can be expressed in terms of firing angles as follows:

$$V_{\text{EFFECTIVE}} = V_M \sqrt{\left[\frac{1}{2T} \left((\text{teta1} + \text{teta2} - \text{alfa1} - \text{alfa2} - \text{alfa4} + \text{alfa22}) + \right. \right. \\ \left. \left. \frac{1}{2} (\sin(2 \cdot \text{alfa1}) + \sin(2 \cdot \text{alfa2}) + \sin(2 \cdot \text{alfa4}) - \right. \right. \\ \left. \left. \sin(2 \cdot \text{alfa22}) - \sin(2 \cdot \text{teta1}) - \sin(2 \cdot \text{teta2})) \right) \right]} \quad (2.2)$$

where,

alfa1 : Firing angle of thyristor T1;

alfa2 : Firing angle of thyristor T2;

alfa22 : Firing angle of thyristor T2 at the next period;

alfa4 : Firing angle of thyristor T4;

teta1 : It is the angle which the thyristor T1 turns off;

teta2 : It is the angle which the thyristor T4 turns off;

T= alfa22-alfa2;

V_M : Peak value of supply phase-R voltage.

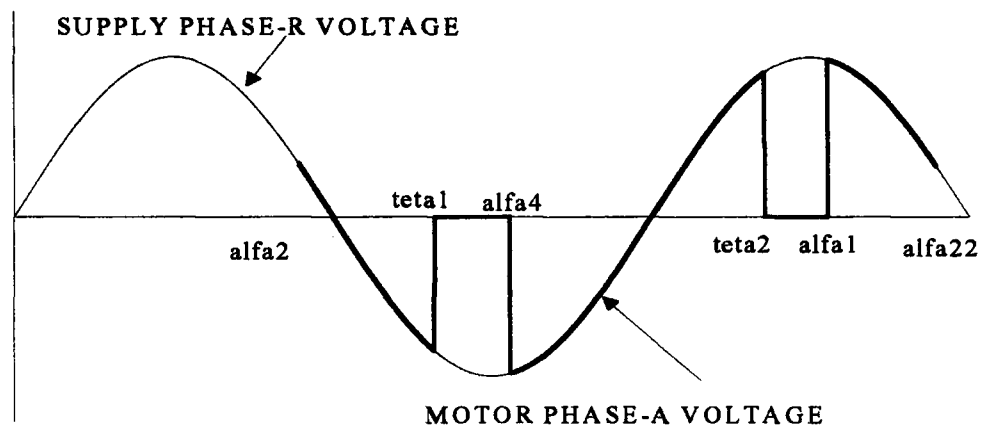


Figure 2.4 Supply and motor phase voltages.

In summary, a thyristor can be turned on only if the voltage on it is positive and the firing signal comes to its gate. It turns off only if the current passing through it becomes zero.

When a voltage controller is used for controlling the motor terminal voltages, the number of motor phases connected to the supply changes during operation time. As a result, motor operates at different operational modes.

2.2.1 Three phase mode

In this mode all of the motor phases are connected to the supply as shown in figure 2.5. Depending on the turning on or turning off of the thyristors operational mode changes to two phase mode or does not change. If the triggering angle is equal or less than the power factor angle, operational mode will always be three phase mode, otherwise will change to two phase mode.

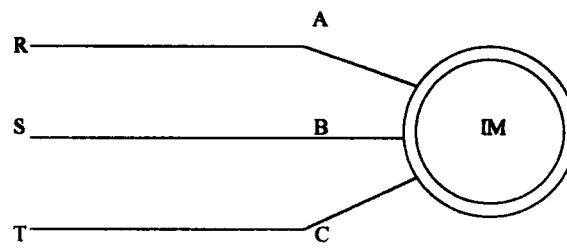


Figure 2.5 Three-phase operation.

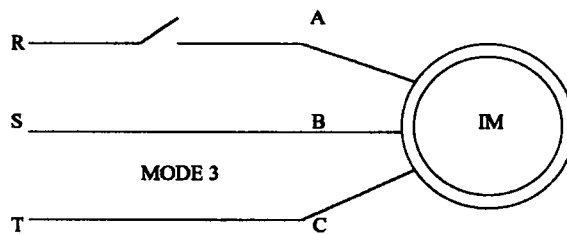
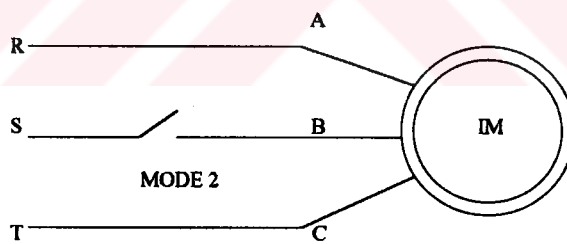
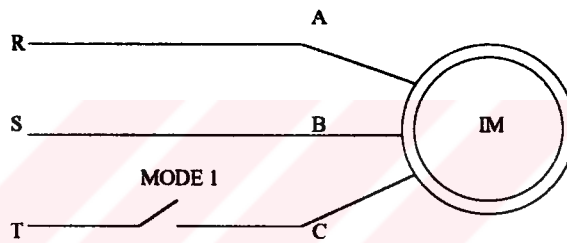


Figure 2.6 Two-phase operation.

2.2.2 Two phase mode

In this mode any two of the motor phases will remain connected to the supply. There are three different types of submodes in this mode. Mode 1, Mode 2 and Mode 3 occur when motor terminals AB, AC and BC are connected to the supply respectively as shown in figure 2.6. Depending on the triggering angle this operational mode switches to three phase mode or disconnected mode. Using the motor-2, the specifications and parameters of which are given in Appendix C , the critical firing angle is found to lie in a range between 118 and 119 degrees . If the firing angle is less than this critical value, operational mode turns out to be three phase mode, otherwise operational mode becomes disconnected mode.

2.2.3 Disconnected mode

In this mode none of the motor phases is connected to the supply as shown in figure 2.7, but only one thyristor is ready to become active. When the next thyristor is fired, motor begins to operate in two phase mode. In this mode the stator currents are zero and the rotor currents start with their values at the end of the previous mode and decay to zero.

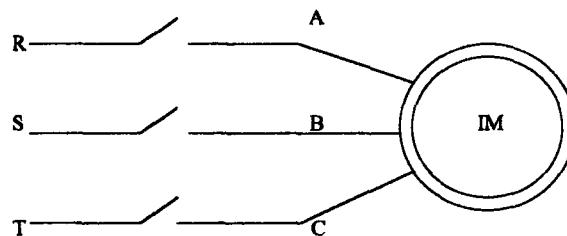


Figure 2.7 Operation in disconnected mode.

2.3 Problem Definition

In order to find an adequate soft starting strategy and to find out the system performance during starting a mathematical model of the system needs to be solved numerically on a digital computer. For that purpose a mathematical model for each operation mode has been developed. A software has been developed and run on a digital computer to coordinate the transitions from one operation state to another one. This mathematical model of the system is described in chapter 3. The software developed is given in appendix A.

2.4 Inputs and Outputs of the System

The computer program needs some inputs to calculate system outputs. These inputs and outputs are shown in figure 2.8.

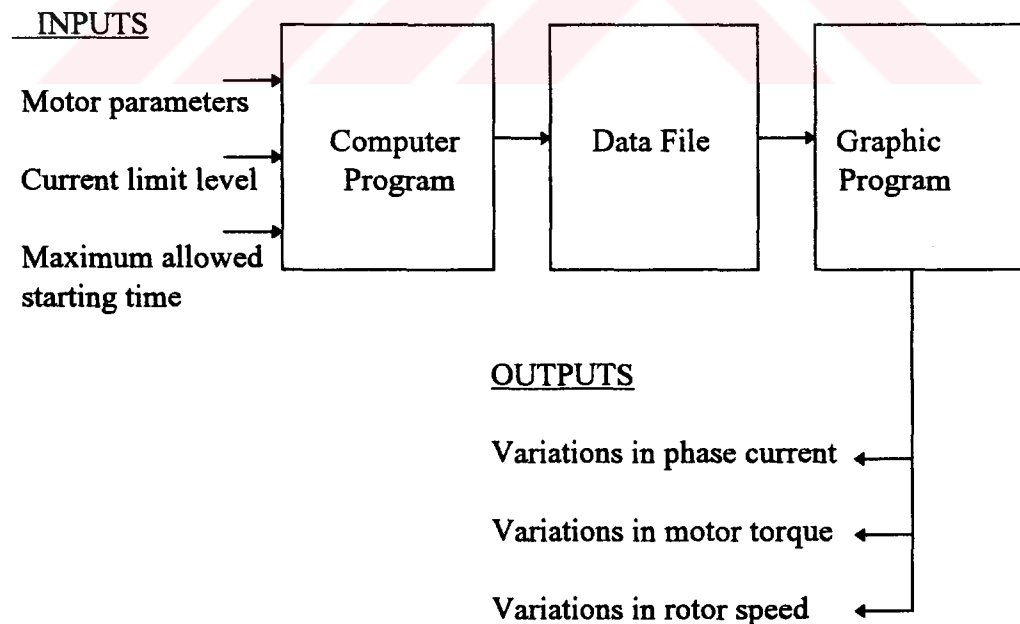


Figure 2.8 Inputs and outputs of the system.

CHAPTER 3

MATHEMATICAL MODEL OF THE SYSTEM

The effects of direct-on starting and soft starting on an induction motor's transient performance are obtained by using a new hybrid mathematical model of the induction machine which accounts for the changing operating modes of the induction machine. The state space representation of induction machine used in the computer simulations is determined for the disconnected, two phase and three phase operational modes.

For all types of operational modes, in deriving the state equations, the rotor variables are transformed into a fixed reference frame, but the stator variables are kept unchanged. Starting with the actual three phase mathematical model of the induction motor, all time-varying inductances are eliminated from the model to reduce the number of equations by using C_1 and C_2 transformations [16] given in appendix B. C_1 is the phase transformation which transforms the three phase variables into equivalent two phase variables. The second transformation C_2 is the commutator transformation which has been used for transforming the rotor variables into the reference frame stationary relative to the stator and as a result time-varying functions are eliminated. Representation diagram of a 3-phase induction machine is shown in figure 3.1. Impedance matrix of an induction motor after the aforementioned transformations is given as,

$$Z_{\text{HYBRID}} = \begin{vmatrix} Z_{11} & Z_{12} C_1 C_2 \\ C_{2t} C_{1t} Z_{21} & C_{2t} C_{1t} Z_{22} C_1 C_2 \end{vmatrix} \quad (3.1)$$

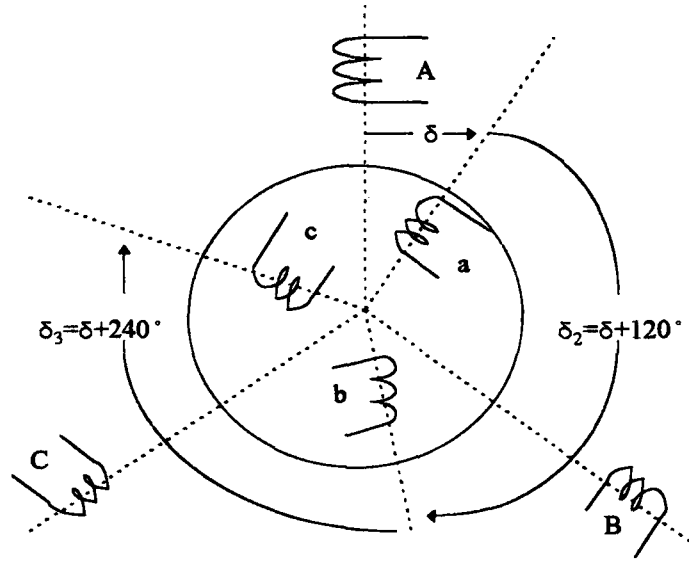


Figure 3.1. Representation diagram of three-phase induction machine.

The voltage equation can be written in the following form,

$$\begin{bmatrix} V_S \\ V_R \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_S \\ I_R \end{bmatrix} \quad (3.2)$$

where , V_S , V_R , I_S , I_R , Z_{11} , Z_{12} , Z_{21} and Z_{22} are stator voltages, rotor voltages, stator currents, rotor currents, stator-stator impedances, stator-rotor impedances, rotor-stator impedances and rotor-rotor impedances respectively. This equation and torque balance equation [17] can be expressed in general form as in equation (3.3) where ,

L : the inductive component of the matrix given in equation (3.3);

R_1 : stator phase resistance (actual value);

R_2 : rotor phase resistance(actual value);

L_{11} : stator phase winding self inductance (actual value);

L_{22} : rotor phase winding self inductance (actual value);

V_A	$R_1 + L_{11} p$	$M_{11} p$	$M_{11} p$	$M_{121} p \cos \delta_1$	$M_{121} p \cos \delta_2$	$M_{121} p \cos \delta_3$	i_A
V_B	$M_{11} p$	$R_1 + L_{11} p$	$M_{11} p$	$M_{121} p \cos \delta_2$	$M_{121} p \cos \delta_1$	$M_{121} p \cos \delta_2$	i_B
V_C	$M_{11} p$	$M_{11} p$	$R_1 + L_{11} p$	$M_{121} p \cos \delta_3$	$M_{121} p \cos \delta_3$	$M_{121} p \cos \delta_1$	i_C
V_a	$M_{121} p \cos \delta_1$	$M_{121} p \cos \delta_3$	$M_{121} p \cos \delta_2$	$R_2 + L_{22} p$	$M_{22} p$	$M_{22} p$	i_a
V_b	$M_{121} p \cos \delta_2$	$M_{121} p \cos \delta_1$	$M_{121} p \cos \delta_3$	$M_{22} p$	$R_2 + L_{22} p$	$M_{22} p$	i_b
V_c	$M_{121} p \cos \delta_3$	$M_{121} p \cos \delta_2$	$M_{121} p \cos \delta_1$	$M_{22} p$	$M_{22} p$	$R_2 + L_{22} p$	i_c

$$T_e = 0.5 \mathbf{i}_t (d\mathbf{L}/d\delta) \mathbf{i}$$

$$(3.3)$$

M_{11} : stator-stator mutual inductance;

M_{22} : rotor-rotor mutual inductance;

M_{121} : peak value of the fundamental component of mutual inductance between stator and corresponding rotor phase winding at $\delta = 0^\circ$.

After the transformations **C1** and **C2** is applied to the equation (3.3), the equation (3.4) is obtained where,

$L_1 = (L_{11} - M_{11})$: stator self inductance;

$L_2 = (L_{22} - M_{22})$: rotor self inductance;

w_r : rotor speed in electrical rad/second;

3.1 Mathematical Model of the Operational Modes

3.1.1 Three-phase model (Mode 0)

This mathematical model is used when the motor operates in three-phase operational mode. The fourth row and column of the equation (3.4) are eliminated because zero sequence currents can not flow in a Y-connected machine without a neutral wire. As $i_C = -(i_A + i_B)$, the third row and column are also omitted. The resulting A B C d q model of an induction motor becomes as in equation (3.5) in state space form. Torque-balance equation is also shown in equation (3.5) where,

$$A = -\sqrt{2}BM'/L'_2 ;$$

$$B = 1/(2L'_1 - 2M'^2/L'_2) ;$$

$$M' = (N_1/N_2)(3/2)M_{121} ;$$

$$L'_2 = (N_1/N_2)^2(L_{22} - M_{22}) : \text{referred rotor self inductance};$$

$$R'_2 = (N_1/N_2)^2 R_2 : \text{referred rotor resistance};$$

(pp): number of pole pairs;

J: inertia;

T_L : Load torque.

$$\begin{array}{c}
 V_A \\
 V_B \\
 V_C \\
 V_0 \\
 V_q \\
 V_d
 \end{array}
 =
 \begin{array}{c}
 R_1 + L_{11} p \\
 M_{11} p \\
 M_{11} p \\
 0 \\
 -(\sqrt{3}/\sqrt{2}) M_{121} w_r \\
 (\sqrt{3}/\sqrt{2}) M_{121} p
 \end{array}
 \begin{array}{c}
 M_{11} p \\
 R_1 + L_{11} p \\
 M_{11} p \\
 0 \\
 (3\sqrt{2}/4) M_{121} p \\
 +(\sqrt{6}/4) M_{121} w_r \\
 -(\sqrt{6}/4) M_{121} p \\
 -(\sqrt{3}/2) M_{121} w_r
 \end{array}
 \begin{array}{c}
 M_{11} p \\
 M_{11} p \\
 R_1 + L_{11} p \\
 0 \\
 -(\sqrt{3}/2) M_{121} p \\
 +(\sqrt{6}/4) M_{121} w_r \\
 -(\sqrt{6}/4) M_{121} p \\
 -(\sqrt{3}/2) M_{121} w_r
 \end{array}
 \begin{array}{c}
 0 \\
 0 \\
 0 \\
 R_2 + L_{20} p \\
 0 \\
 0 \\
 0 \\
 0
 \end{array}
 \begin{array}{c}
 0 \\
 (3\sqrt{2}/4) M_{121} p \\
 -(\sqrt{3}/2) M_{121} p \\
 0 \\
 R_2 + L_2 p \\
 L_2 w_r \\
 0 \\
 0
 \end{array}
 \begin{array}{c}
 (\sqrt{3}/\sqrt{2}) M_{121} p \\
 -(\sqrt{6}/4) M_{121} p \\
 -(\sqrt{6}/4) M_{121} p \\
 0 \\
 -L_2 w_r \\
 R_2 + L_2 p \\
 0 \\
 0
 \end{array}
 \begin{array}{c}
 i_A \\
 i_B \\
 i_C \\
 i_0 \\
 i_q \\
 i_d
 \end{array}$$

(3.4)

$$\begin{array}{c}
 \begin{array}{|c|} \hline i_A \\ \hline \end{array} \\
 \begin{array}{|c|} \hline i_B \\ \hline \end{array} \\
 \begin{array}{|c|} \hline i_q \\ \hline \end{array} \\
 \begin{array}{|c|} \hline i_d \\ \hline \end{array}
 \end{array}
 =
 \begin{array}{|c|} \hline -2BR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{6}/3)AM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -2(\sqrt{6}/3)AM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline (2\sqrt{6}/3)BM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -(2\sqrt{3}/3)AR_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline (2/3)B \\ \hline \end{array}
 \begin{array}{|c|} \hline (2/3)B \\ \hline \end{array}
 \\
 \begin{array}{|c|} \hline 2(\sqrt{6}/3)AM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -2BR_1 + (\sqrt{6}/3)AM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -AR_2 - (\sqrt{6}/3)BM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/3)AR_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline (2/3)B \\ \hline \end{array}
 \\
 \begin{array}{|c|} \hline (\sqrt{6}/2)M\dot{w}_r(A^2/B + 1/L_2) - AR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline -2AR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline -A^2R_2/B - R_2/L_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline w_r - \sqrt{2}AM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -A \\ \hline \end{array}
 \begin{array}{|c|} \hline A \\ \hline \end{array}
 \\
 \begin{array}{|c|} \hline (1/2)Aw_r/B - \sqrt{3}AR_1 - (\sqrt{2}/2)A^2M\dot{w}_r/B \\ \hline \end{array}
 \begin{array}{|c|} \hline Aw_rB - \sqrt{2}A^2M\dot{w}_r/B \\ \hline \end{array}
 \begin{array}{|c|} \hline -w_r + \sqrt{2}AM\dot{w}_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -A^2R_2/B - R_2/L_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/3)A \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/3)A \\ \hline \end{array}
 \end{array}
 +
 \begin{array}{|c|} \hline i_A \\ \hline \end{array}
 \begin{array}{|c|} \hline i_B \\ \hline \end{array}
 \begin{array}{|c|} \hline i_q \\ \hline \end{array}
 \begin{array}{|c|} \hline i_d \\ \hline \end{array}
 \begin{array}{|c|} \hline V_{AB} \\ \hline \end{array}
 \begin{array}{|c|} \hline V_{AC} \\ \hline \end{array}$$

$$T_e = -(\rho p) \left((\sqrt{6}/2) M \ddot{i}_q + (\sqrt{2}/2) M \ddot{i}_d i_A + \sqrt{2} M \ddot{i}_d i_B \right)$$

$$p w_r = (1/J)(T_e - T_L)$$

(3.5)

3.1.2 Two-phase model

3.1.2.1 Mode 1

This mathematical model is used when the motor phases A and B are connected to the supply. The fourth row and column of the equation (3.4) are deleted because of the reason mentioned above. Using $i_C=0$ and $i_B=-i_A$, the third and second rows and columns are also omitted and the voltage and torque balance equations become as in equation (3.6).

3.1.2.2 Mode 2

This mathematical model is used when the motor phases A and C are connected to the supply. The fourth row and column of the equation (3.4) are deleted because of the reason mentioned above. Using $i_B=0$ and $i_C=-i_A$, the second and third rows and columns are also omitted and the voltage and torque balance equations become as in equation (3.7).

3.1.2.3 Mode 3

This mathematical model is used when the motor phases B and C are connected to the supply. The fourth row and column of the equation (3.4) are deleted because of the reason mentioned above. Using $i_A=0$ and $i_C=-i_B$, the first and third rows and columns are also omitted and the voltage and torque balance equations become as in equation (3.8).

3.1.3 Disconnected Model (Mode 4)

This mathematical model is used when none of the motor phases are connected to the supply. The fourth row and column of the equation (3.4) are

$$\begin{array}{c}
 \begin{array}{|c|} \hline i_A \\ \hline \end{array} \\
 \begin{array}{|c|} \hline p \\ \hline \end{array}
 \end{array}
 \begin{array}{|c|} \hline i_q \\ \hline \end{array}
 =
 \begin{array}{|c|} \hline -2R_1B \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/2)Aw_f/B+AR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{6}/2)M'w_fB+(1/2)AR_2' \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{2}/2)M'w_fB-(\sqrt{3}/2)AR_2' \\ \hline \end{array}
 \begin{array}{|c|} \hline B \\ \hline \end{array}
 \begin{array}{|c|} \hline V_{AB} \\ \hline \end{array}$$

$$\begin{array}{|c|} \hline i_q \\ \hline \end{array}
 =
 \begin{array}{|c|} \hline -(\sqrt{6}/4)AM'w_f-R_2'/L_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/4)A^2R_2'/B \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/4)A^2R_2'/B \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{2}/4)AM'w_f+w_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/2)A \\ \hline \end{array}$$

$$\begin{array}{|c|} \hline i_d \\ \hline \end{array}
 =
 \begin{array}{|c|} \hline -(1/2)Aw_f/B-\sqrt{3}AR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline (3\sqrt{2}/4)AM'w_f \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{6}/4)AM'w_f-R_2'/L_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/4)A^2R_2'/B \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/2)A \\ \hline \end{array}$$

$$T_e = - (pp) ((\sqrt{6}/2)M' i_q i_A - (\sqrt{2}/2)M' i_d i_A) \quad (3.6)$$

$$\begin{array}{c}
 \begin{array}{|c|} \hline i_A \\ \hline \end{array} \\
 \begin{array}{|c|} \hline p \\ \hline \end{array}
 \end{array}
 \begin{array}{|c|} \hline i_q \\ \hline \end{array}
 =
 \begin{array}{|c|} \hline -2R_1B \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/2)Aw_f/B-AR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{6}/2)M'w_fB+(1/2)AR_2' \\ \hline \end{array}
 \begin{array}{|c|} \hline (1/2)AL_2w_f-(\sqrt{3}/2)AR_2' \\ \hline \end{array}
 \begin{array}{|c|} \hline B \\ \hline \end{array}
 \begin{array}{|c|} \hline V_{AB} \\ \hline \end{array}$$

$$\begin{array}{|c|} \hline i_q \\ \hline \end{array}
 =
 \begin{array}{|c|} \hline (\sqrt{6}/4)AM'w_f-R_2'/L_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/4)A^2R_2'/B \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/4)A^2R_2'/B \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{2}/4)AM'w_f+w_r \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/2)A \\ \hline \end{array}$$

$$\begin{array}{|c|} \hline i_d \\ \hline \end{array}
 =
 \begin{array}{|c|} \hline (1/2)Aw_f/B-\sqrt{3}AR_1 \\ \hline \end{array}
 \begin{array}{|c|} \hline (3\sqrt{2}/4)AM'w_f \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{6}/4)AM'w_f-R_2'/L_2 \\ \hline \end{array}
 \begin{array}{|c|} \hline -(\sqrt{3}/4)A^2R_2'/B \\ \hline \end{array}
 \begin{array}{|c|} \hline (\sqrt{3}/2)A \\ \hline \end{array}$$

$$T_e = - (pp) ((\sqrt{6}/2)M' i_q i_A + (\sqrt{2}/2)M' i_d i_A) \quad (3.7)$$

deleted because of the reason mentioned above. Using $i_A=0$, $i_B=0$ and $i_C=0$, the first, second and third rows and columns are also omitted and the voltage and torque balance equations become as in equation (3.9).

$$p \begin{vmatrix} i_B \\ i'_q \\ i'_d \end{vmatrix} = \begin{vmatrix} -2R_1B & -AR'_2 & -\sqrt{2}M'w_rB \\ -2R_1A & A^2R'_2/B - R'_2/L'_2 & -\sqrt{2}AM'w_r + w_r \\ Aw_r/B & -w_r & -R'_2/L'_2 \end{vmatrix} \begin{vmatrix} i_A \\ i'_q \\ i'_d \end{vmatrix} + \begin{vmatrix} B \\ 0 \\ A \end{vmatrix} \begin{vmatrix} V_{BC} \end{vmatrix}$$

$$T_e = - (pp) (\sqrt{2}) M' i'_d i_B \quad (3.8)$$

$$p \begin{vmatrix} i'_q \\ i'_d \end{vmatrix} = \begin{vmatrix} -R'_2/L'_2 & w_r \\ -w_r & -R'_2/L'_2 \end{vmatrix} \begin{vmatrix} i'_q \\ i'_d \end{vmatrix}$$

$$T_e = 0 \quad (3.9)$$

3.2 Solution Method

To solve these non-linear differential equations, the fourth order Runge-Kutta numerical solution method is used. To ensure the continuity of the solutions when an operational mode changes, the final values of the last mode are taken as the initial values of the next mode. Further information about the computer program is given in appendix A. The program itself is also given in that appendix.

3.3 Transition Between Operational Modes

The transition between operational modes will occur as described below:

1. Motor operating in three phase mode (Mode 0): The motor continues to stay in this mode until the thyristor which has been turned on first turns off. Only after that thyristor turns off, the next thyristor, which is connected in parallel to it, can be activated and the motor continues to operate in three phase mode. If the next thyristor is not turned on yet after the first one turns off, the operational mode changes from three phase mode to two phase mode. For example, if thyristors T3, T4 and T5 are active, the thyristor T6 can be active only after the thyristor T3 turns off and operational mode becomes the same in three phase mode. If the thyristor T6 is not turned on yet after the thyristor T3 turns off, the operational mode becomes two phase mode. Change of operational modes from Mode 0 into other modes are shown in table 3.1.

2. Motor operating in two phase mode (Mode 1, Mode 2 or Mode 3): If the first active thyristor turns off before any thyristor is turned on, the operational mode becomes disconnected mode. If the third thyristor is turned on before the first turned on thyristor is ceased, the operational mode becomes three phase mode. If the next thyristor is fired at the same instant with the turning on the first one, the motor begins to operate in another two phase mode. For example, if thyristors T6 and T1 is assumed to be active and after sometime if the thyristor T6 turns off before the thyristor T2 is turned on, disconnected mode becomes the new mode. If the thyristor T2 is turned on before the thyristor T6 is ceased, the operational mode will be three phase mode. If the thyristor T2 becomes active at the same instant with the turning off the thyristor T6, motor begins to operate in another two phase mode. Change of operational modes from Model, Mode 2 and Mode 3 to other modes are shown in table 3.2, table 3.3 and table 3.4 respectively.

3. Motor operating in disconnected mode (Mode 4): The motor continues

Table 3.2 Transition between operational modes when the initial operational mode is Mode 1.

Before the mode changes				
Active thyristors :	61	34	61	34
Mode :	1	1	1	1
After the mode changes				
Active thyristors :	If the firing angle is between σ and the power factor angle		If the firing angle is equal to σ	
	612	345	12	45
	BAC		AC	
Motor terminals connected to the supply:	BAC		AC	
Mode :	0	0	2	2
			If the firing angle is between σ and 150°	
			NONE	NONE
			4	4

where, σ is the angle at which the system can run at discontinuous mode.

Table 3.3 Transition between operational modes when the initial operational mode is Mode 2.

Before the mode changes				
Active thyristors :	12	45	12	45
Mode :	2	2	2	2
After the mode changes				
	If the firing angle is between σ and the power factor angle	If the firing angle is equal to σ	If the firing angle is between σ and 150°	
Active thyristors :	123	23	56	5
Motor terminals connected to the supply:	ACB	CB	CB	NONE NONE
Mode :	0	0	3	4

where, σ is the angle at which the system can run at discontinuous mode.

Table 3.4 Transition between operational modes when the initial operational mode is Mode 3.

Before the mode changes			
Active thyristors :	23	56	23 56
Mode :	3	3	3 3
After the mode changes			
		If the firing angle is equal to σ	If the firing angle is between σ and 150°
Active thyristors :	234 561	34 61	3 6
Motor terminals connected to the supply:	CBA CBA	BA BA	NONE NONE
Mode :	0 0	2 2	4 4

where , σ is the angle at which the system can run at discontinuous mode.

Table 3.5 Transition between operational modes when the initial operational mode is Mode 4.

Before the mode changes					
Active thyristors :	1	2	3	4	5
Mode :	4	4	4	4	4
After the mode changes					
Active thyristors :	12	23	34	45	56
Motor terminals connected to the supply:	AC	CB	BA	AC	CB
Mode :	2	3	1	2	3
					1
					BA
					61

to stay in this mode until the next thyristor is fired and it begins to operate in two phase mode. For example, assume thyristor T4 is ready to operate. Until the thyristor T5 is triggered the motor stays in discrete mode and then operational mode becomes two phase mode. Change of operational modes from Mode 4 to other modes are shown in table 3.5.

3.4 Machine Parameters

In this thesis simulation results are taken for two different motor parameters which are given in appendix C. To obtain the simulations, saturation is ignored and motor parameters are assumed to be constant. These assumptions are also made by similar papers about transient performance of induction motors as in references [13] and [9].

In fact, it is clear that motor parameters change with the operating point. This change is mainly due to the followings [18]:

1. Increase in stator and rotor resistances at full load due to temperature rise;
2. Increase in rotor resistance at starting due to skin effect;
3. Decrease in stator and rotor leakage reactances at starting due to saturation effect.

The most changing parameters are the stator and rotor leakage reactances during starting. To calculate the variation of the leakage reactances with respect to the current variation a blocked rotor test has been performed. Also effects of the variation of leakage reactances and other motor parameters such as total resistance and magnetizing reactance on transient performance of an induction motor has been calculated by using the computer program and results are given in the below sections.

3.4.1 Sensitivity analysis with respect to changes in motor parameters

3.4.1.1 Variation of the leakage reactance with respect to the current variation

To obtain the variation of the leakage reactance with respect to the stator current, a locked rotor test is done. For this purpose a motor with a name-plate shown below is used.

Wye/Delta , 220/380V, 14/8.1A, 3.5KW, 1400 rpm, 0.8pf.

During the experiment, current is changed from 4A to 26.5A and the leakage reactance is calculated as described below.

The aim of the locked rotor test is to calculate the resistance and the leakage reactance of the motor. During this test, the rotor is kept stationary by the use of a locking bar to avoid the rotation of the rotor and make the slip unity. Therefore the rotor resistance becomes independent of the slip. The exciting branch is neglected because magnetizing reactance is much more higher than the rotor parameters. The approximate equivalent circuit of the machine becomes as shown in figure 3.2.

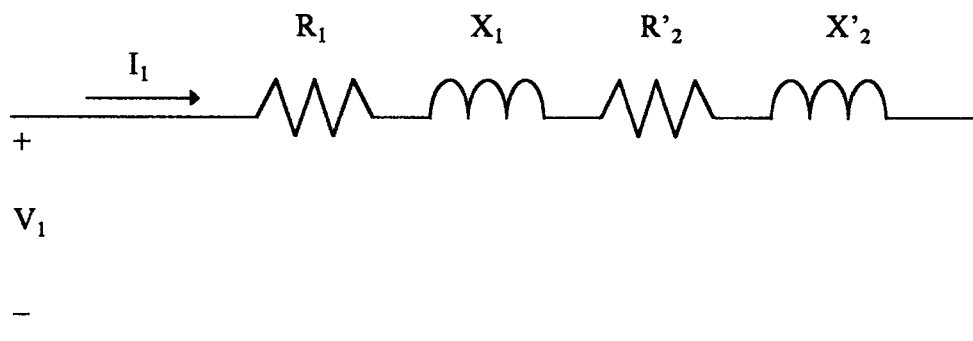


Figure 3.2 Approximate equivalent circuit for locked rotor test.

Motor parameters are calculated as follows,

$$I_1 = I_2'$$

$$P_{IN} = (R_1 + R_2') (I_2')^2$$

$$|Z| = |(R_1 + R_2') + j(X_1 + X_2')| = \sqrt{(R_1 + R_2')^2 + (X_1 + X_2')^2} = V_1 / I_2'$$

$$R_1 = R_2' \text{ and } X_1 = X_2'. \quad (3.10)$$

3.4.1.2 Results of the experiment

In the experiment a digital wattmeter is used. The connection diagram for the experiment is shown in figure 3.3.

The results and I-X curve obtained from the experiment are shown in table 3.6 and in figure 3.4 respectively, where,

I : Line current in amperes;

V: Line-to-line voltage in volts;

P: Three-phase real power in watts;

R: The sum of rotor and stator resistances in ohms;

X: Rotor or stator leakage reactance in ohms ,which is calculated by assuming R is 2.3 ohm.

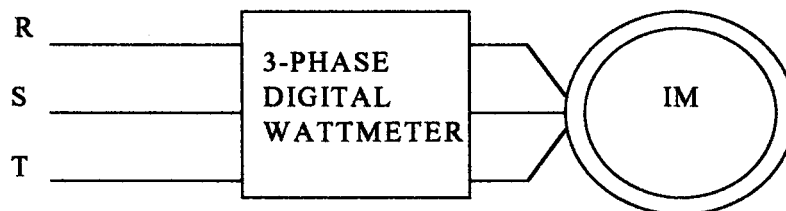


Figure 3.3 Connection diagram for the experiment.

Table 3.6 Experimental results.

I, A	V, V	P, W	R, Ω	X, Ω	% variation in I	% variation in X
4.09	54.2	118	2.35	3.65	-49.32	3.69
6.00	77.7	251	2.32	3.56	-25.65	1.14
8.07	103.4	447	2.29	3.52	0.00	0.00
10.07	127.2	685	2.28	3.49	24.78	-0.85
12.08	151.9	1014	2.32	3.44	49.69	-2.27
14.11	176.4	1379	2.31	3.42	74.84	-2.84
15.88	195.0	1738	2.30	3.35	96.78	-4.83
18.53	225.0	2380	2.31	3.31	129.62	-5.97
20.00	236.0	2400	2.00	3.21	147.83	-8.81
26.00	296.0	4040	1.99	3.08	222.18	-12.50
26.50	298.0	4240	2.01	3.04	228.38	-13.64

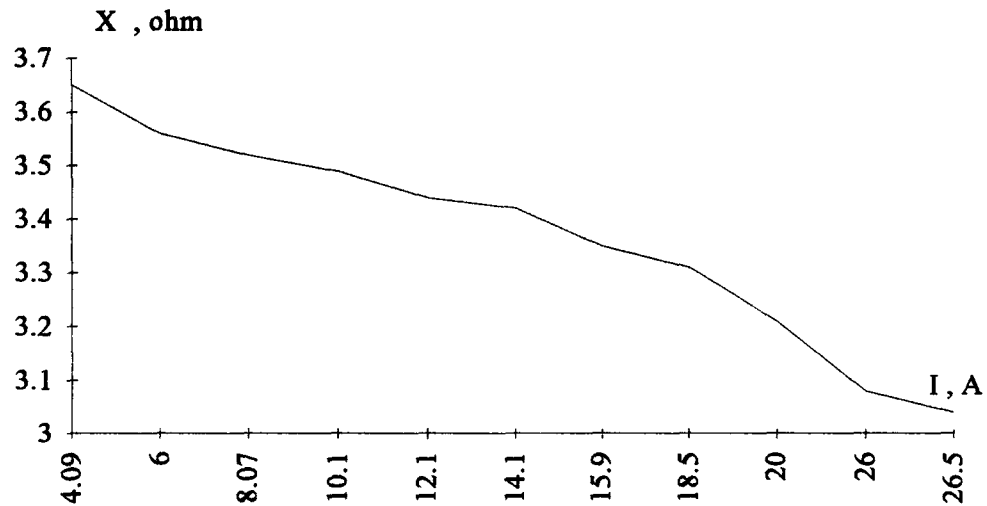


Figure 3.4 I-X curve obtained from the experiment

3.4.1.3 Simulation results

Effects of the variation of the leakage reactance on the current and torque magnitude is also investigated by using the computer program. In the program, the leakage reactance of motor-2 is changed and the variation of the current and torque peaks are calculated in percentage. Specifications and parameters of motor 2 are shown in appendix C. The results are shown in table 3.7.

Table 3.7 Torque and current variation with respect to the leakage reactance.

% variation in X	-30.0	-20.0	-10.00	0.0	10.0	20.0	30.0
% variation in I	25.37	15.59	7.23	0.0	-6.31	-11.85	-16.77
% variation in Te	63.8	37.34	16.55	0.0	-13.37	-24.3	-33.33

3.4.1.4 Effects of the variation of the magnetizing reactance on electromagnetic torque and line currents

Magnetizing reactance changes during starting time. Unsaturated value of the magnetizing reactance is greater than the saturated value. In this part, effects of the magnetizing reactance on torque and current is investigated with increased reactance values by using the computer program. Results and motor parameters are shown in table 3.8 and appendixA respectively, where ,

T_e : Electromagnetic torque;

X_M : Magnetizing reactance;

I : Phase-A stator current.

Table 3.8 Torque and current variation with respect to the magnetizing reactance.

% variation in X_M	-30.0	-20.0	-10.00	0.0	10.0	20.0	30.0
% variation in I	1.14	0.67	0.3	0.0	-0.24	-0.45	-0.62
% variation in T_e	-1.8	-1.06	-0.47	0.0	0.39	0.71	0.99

3.4.1.5 Effects of the variation of the motor resistance on electromagnetic torque and line currents

To determine the effects of the variation of the motor resistances on torque and current, both rotor and stator resistances are changed at the same ratio and results are recorded in table 3.9, where,

Te: Electromagnetic torque;

R: Total motor resistance, $R=R_1 + R_2$.

I : Phase-A stator current;

Table 3.9 Torque and current variation with respect to the motor resistance.

% variation in R	-30.0	-20.0	-10.00	0.0	10.0	20.0	30.0
% variation in I	9.84	6.35	3.08	0.0	-2.91	-5.65	-8.25
% variation in Te	-17.17	-10.59	-4.9	0.0	4.19	7.76	10.77

3.4.2 Results of the Sensitivity Analysis

Among the machine parameters, the variation of the total leakage reactance is the most effective on current and torque variation as it can be seen from the simulation results. Besides the total leakage reactance, the least effective parameter is the magnetizing reactance.

Magnetizing reactance and total motor resistance can easily be assumed constant because of their small variation of the order of %.

Leakage reactances of an induction motor vary with the operating conditions. The principle cause of this variation is the magnetic saturation of the leakage paths. Saturation increases with increasing current and reduces the leakage reactance. At starting conditions starting current may rise to from 400 to 700 per cent of full load current for class B motors. Thus at starting conditions a considerable decrease in the leakage reactances [18]. Because the aim of this

thesis is to perform softstart of induction motors, current will be limited between 200 and 400 per cent of full load current and saturation will not occur, therefore the total leakage reactance will not change considerably. As a result, the total leakage reactance can be assumed constant during starting in the computer program.



CHAPTER 4

RESULTS

The aim of the thesis is to find out an operating strategy for which the stator current never exceeds a prespecified limit value and also oscillations in electromagnetic torque become minimum during starting period of the motor. Results obtained from the digital simulation of the system are presented in this chapter. The same results have been obtained for two different motors whose parameters are given in Appendix C in order to allow making a comparative study between low voltage and high voltage motor performances. Load torques for the motors are given in Appendix D.

This chapter consists of two main parts. In the first part, the strategies minimizing the torque pulsations are explained and the related simulation results are given for both motors. In the second part, the method used for limiting the starting current is given and simulation results obtained from the computer program are shown.

4.1 Minimization of the Torque Pulsations

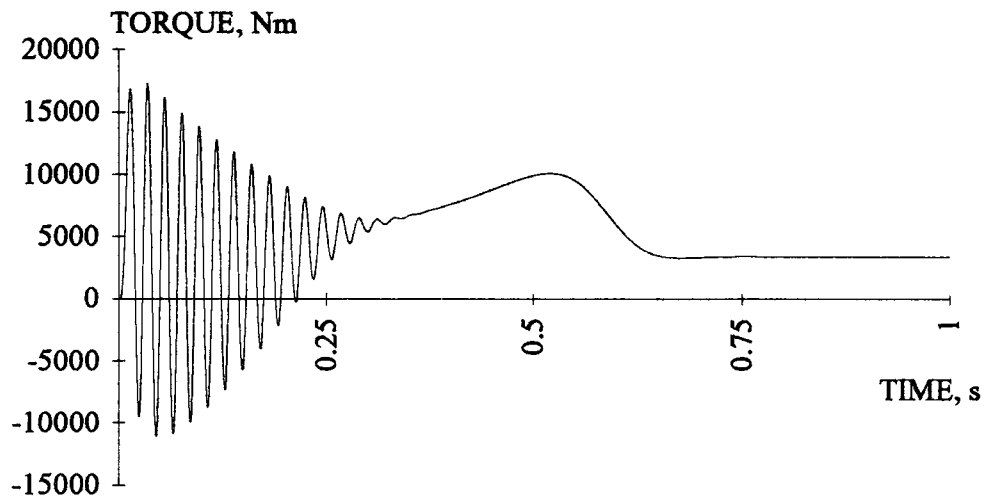
Switching of induction motor terminals to the supply lines (simultaneous or nonsimultaneous closing of circuit breaker poles) may cause severe transient torque pulsations at the supply frequency (50 Hz). The magnitude of torque pulsations during starting depends on closing instants of the three contactor poles in the first period of the operation. For our case, this corresponds to the firing instants of the three back-to-back connected thyristor switches. That is by triggering the thyristors into conduction at proper points on the related line to

neutral supply voltage waveforms, transient torque pulsations are shown to be minimized [17]. It is worth noting that each triggering strategy for back-to-back connected thyristor pairs can not be applied over the whole control range of α but in only one of the three α ranges as specified below. The strategies used in the thesis to minimize torque pulsations are found to be as follows:

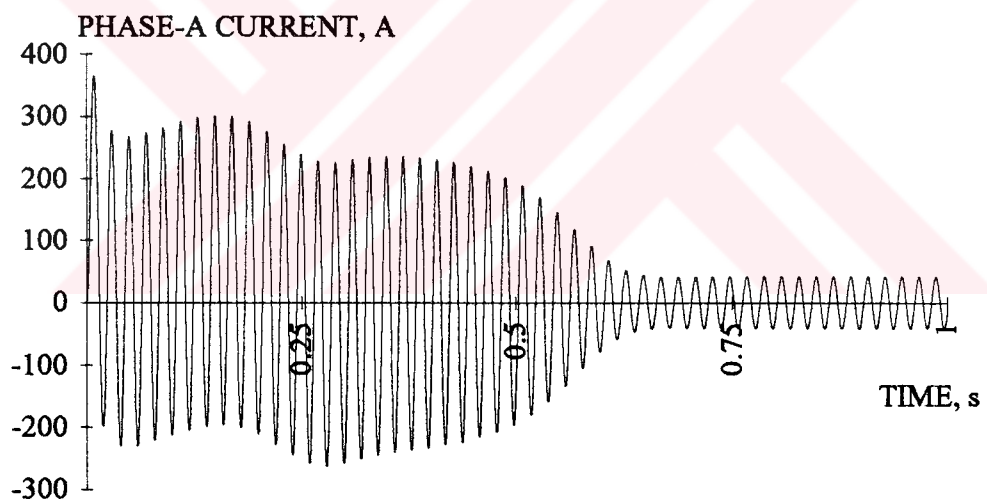
1. Apply triggering strategy in subsection 4.1.1 if the line current is continuous;
2. Apply triggering strategy in subsection 4.1.2 if the line current is discontinuous and the triggering angle α is less than for the power factor angle at slip equal to 1;
3. Apply triggering strategy in subsection 4.1.3 if the triggering angle α is greater than the power factor angle at slip equal to 1.

An important property of the above triggering strategies is that all of them correspond to nonsimultaneous closing of contactor poles. As reported in a previous study [17], it is never possible to reduce transient torque pulsations below a certain significant level when all the three phases of the motor are connected to supply terminals simultaneously. A typical set of waveforms for simultaneous switching of the motor-2 is shown in figure 4.1.

As can be understood from the foregoing explanations triggering strategy for the three thyristor-pairs and firing angle for each thyristor are different concepts. This is because stator current is kept below a prespecified limit value by voltage control by varying α and at the same time a proper triggering strategy is applied to all six thyristors only in the first cycle of the supply voltage waveform to minimize the transient torque oscillations. Reference point for α has been defined as the zero crossing point of the associated phase voltage waveform on the ascending portion of the positive half cycle for forward thyristor and on the descending edge of the negative half cycle for the backward thyristor for each of the thyristor pairs.



a)



b)

Figure 4.1 a) Electromagnetic torque vs. time, b) phase-A current vs. time with simultaneous switching of motor phases to the supply for motor-2.

4.1.1 The triggering strategy in the case of continuous motor current

If the firing angle α causes flow of continuous current through motor phases then the triggering strategy as described below is to be applied to the operation of the softstarter in order to minimize transient torque pulsations in the starting period. This strategy also minimizes the ac envelope of the starting current waveform thus approximating it to a decaying exponential, minimizing starting time as well.

In this triggering strategy first, thyristor T1 shown in figure 2.3 receives a firing pulse just at a prespecified α but it does not trigger into conduction because none of the remaining thyristors are neither conducting current nor receive a firing pulse. Thyristor T1 will trigger into conduction when thyristor T2 receives a firing pulse with phase delay of 120° with respect to the reference point of thyristor T1 (zero crossing point of phase-R voltage on the ascending edge of the positive half cycle; figure 4.2). Thyristor T3 should receive a firing pulse with 90° delay with respect to the firing pulse of thyristor T2. Thyristors T4, T5 and T6 will receive their firing pulses at their own α 's.

In summary, several trials on the system for this particular case have shown us that thyristors T1, T2, T3, T4, T5 and T6 should receive successively their firing respectively at points α , 120° , $120^\circ+90^\circ$, $180^\circ+\alpha$, $240^\circ+\alpha$ and $300^\circ+\alpha$ with respect to the reference point of thyristor T1 firing angle (zero crossing point of phase-R voltage on ascending edge of positive half cycle). Further than this, thyristor T1 will not trigger into conducting before thyristor T2 receives a firing pulse. In any period during starting of the motor stator current may be continuous even for a non zero α value. It means that during that period motor phases receive full supply voltage and hence α control would have no effect in voltage control for softstarting purposes. Continuity and discontinuity of the current waveform will be dictated not only by α value but also by the input power factor of the motor (i.e. motor parameters and instantaneous value of the slip).

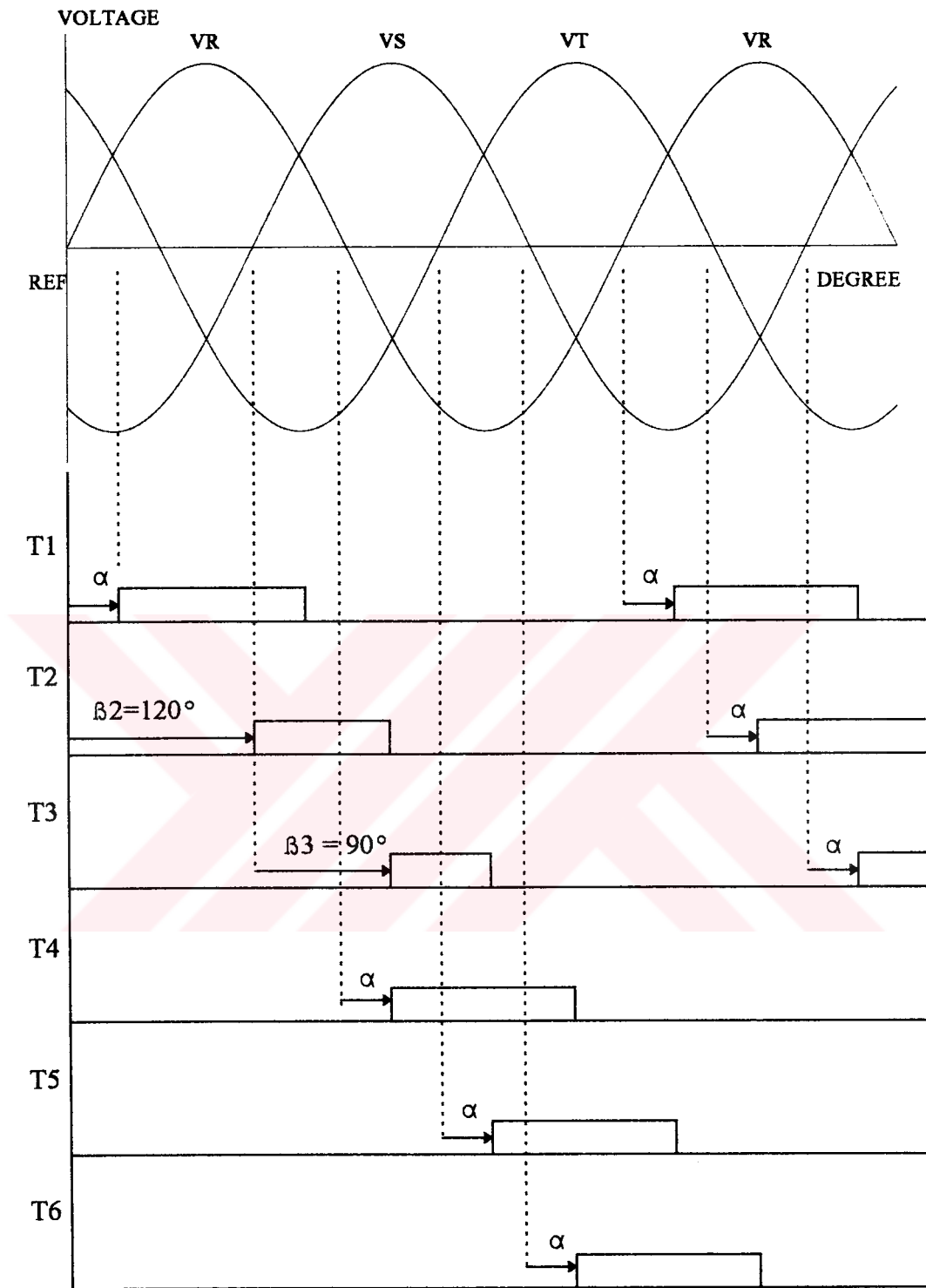
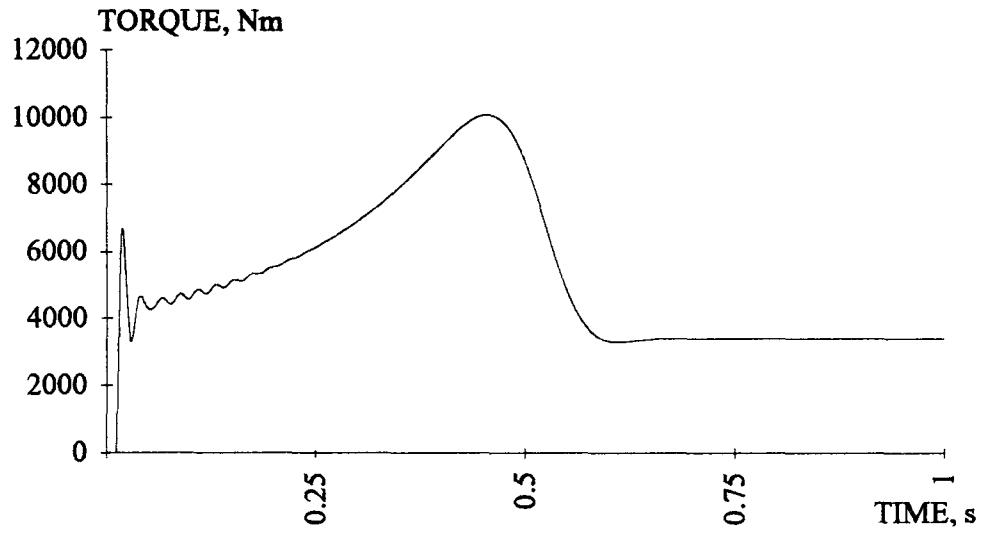
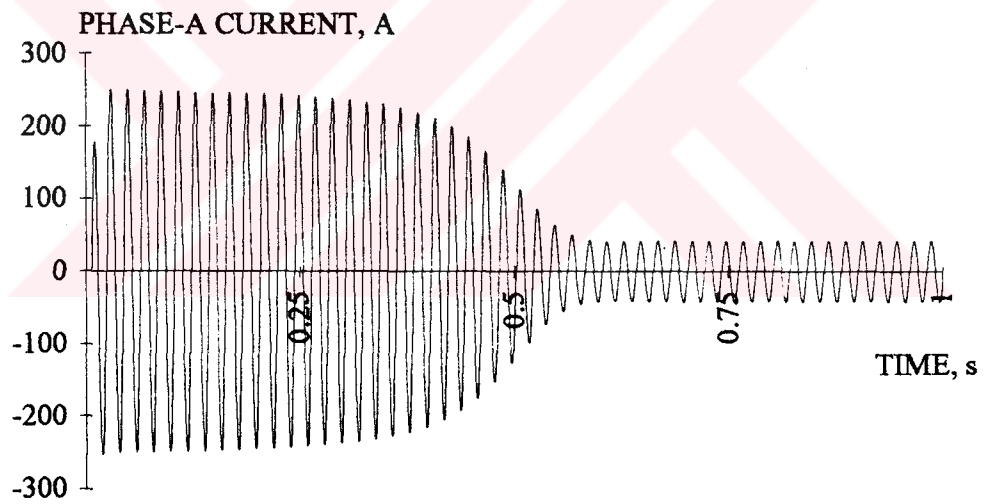


Figure 4.2 Firing instants of the thyristors with nonsimultaneous starting to minimize torque pulsations if the line current is continuous.

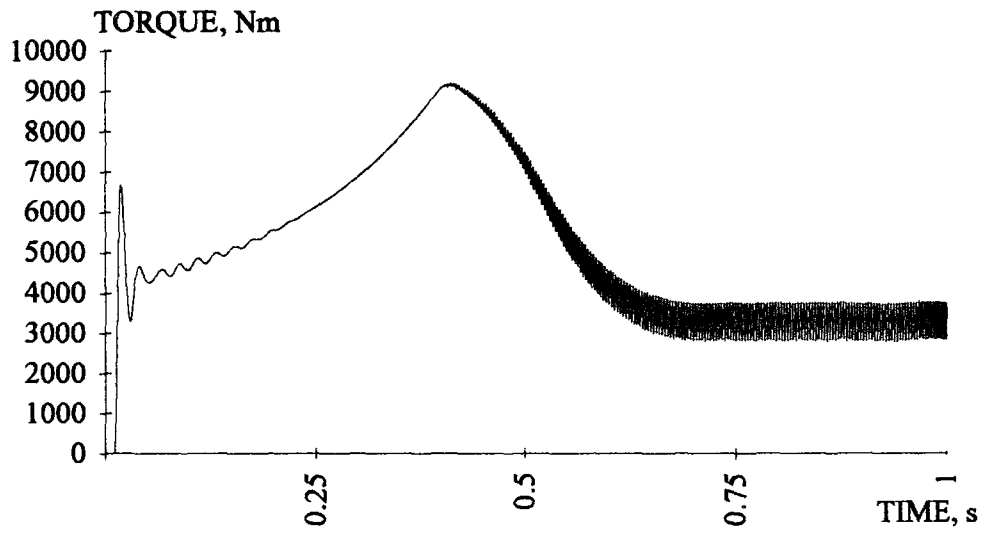


a)

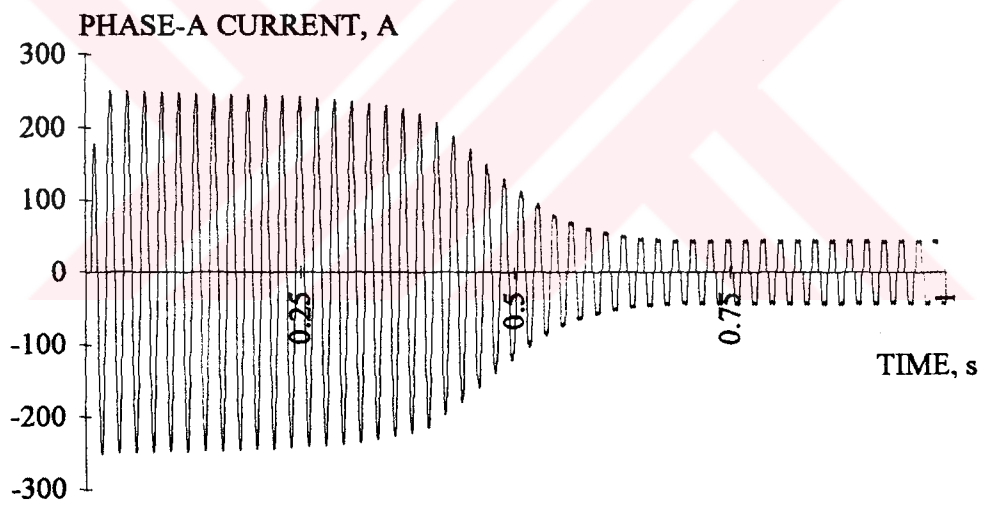


b)

Figure 4.3 a) Electromagnetic torque vs. time, b) phase-A current vs. time with nonsimultaneous switching of motor phases to the supply and with minimized torque pulsations for motor-2 when $\alpha=30^\circ$.

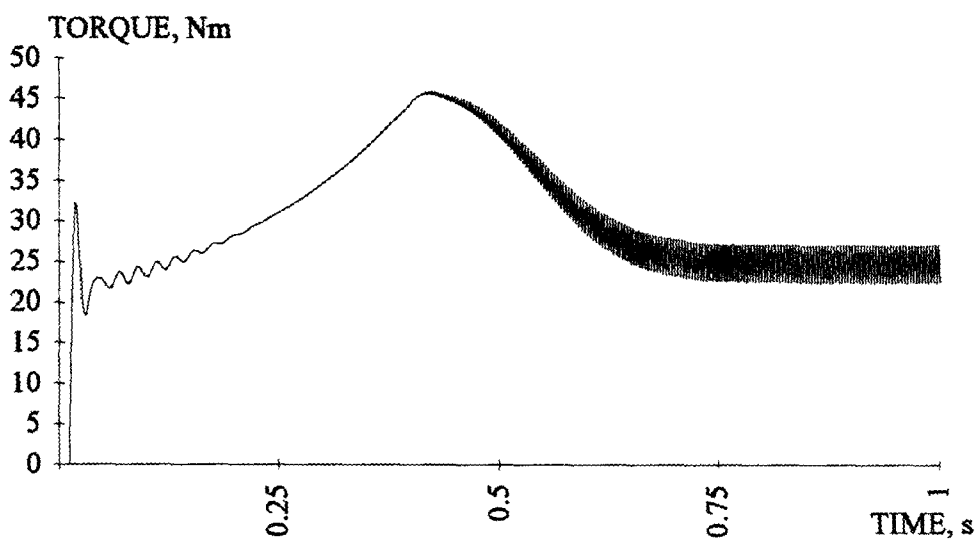


a)

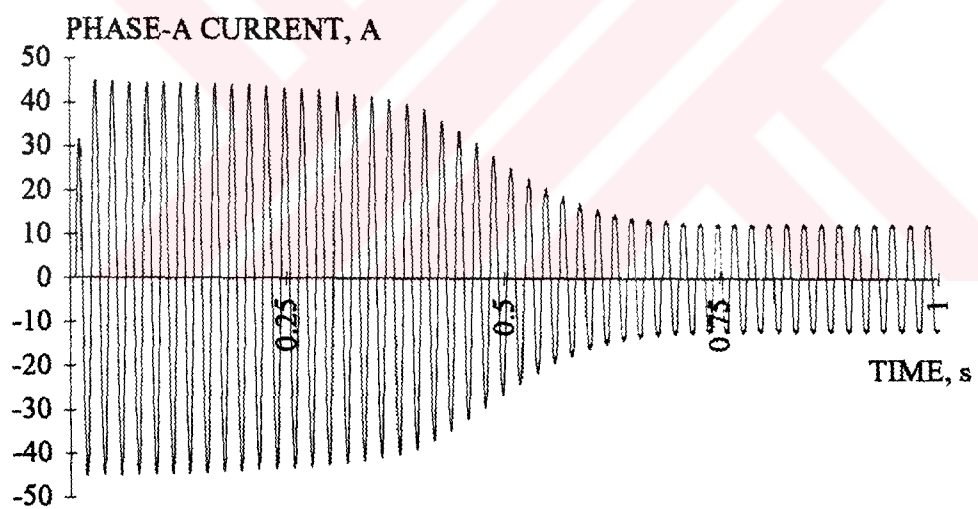


b)

Figure 4.4 a) Electromagnetic torque vs. time, b) phase-A current vs. time with nonsimultaneous switching of motor phases to the supply and with minimized torque pulsations for motor-2 when $\alpha=60^\circ$.



a)



b)

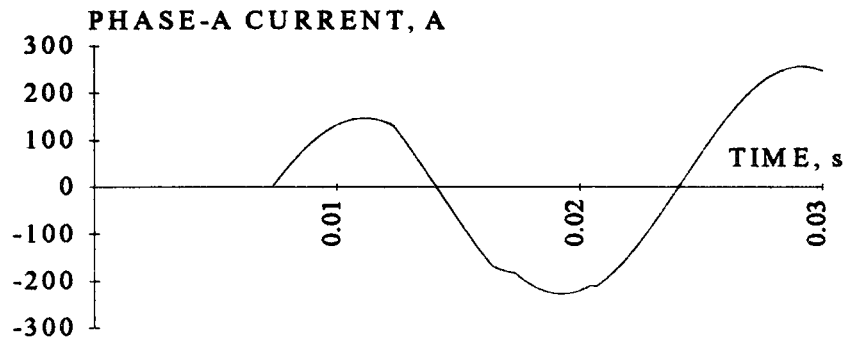
Figure 4.5 a) Electromagnetic torque vs. time, b) phase-A current vs. time with nonsimultaneous switching of motor phases to the supply and with minimized torque pulsations for motor-1 when $\alpha=60^\circ$.

For small values of α and if it is kept constant over the entire starting period, in the early phases of the starting period current will normally be continuous but as the machine speeds up input power factor improves thus making current discontinuous. It is obvious that in order to have a discontinuous current waveform α should be delayed beyond the phase angle of lag between motor current and associated voltage waveforms.

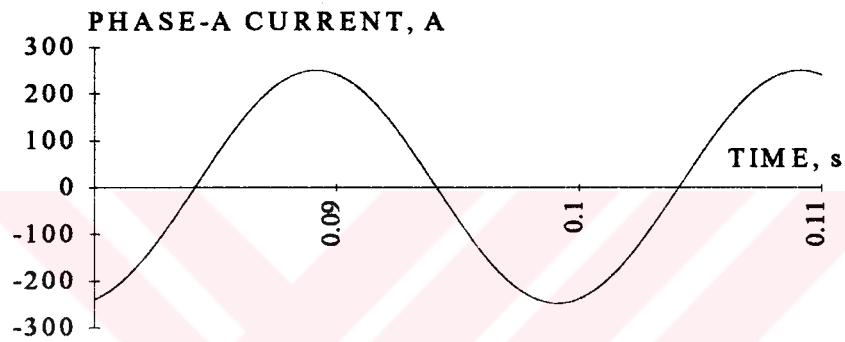
Three sets of motor current waveforms are given in figures 4.3, 4.4 and 4.5 to illustrate the optimum triggering strategy for continuous current case. For $\alpha=30^\circ$ (figure 4.3) current remains continuous over the entire starting period and the system performance becomes identical with that of the direct on starting. However, for $\alpha=60^\circ$ (figures 4.4 and 4.5) current will remain continuous only in the early phases of the starting period and the system functions as a softstarter only in a limited range of relatively high operating speeds where motor current naturally starts to decrease.

4.1.2 The triggering strategy if the line current is discontinuous and the triggering angle α is less than the power factor angle at unity slip

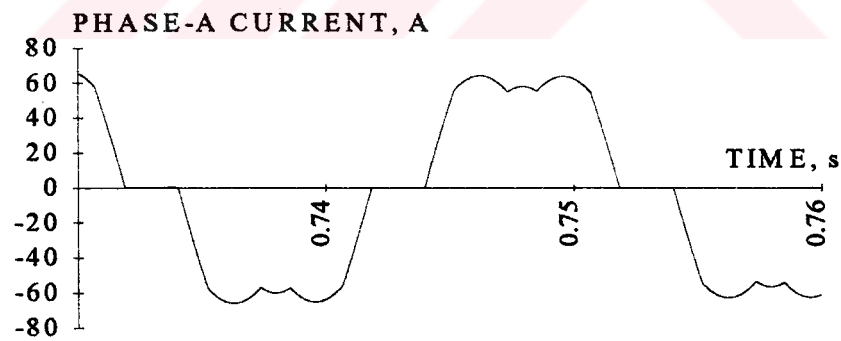
This type of operation will take place for a control range of $63^\circ < \alpha < 73^\circ$ for motor-1 and $65^\circ < \alpha < 75^\circ$ for motor-2. Results of several trials for different firing angles have shown that when α is varied in the above ranges for the mentioned motors, the stator current waveform will become discontinuous in the first few cycles of the applied voltage then becomes continuous over a considerable portion of starting period and finally turns back to discontinuous waveform as shown in figures 4.6, 4.7 and 4.8. As mentioned earlier, power factor of the motor at standstill has been calculated from the per-phase equivalent circuit by assuming balanced steady-state operation. As can be understood from the above explanations, current will be discontinuous time-to-time even though the firing angle is less than the power factor angle of the motor. This may be attributed to the fact that switchings which take place in an



a)

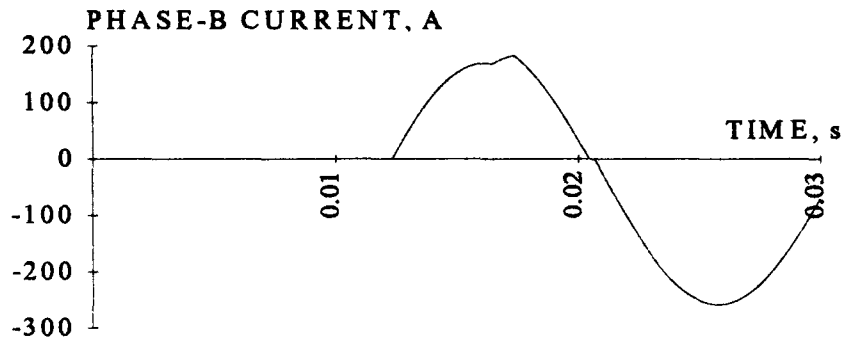


b)

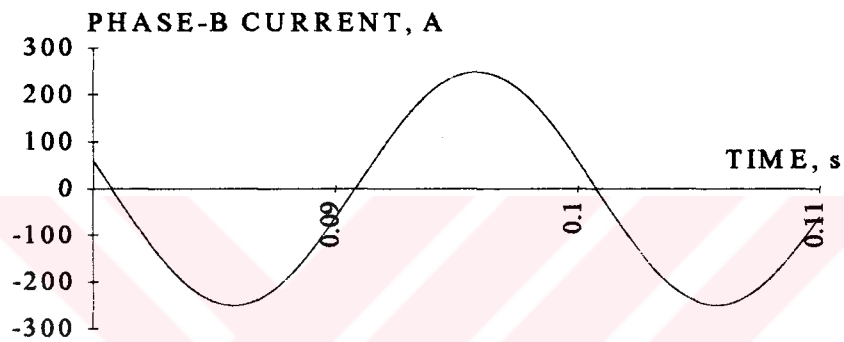


c)

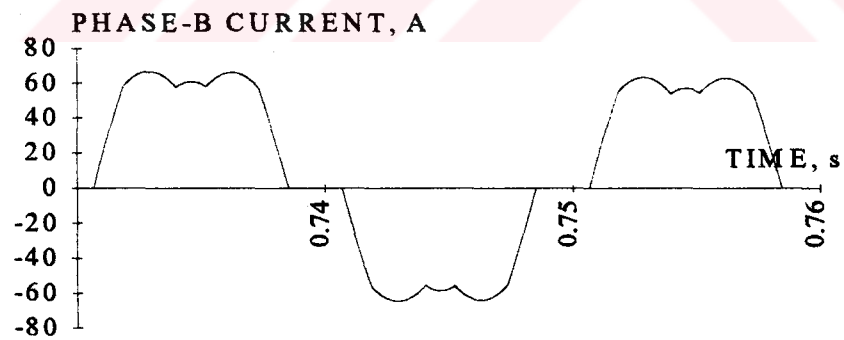
Figure 4.6 a) Starting, b) transient and c) steady-state current vs. time which are the expanded types of the phase-A current of motor-2 obtained by using the β_2 function and assuming $\beta_3=90^\circ$ as described in subsection 4.1.2 when $\alpha=72^\circ$.



a)

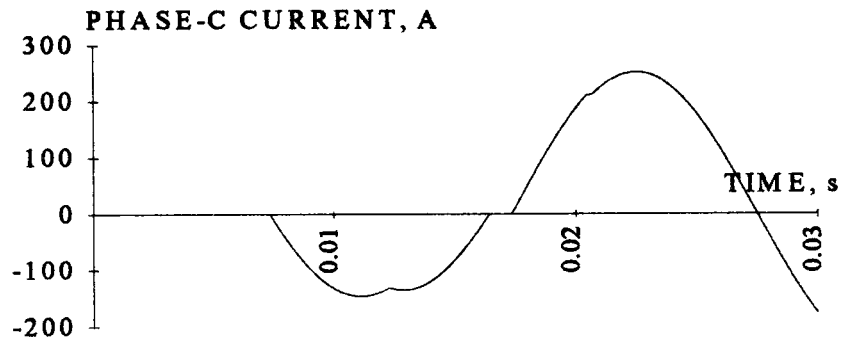


b)

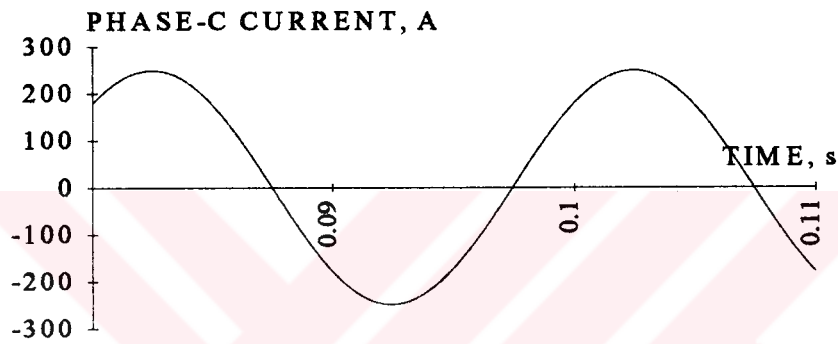


c)

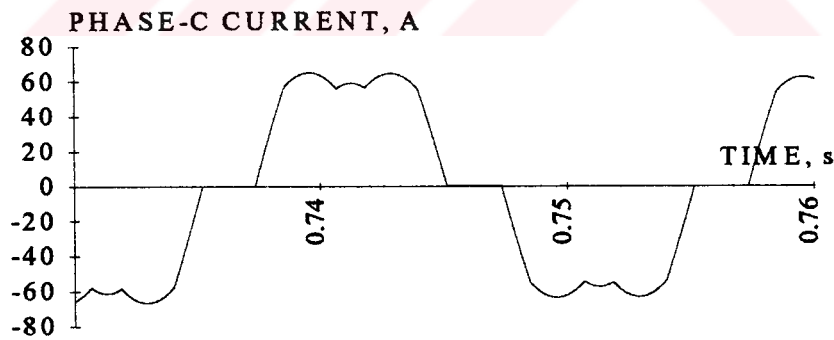
Figure 4.7 a) Starting, b) transient and c) steady-state current vs. time which are the expanded types of the phase-B current of motor-2 obtained by using the β_2 function and assuming $\beta_3=90^\circ$ as described in subsection 4.1.2 when $\alpha=72^\circ$.



a)



b)



c)

Figure 4.8 a) Starting, b) transient and c) steady-state current vs. time which are the expanded types of the phase-C current of motor-2 obtained by using the β_2 function and assuming $\beta_3=90^\circ$ as described in subsection 4.1.2 when $\alpha=72^\circ$.

induction motor softstarter are not being transient-free switchings because of the three-phase nature of the circuitry. Another important observation is that transition from discontinuous current mode to continuous and back to discontinuous modes during starting period takes place not for all α 's less than motor power factor but for a limited range of α 's which are close to the power factor angle of the motor.

The results of the several trials have also shown that for the above operation mode, the triggering strategy of the back-to-back connected thyristor pairs which minimize the transient torque pulsations should be different than that of the operation mode in subsection 4.1.1.

Optimum firing strategy for motor-2 is as given in table 4.1. Here α is the firing angle of the first thyristor T1. Thyristors T1, T2, T3, T4, T5 and T6 should receive successively their firing pulses respectively at points α , β_2 , $\beta_2+\beta_3$, $\alpha+180^\circ$, $\alpha+240^\circ$ and $\alpha+300^\circ$ (figure 4.9). It should be noted that thyristor T1 does not trigger into conduction until the second thyristor receives a firing pulse at β_2 in the first cycle and firing angles of all thyristors are defined with respect to a common reference point (zero crossing point of phase-R voltage as explained in subsection 4.1.1).

Table 4.1 β_2 and β_3 angles with respect to α angles for motor-2.

α	66°	68°	70°	72°	74°
β_2	121°	124°	128°	132°	135°
β_3	90°	89°	88°	90°	91°

In this operating mode, the optimum initial firing instant of β_2 given in table 4.1 can be approximated by a straight line as given in equation 4.1 and

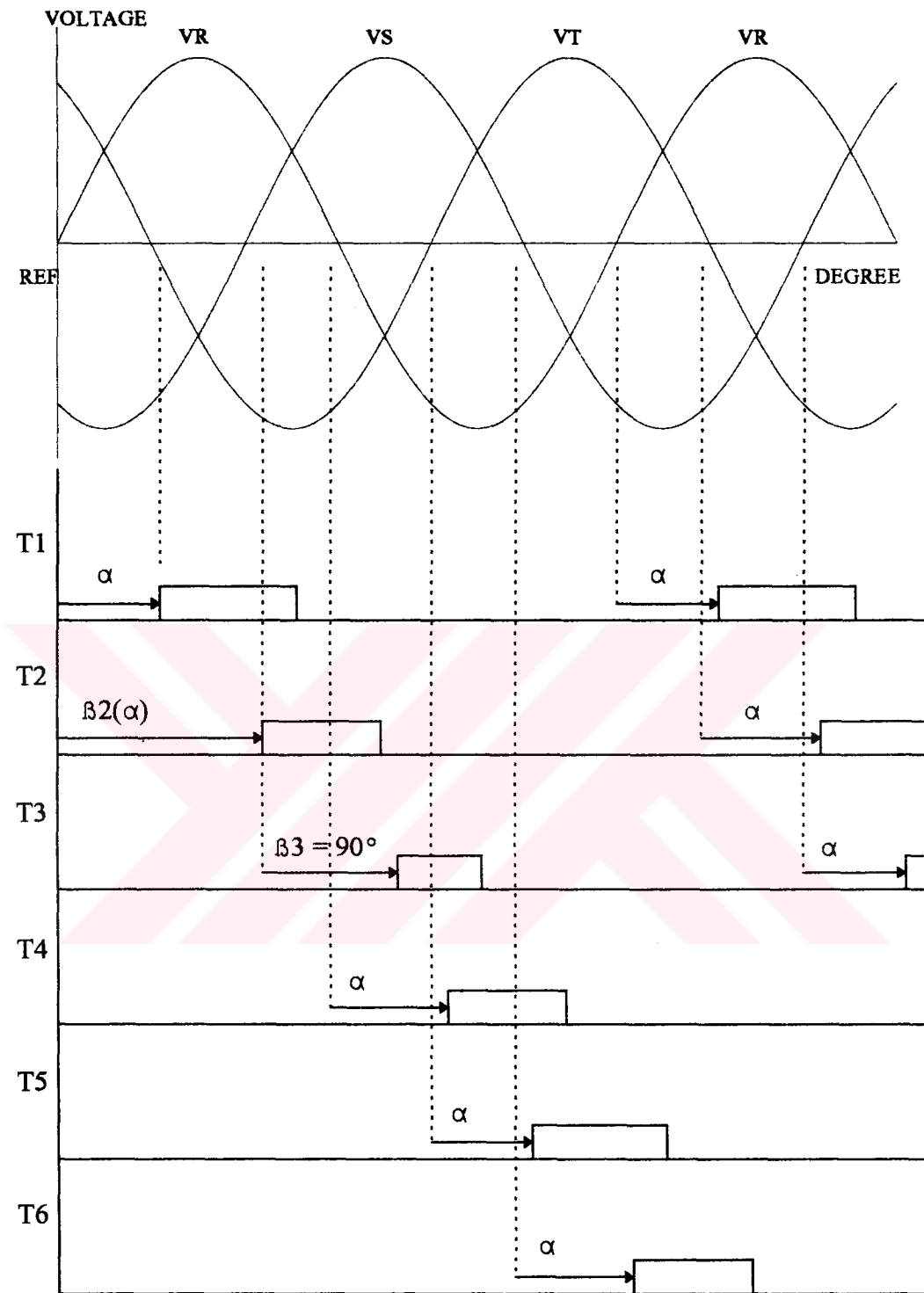
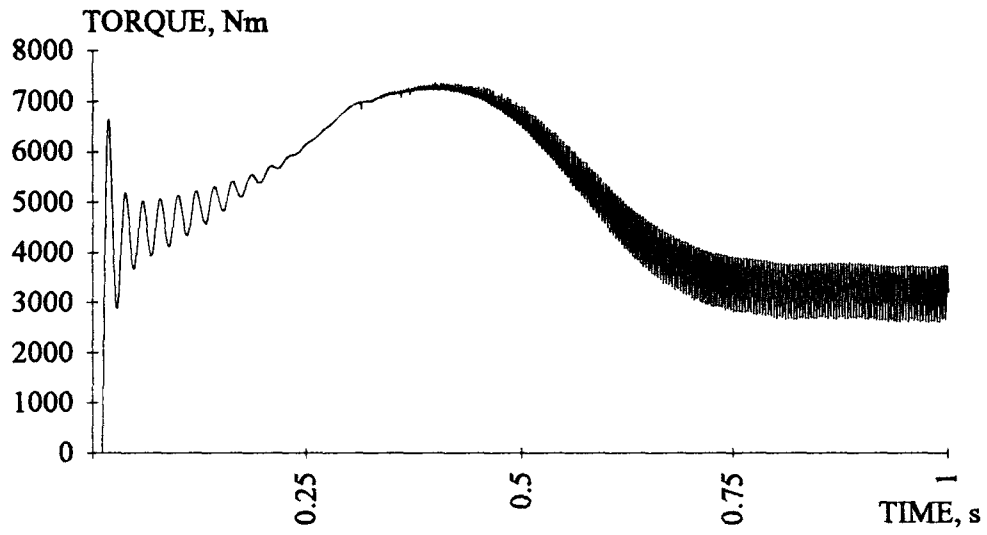
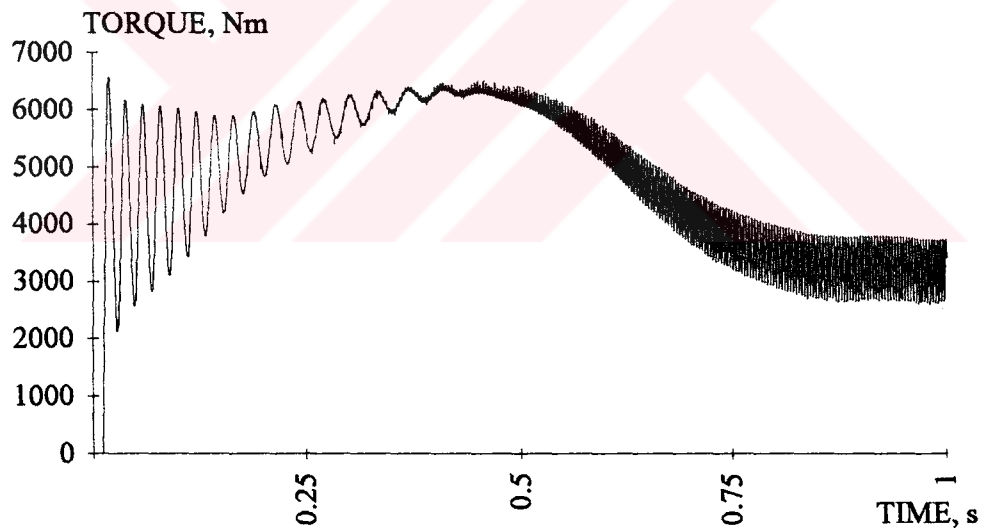


Figure 4.9 Firing instants of the thyristors with nonsimultaneous starting to minimize torque pulsations if the triggering angle α is less than the power factor angle when slip=1 and the line current is discontinuous in the first few periods of starting.

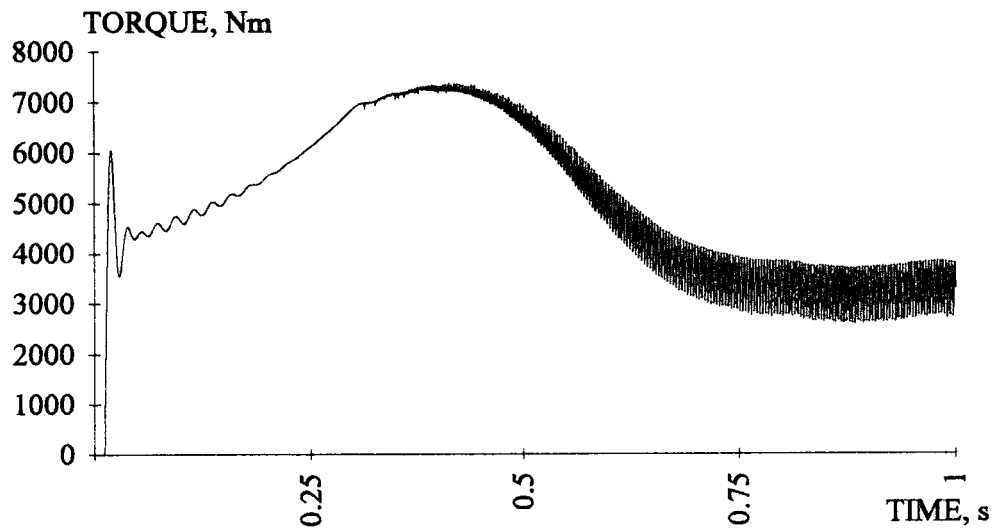


a)

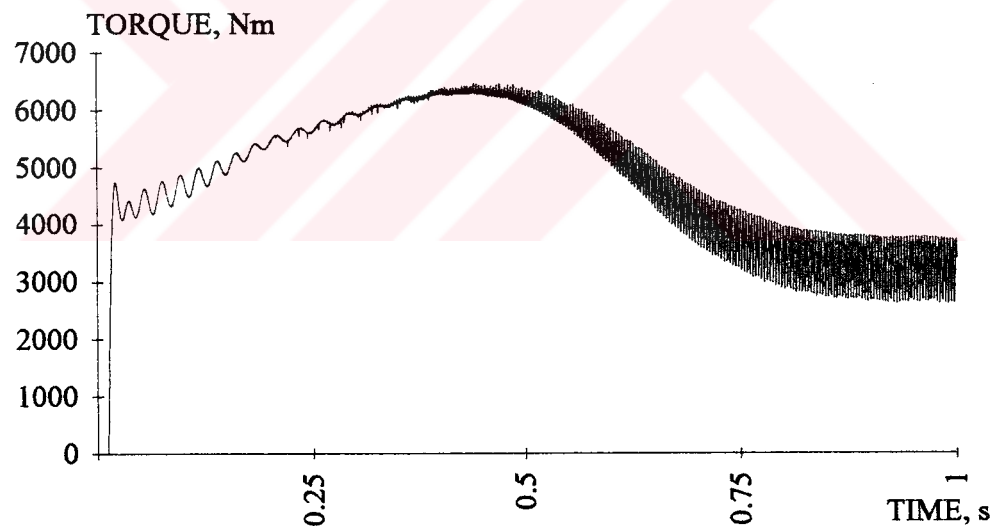


b)

Figure 4.10 Electromagnetic torque vs. time obtained by using the firing strategy mentioned in subsection 4.1.1 for motor-2 when a) $\alpha = 68^\circ$ and b) $\alpha = 72^\circ$.

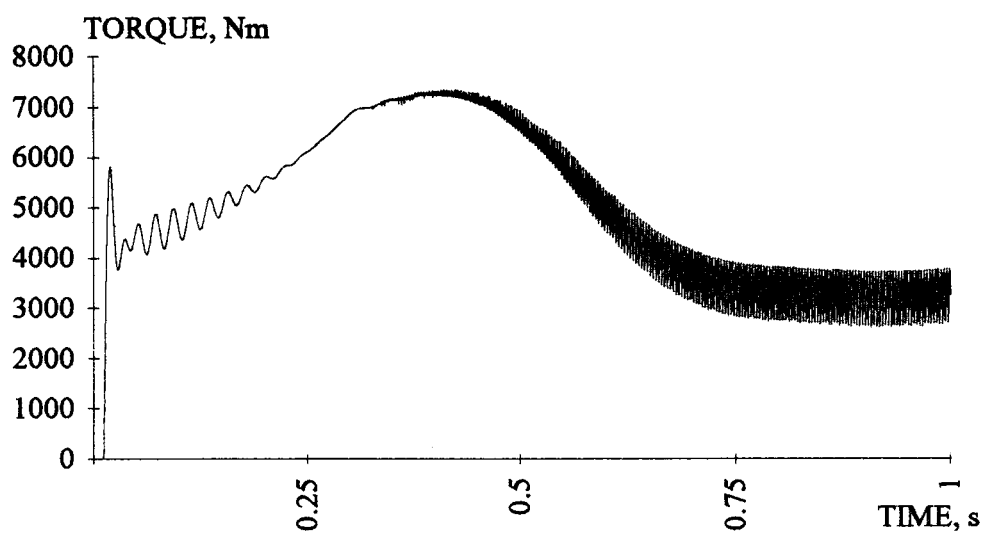


a)

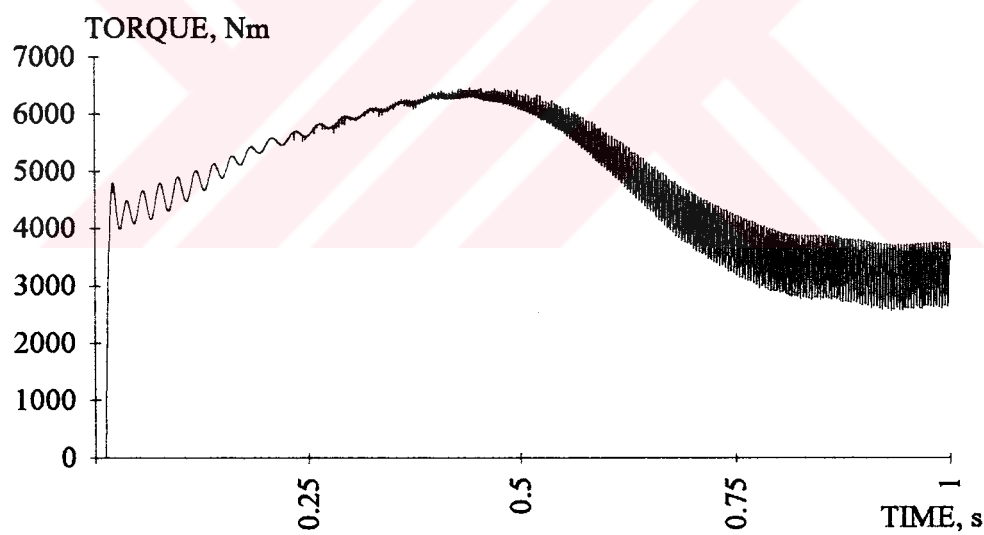


b)

Figure 4.11 Electromagnetic torque vs. time obtained by using the β_2 and β_3 values given in table 4.1 for motor-2 when a) $\alpha = 68^\circ$ and b) $\alpha = 72^\circ$.

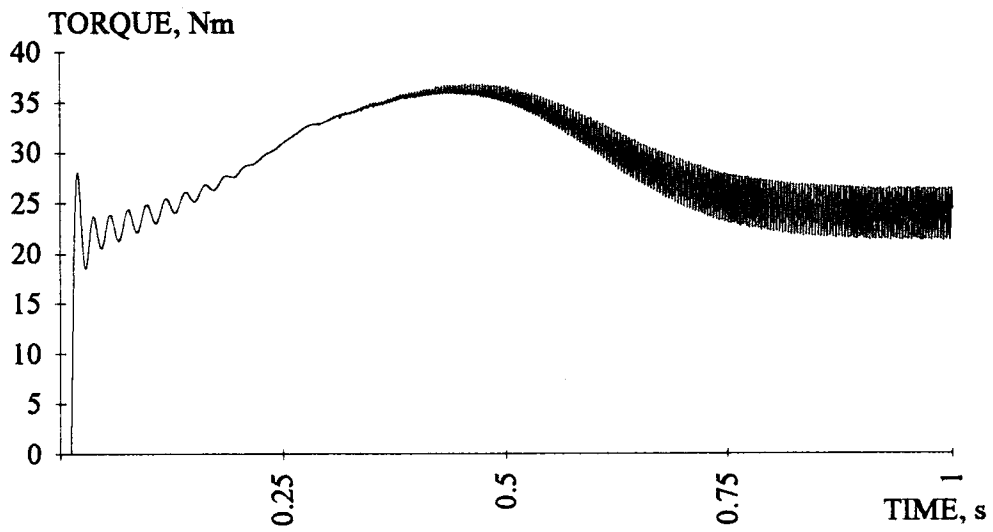


a)

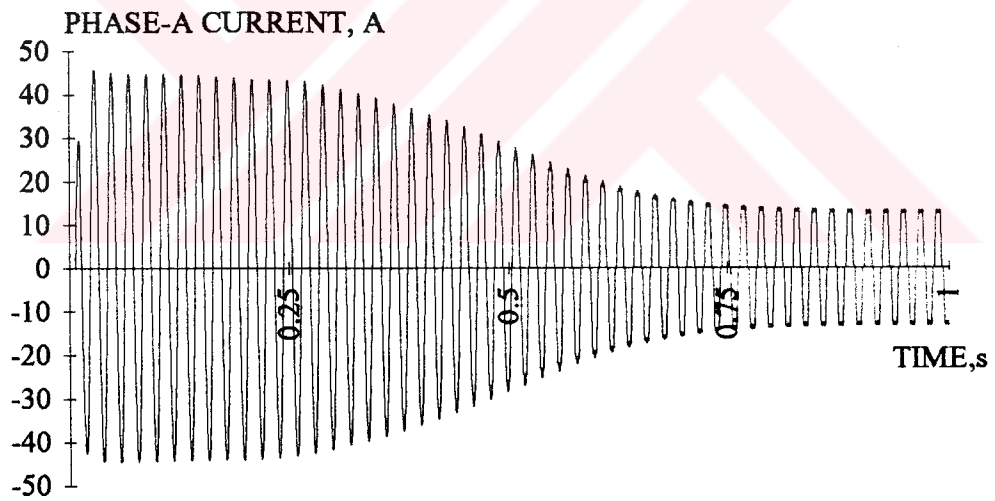


b)

Figure 4.12 Electromagnetic torque vs. time obtained by using the β_2 function and assuming $\beta_3 = 90^\circ$ for motor-2 when a) $\alpha = 68^\circ$ and b) $\alpha = 72^\circ$.



a)



b)

Figure 4.13 a) Electromagnetic torque vs. time, b) current vs. time obtained by using the β_2 function and assuming $\beta_3=90^\circ$ for motor-1 when $\alpha=72^\circ$.

slight changes in β_3 can be disregarded by taking constant $\beta_3=90^\circ$ as in subsection 4.1.1 for simplification purposes.

$$\begin{aligned}\beta_2-121 &= ((135-121)/(76-66)) * (\alpha-66) \\ \beta_2 &= 1.75\alpha + 5.5\end{aligned}\tag{4.1}$$

To minimize the electromagnetic torque oscillations in this mode of operation, three different strategies can be employed. These are,

I. The strategy found in subsection 4.1.1 can also be applied in this operating mode;

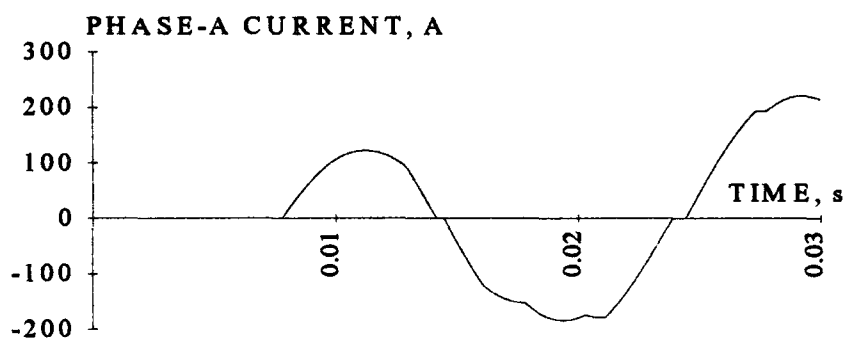
II. Actual values of initial firing instants mentioned in table 4.1 (β_2 and β_3) can be applied.

III. The approximate function of $\beta_2(\alpha)$ and constant $\beta_3=90^\circ$ can be used as the initial firing strategy.

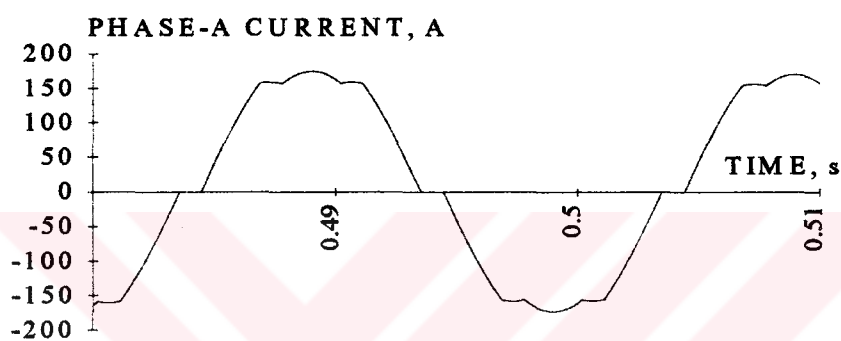
It is seen from the results the strategy employed in **I** significantly improved the torque oscillations (figure 4.10) as compared to triggering without adopting the initial firing strategy in the first cycle of operation. As compared to the simulation results obtained for optimized values of β_2 and β_3 (table 4.1) however, strategy proposed in subsection 4.1.1 results in considerably higher torque oscillations in this mode of operation (figure 4.11). It can be observed from figure 4.12 that the approximate function proposed for β_2 ($\beta_2(\alpha)$) and constant β_3 also give acceptable results close to the optimum case for both motor-1 (figure 4.13) and motor-2 with minimized starting torque oscillations.

4.1.3 The triggering strategy if the triggering angle α is greater than the power factor angle at unity slip

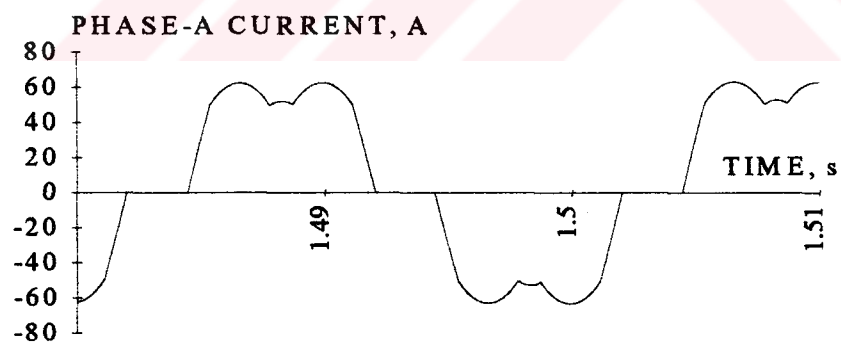
When the triggering angle α is greater than the power factor angle when slip is equal to 1, the line current becomes discontinuous at every period of the starting as shown in figure 4.14. To minimize torque pulsations, a different method from the methods described in subsections 4.1.1 and 4.1.2 should be used.



a)



b)



c)

Figure 4.14 a) Starting, b)transient and c) steady-state current vs. time simulations, which are expanded types of figure 4.16, obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-2 when $\alpha=80^\circ$.

In this method, reference point is chosen as the zero crossing point of phase-R voltage as in subsection 4.1.1. Starting operation will begin after triggering the thyristor T2 at angle β_2 . At that angle thyristors T1 and T2 trigger into conduction and the current starts to flow through phase-A and phase-C coils resulting in two-phase operation. When the thyristor T3 receives a firing pulse β_3 degrees later than that of thyristor T2, it will trigger into conduction, resulting in either three-phase or two-phase operation. Three-phase operation of the motor arises if thyristor T1 does not turn off when thyristor T3 triggers into conduction, otherwise two-phase operation takes place. Thyristor T4 receives a firing pulse at $\alpha+180^\circ$ and triggers into conduction at the turn off instant of thyristor T1. Then remaining thyristors will receive firing pulses at their own α 's. The pattern of firing pulses for the six thyristors are shown in figure 4.15. Depending upon the operating conditions, some of the thyristors trigger into conduction at the time instants later than those shown in figure 4.15.

Table 4.2 shows the optimum triggering strategy for different α 's greater than the power factor angle of the motor at unity slip (α, β_2 and β_3 have been defined as in subsection 4.1.1).

Table 4.2 β_2 and β_3 angles with respect to α angles for motor-2.

α	80°	90°	100°	110°
β_2	$\alpha+60^\circ$	$\alpha+60^\circ$	$\alpha+60^\circ$	$\alpha+60^\circ$
β_3	93°	87°	80°	74°

Here again, β_3 can be approximated by a straight line as given in equation 4.2.

$$\beta_3 - 93 = ((93 - 74) / (110 - 80)) * (\alpha - 80)$$

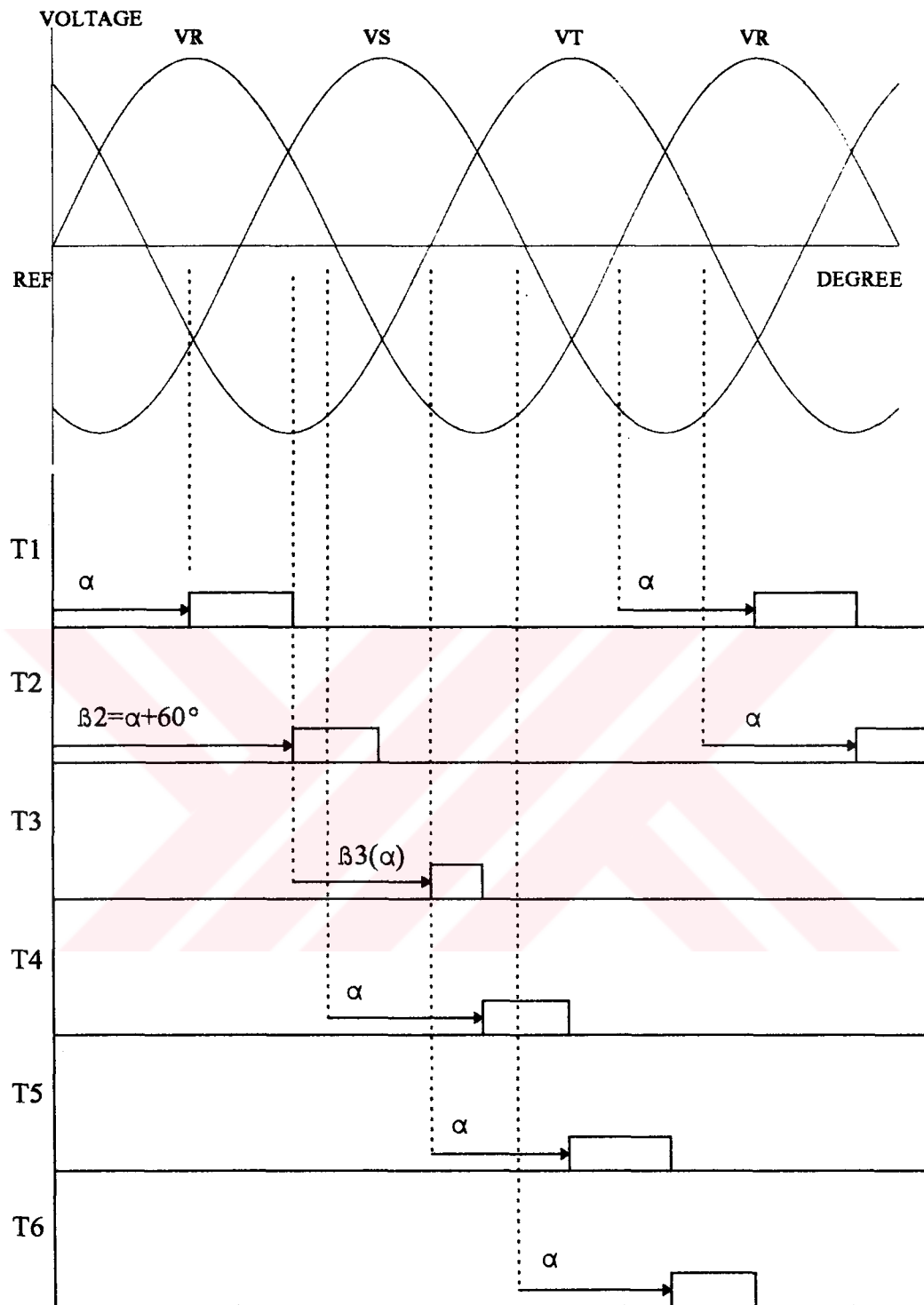
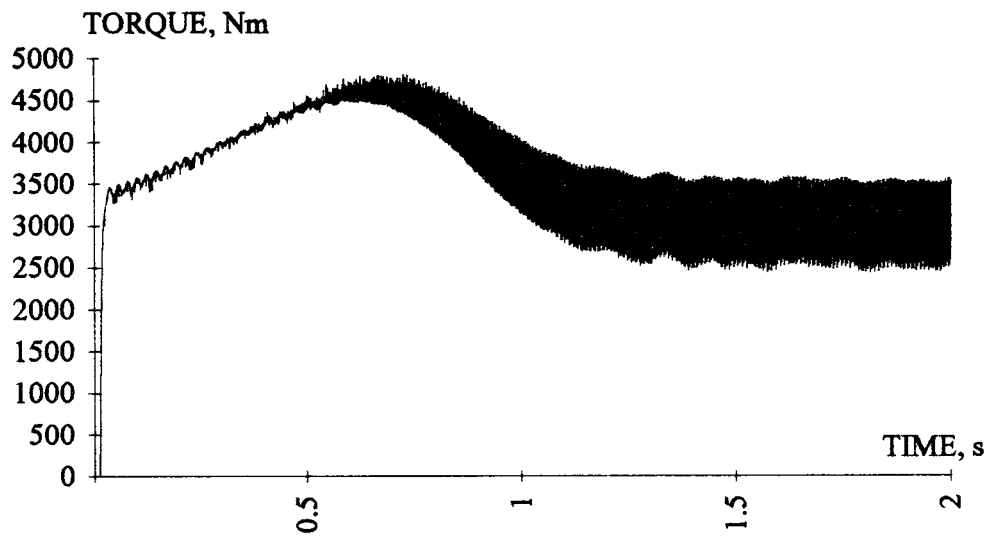
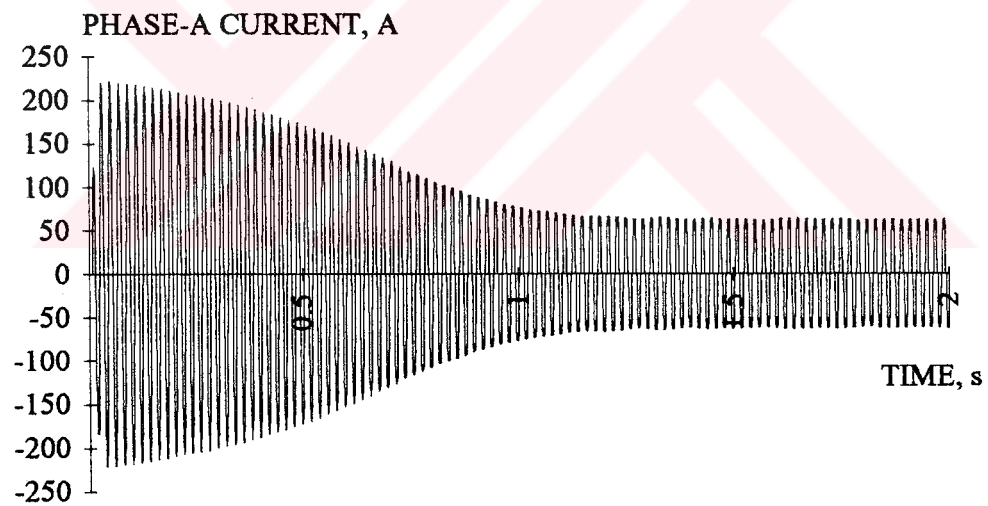


Figure 4.15 Firing instants of the thyristors with nonsimultaneous starting to minimize torque pulsations if the triggering angle α is greater than the power factor angle at slip=1.

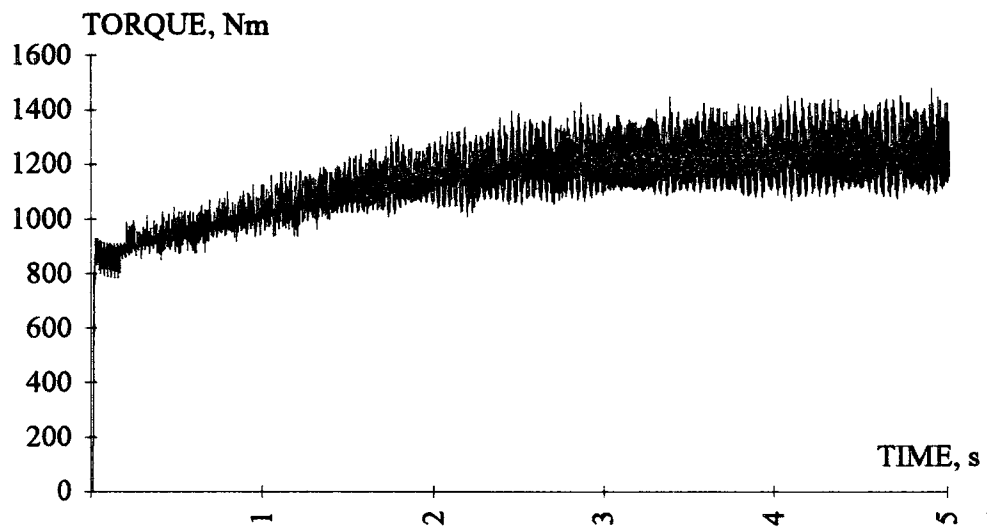


a)

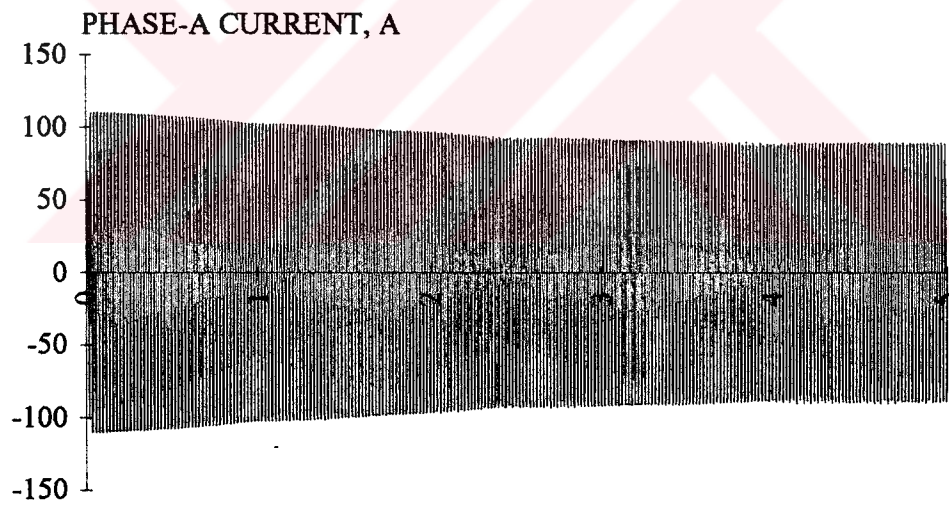


b)

Figure 4.16 a) Electromagnetic torque vs. time, b) phase-A current vs. time obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-2 when $\alpha=80^\circ$.

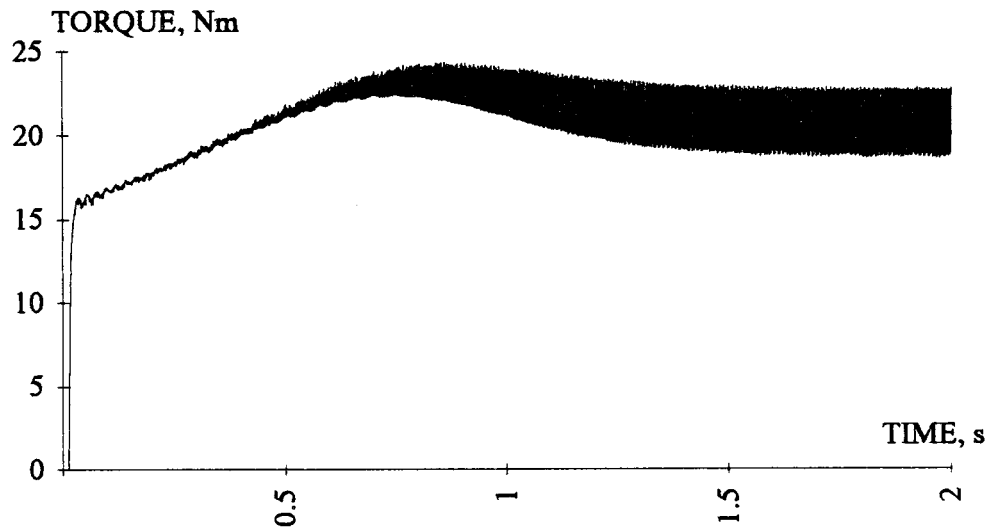


a)

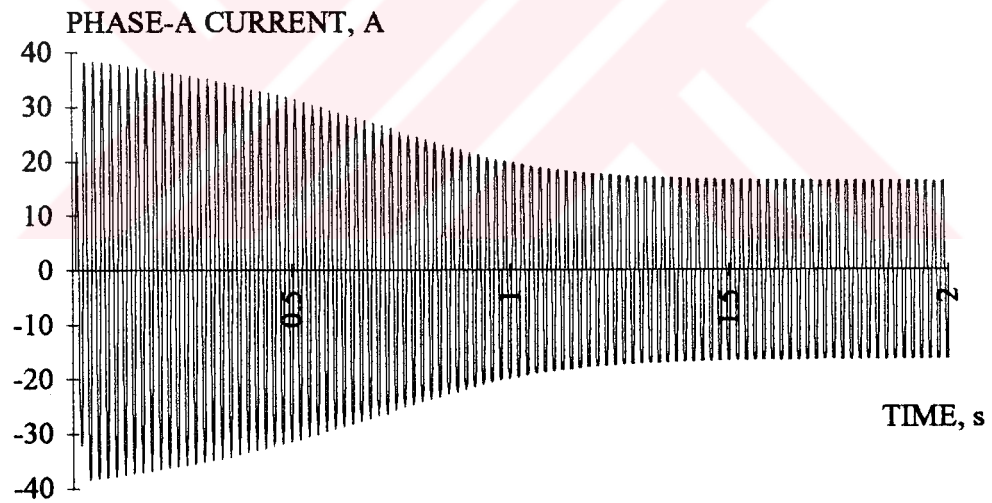


b)

Figure 4.17 a) Electromagnetic torque vs. time, b) phase-A current vs. time obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-2 when $\alpha=100^\circ$.



a)



b)

Figure 4.18 a) Electromagnetic torque vs. time, b) phase-A current vs. time obtained by taking β_2 as in table 4.2 and using the β_3 function for motor-1 when $\alpha=80^\circ$.

$$\beta_3 = -(19/30) * \alpha + 143.67 \quad (4.2)$$

This straight line approximation of β_3 variation as a function of α can make the implementation of the control circuitry easier and hence, depending upon the type of the control circuit technology, it can be preferred in the implementation phase.

For this operating mode, electromagnetic torque vs. time and current vs. time waveforms are given in figure 4.16, figure 4.17 and figure 4.18 for different firing angles for both motor-1 and motor-2. These waveforms are drawn using the approximated β_3 function and show that torque oscillations are considerably reduced during the initial phases of starting. Considerable torque pulsations occur at steady-state due constant α triggering of thyristors which cause discontinuous line currents (figure 4.14) at steady state. For softstarting purposes however α will be controlled and reach 0° at steady-state as explains in section 4.2.

4.2 Limiting the Starting Current

To limit the starting current to a prespecified value, rms. value of voltage applied to the motor terminals should be controlled continuously during the starting period. This is achieved by controlling the thyristor firing angles in the starting period by a proper open loop or closed loop control strategy. The control strategies examined within the scope of this thesis have already been explained in chapter 1. For a given motor-load combination, since the acceleration time is dictated by load characteristics and inertia, in a softstarter current limit and acceleration time can not be programmed simultaneously. Here, it is assumed that the user will set only the limit value of the starting current and maximum allowable value of acceleration time. If the implemented circuitry can not meet the prespecified maximum acceleration time by keeping the stator current constant at the limit value during the starting time, then the control circuitry

generates a warning signal. For such cases, the maximum allowable value of acceleration time setting needs to be readjusted by the user for the given load.

It is worth to note that, in all of the current limit strategies described here, the optimum triggering strategy(ies) explained in section 4.1 have also been applied in order to minimize electromagnetic torque oscillations. This is considered to be important in order to make a rigorous comparison between the results of various starting current limiting strategies in addition to actual physical reasons such as minimizing the stresses on the shaft system, accelerating the load in a shorter time etc.

The open loop control strategies which will limit the starting current of the motor and examined in this thesis are the application of ramp triggering function (figure 4.19) and cosine triggering function (figure 4.20).

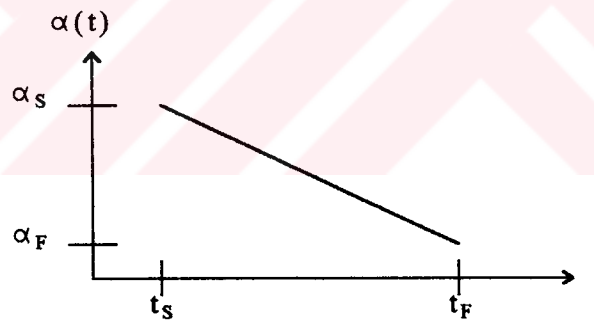


Figure 4.19 Ramp triggering function.

Ramp triggering function is a straight line passing through the starting point and final point of the starting period. Consequently, before putting the device in operation, the user should specify initial value of triggering angle and the time period in which firing angle will be varied from the initial value to final

value on a straight line ($t_F - t_S$). Since the final value of triggering angle is zero, the motor always works at rated voltage in the steady state. When this current limiting strategy is applied, the user should make several trials on $t_F - t_S$ setting of the device in order to obtain optimum starting performance. The reasons can be explained as follows.

1. If $t_F - t_S$ is kept shorter than the required value, firing angle reaches zero and hence applied voltage reaches the rated value before the machine speeds up sufficiently resulting in a flow of starting current exceeding the limit value.

2. On the other hand, if $t_F - t_S$ kept longer than the required value, the emf builds up more rapidly than applied voltage resulting in a lower starting current than the prespecified limit.

The second open loop control strategy i.e. the application of cosine triggering function has similar properties and drawbacks with ramp triggering function case. Here again, the initial value of the firing angle and $t_F - t_S$ period will be specified by the user. However, the control system will change the firing angle from initial value to zero over the prespecified period cosinusoidally instead of a straight line approximation. Although the implementation of this strategy is easier than closed loop triggering strategies, it also necessitates several trials which should be made by the user in finding the optimum $t_F - t_S$ setting of the device.

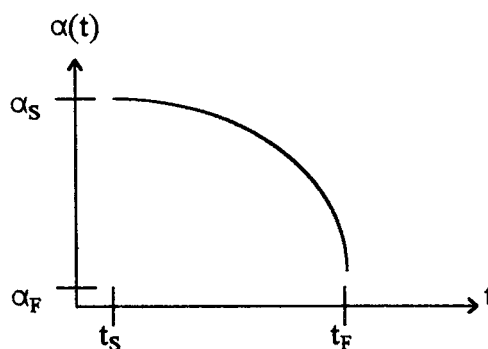


Figure 4.20 Cosine triggering function.

A closed loop triggering angle control strategy has been proposed and investigated within the scope of this thesis. The basic control philosophy of this closed loop control system is as illustrated in figure 4.21. In this figure, variations in α and stator current I_{STATOR} are not drawn in scale and exaggerated for the sake of illustration.

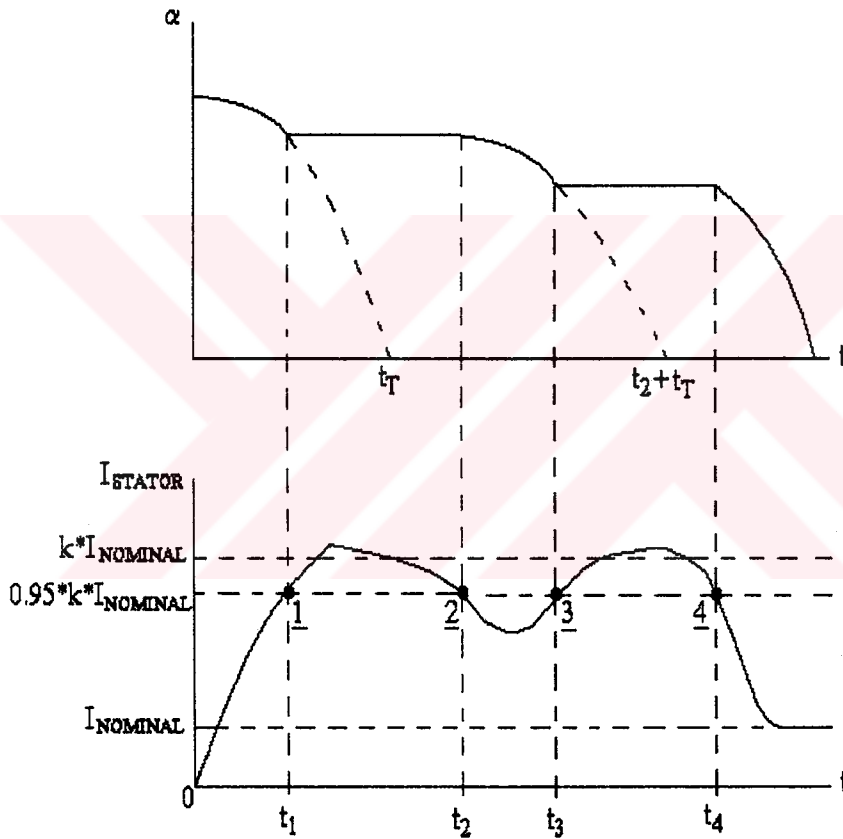


Figure 4.21 The starting current limiting method proposed in this thesis.

In this control system, peak value of starting current in phase-A of the motor needs to be monitored continuously. This will be achieved by

implementing a feedback current loop. Firing angle of thyristors are varied cosinusoidally and then kept constant in order to keep the starting current within a band around the limit value of the starting current. Limiting value of the starting current will be set by user to any value externally. Also the band used to limit the starting current and quarter period of each cosinusoidal wave will be specified by the user. Cosinusoidal triggering angle - constant triggering angle type of operation will be applied automatically and successively until the motor reaches its steady state speed.

As illustrated in figure 4.21, at $t=0$, softstarter is switched on to accelerate the motor-load combination at a current limit value of $k \cdot I_{\text{NOMINAL}}$. Theoretically, k is between unity and 5-7 depending on the motor type. In commercial systems, k can be adjusted to any value between 2 and 6 by the user. First the control system calculates the initial value α to give the desired limit value of starting current by the use of mathematical model given in chapter 3 and then generates a cosinusoidally varying triggering function with a quarter period of 1 second ($T = t_T$ as defined in figure 4.21). Motor current rises rapidly in the first few cycles of applied supply voltage between $t=0$ and t_1 . When it reaches to and tends to exceed 95% of the prespecified current limit value (point 1 in figure 4.21), control system changes its mode from cosinusoidal variation of α to constant α case. The control system keeps α constant at its final value at t_1 . As can be understood from the waveform illustrating current variations in figure 4.21, the motor current continues to increase and makes an overshoot and gradually turns back to 95% of prespecified current value ($t=t_2$). As soon as the peak current turns back to 95% of prespecified limit at t_2 , control system generates a new cosinusoidally varying triggering function with a peak value of $\alpha(t_2)$ and a quarter period of 1 second. It is clear that α ceases at $t=t_2+t_T$ according to the new cosinusoidal variation. Motor current makes an overshoot in the period between t_2 and t_3 and then, reaches and tends to exceed $0.95 \cdot k \cdot I_{\text{NOMINAL}}$ at $t=t_3$. Here again, control system stands to keep α at $\alpha(t_3)$.

This type of α variation repeats itself successfully until the motor reaches its steady state.

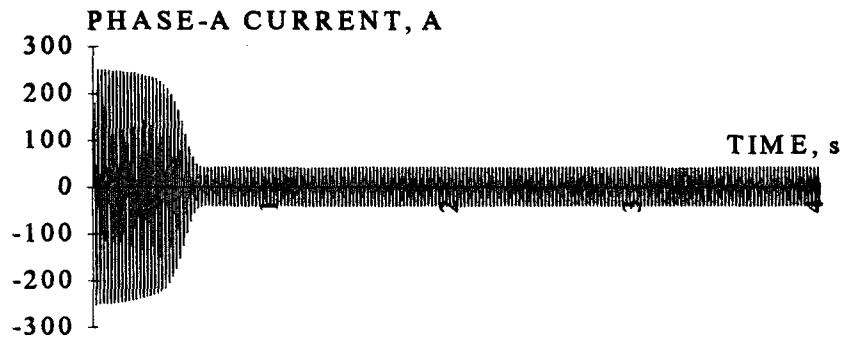
The simulation results have shown that, the variation in starting current is not more than +2 to -7% of $k \cdot I_{\text{NOMINAL}}$ for both the motors when $0.95 \cdot k \cdot I_{\text{NOMINAL}}$ has been chosen as the threshold value of current limit. If the threshold value were chosen as the limit value itself, current oscillation with much higher magnitudes would be obtained.

In order to make a comparison between the two open loop control strategies and the closed loop strategy proposed in this work, the response of the softstarter-motor-load combination have been obtained for several cases. In order to make a more rigorous comparison between different control strategies, the initial value of the triggering angle ($\alpha(0)$) and $t_F - t_S$ are adjusted to the same value for all control strategy in each case.

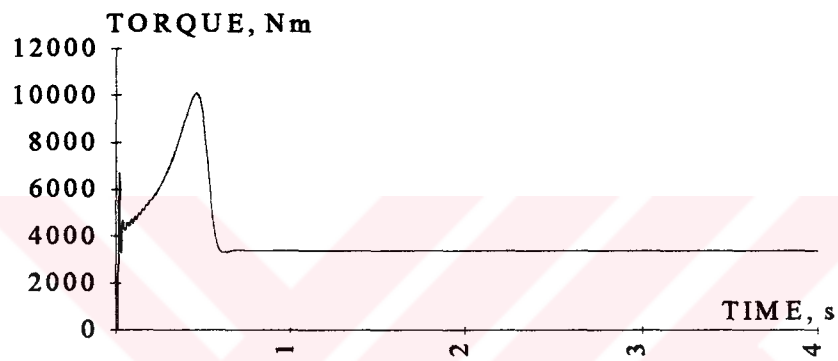
Some sample responses of the system are given in figures 4.22-4.32. Figure 4.22 shows the variation in starting current, torque and triggering angle as a function of time when direct-on starting technique with minimized torque pulsations is applied. This gives us information about the maximum obtainable value of starting current and minimum value of acceleration time since maximum applicable voltage is exerted on stator side.

Figure 4.23 and 4.24 show the response of the system respectively against ramp and cosine triggering function cases for the same initial α value ($\alpha=100^\circ$) and total α variation period (0.5 second). Similar responses are given in figures 4.25 and 4.26, 4.27 and 4.28, 4.29 and 4.30 respectively for α variation periods of 1, 3.69 and 4 seconds. Following comments can be drawn from these waveforms:

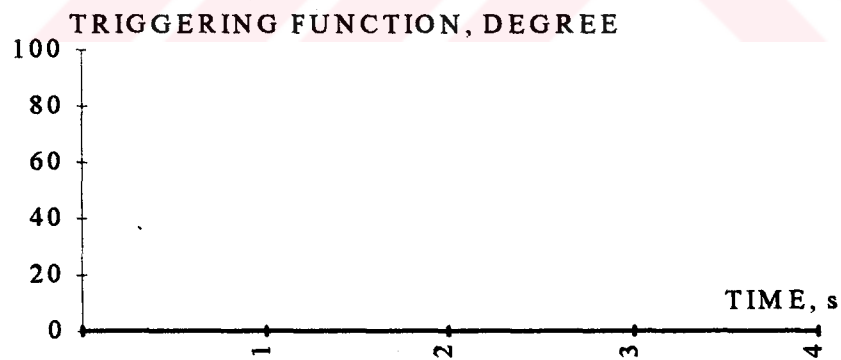
1. In none of these open loop control strategies for the triggering angle, starting current remains constant. However, starting current which remains constant at a prespecified limit value is desirable for better utilization of the available starting facilities and shorter starting time.



a)

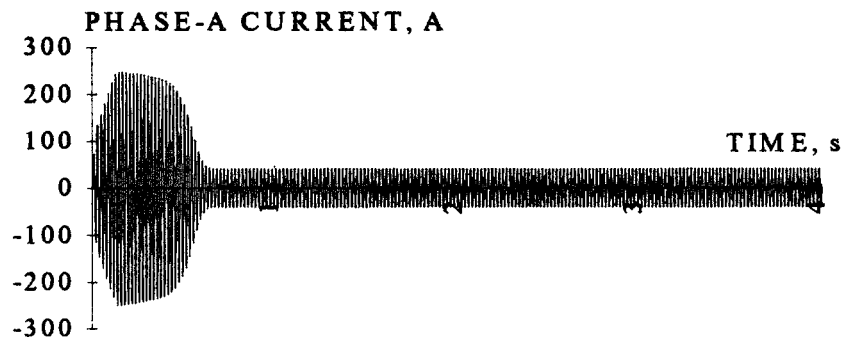


b)

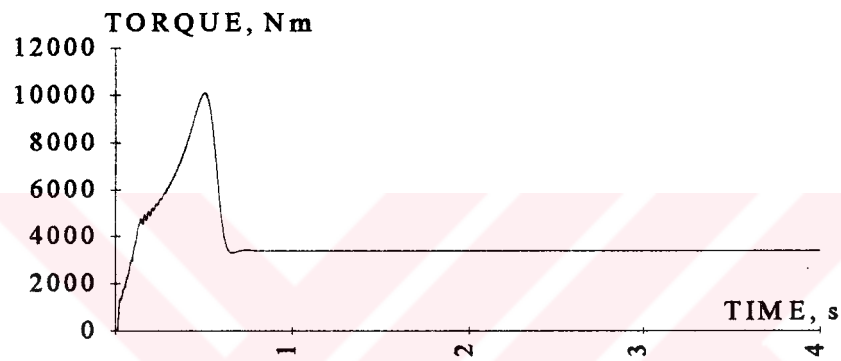


c)

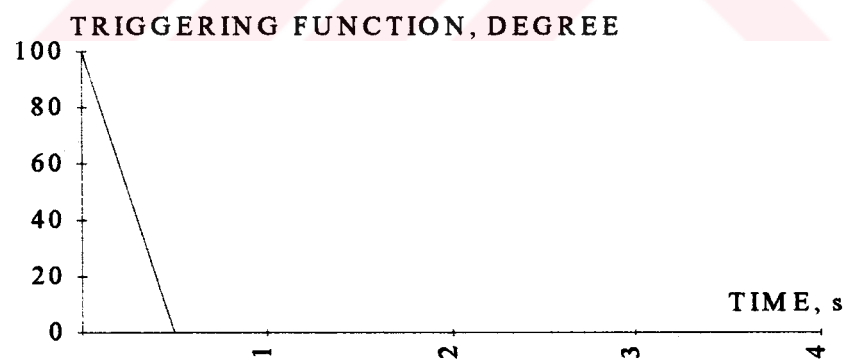
Figure 4.22 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 obtained by using the method in subsection 4.1.1 to minimize torque pulsations when $\alpha=0^\circ$.



a)

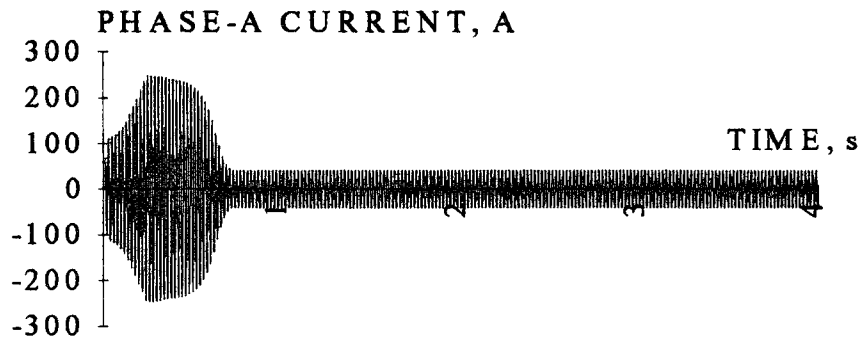


b)

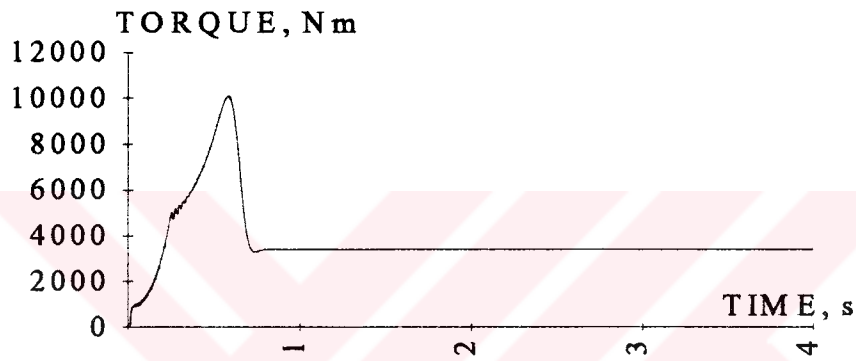


c)

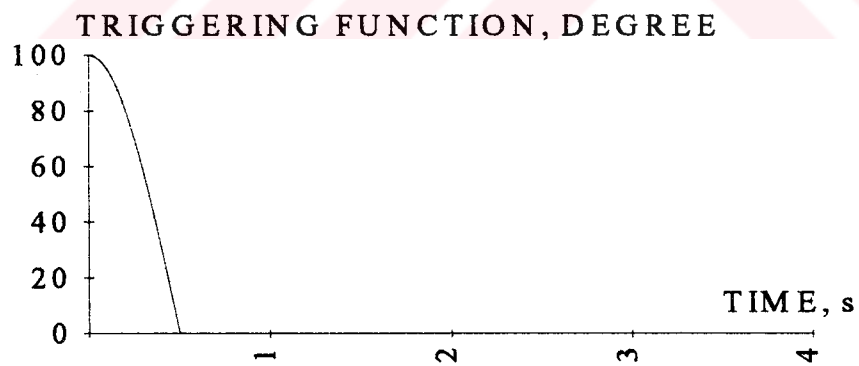
Figure 4.23 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here, $\alpha_s=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_s=0.5s$.



a)

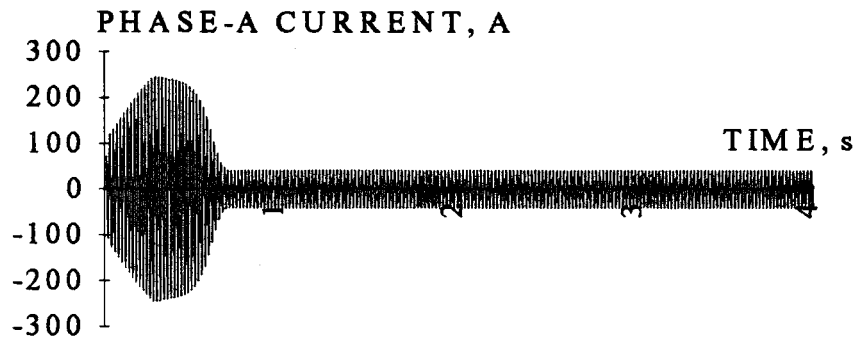


b)

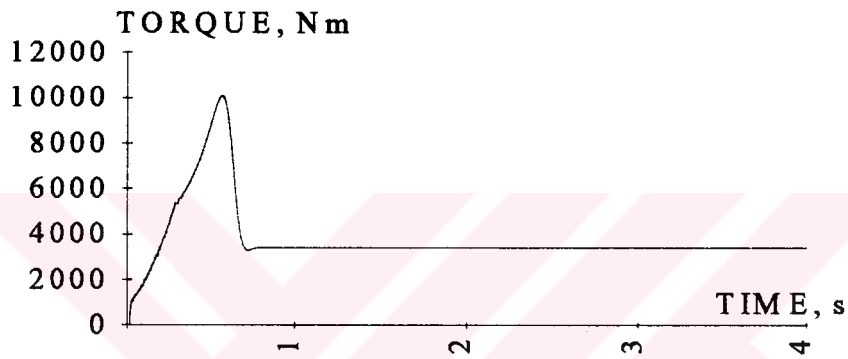


c)

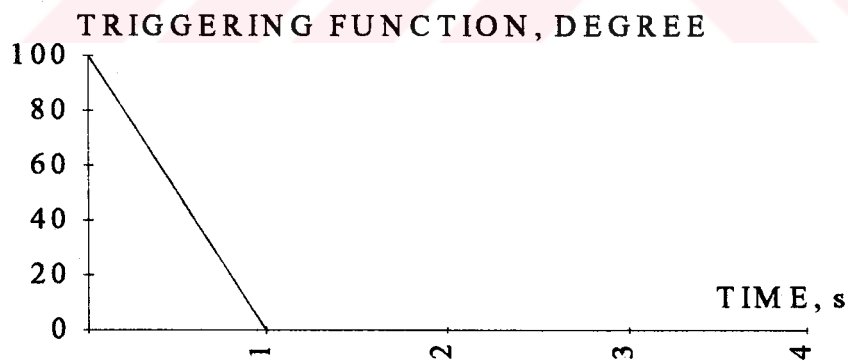
Figure 4.24 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=0.5s$.



a)

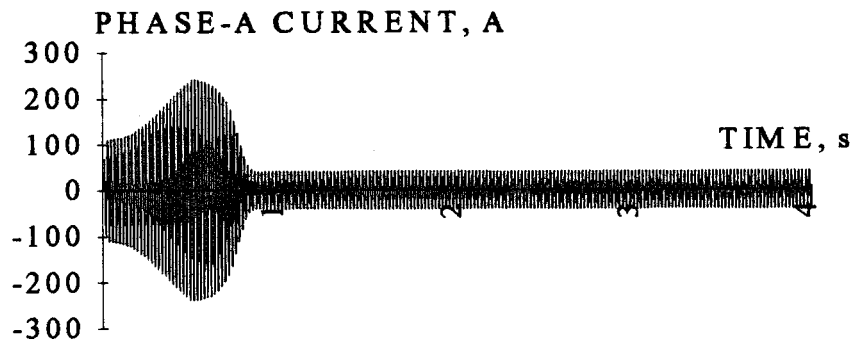


b)

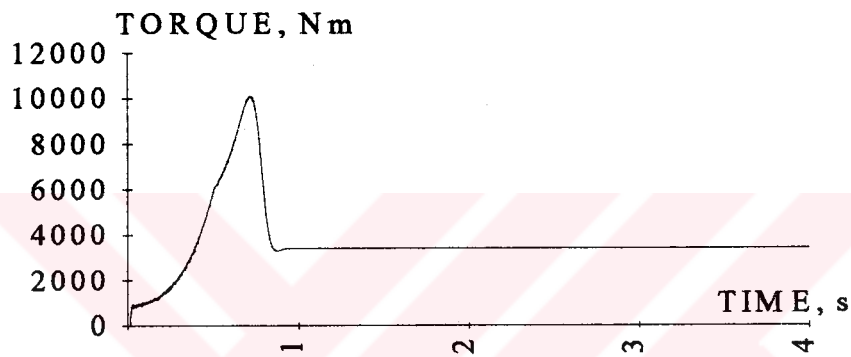


c)

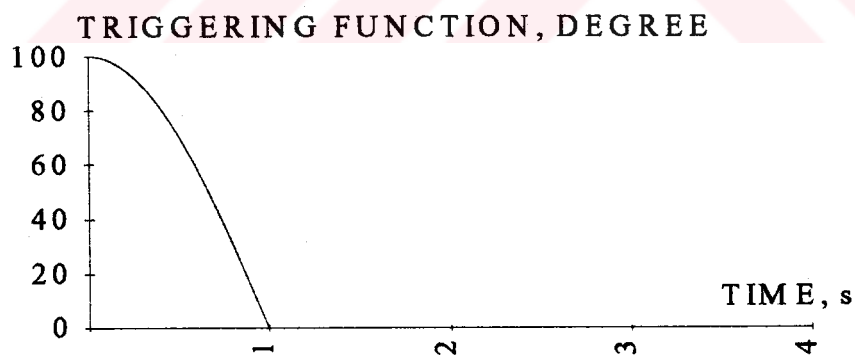
Figure 4.25 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$.



a)

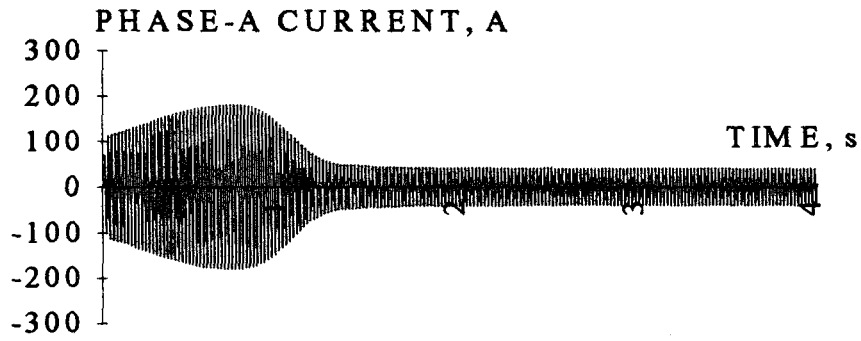


b)

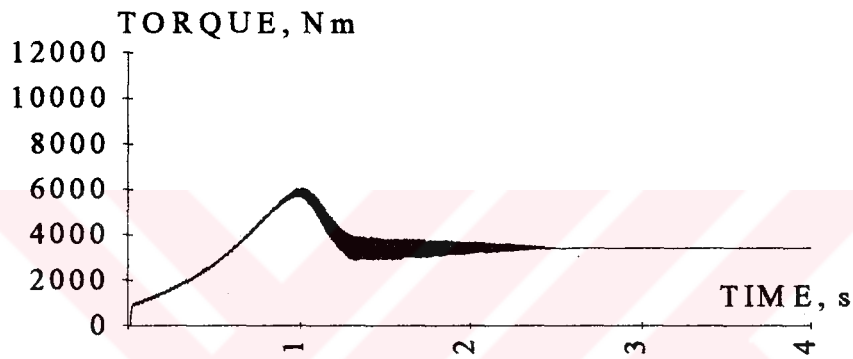


c)

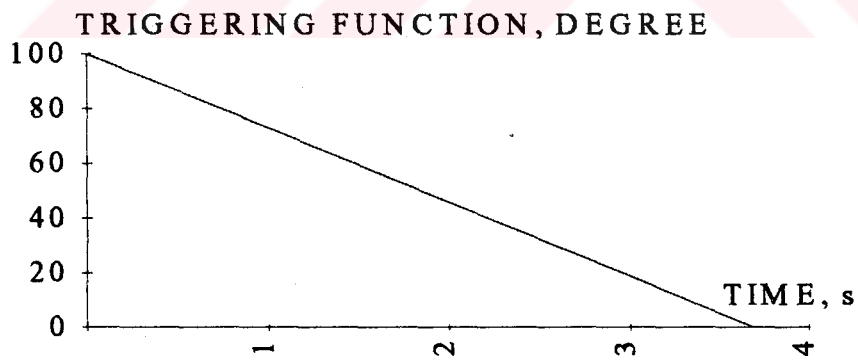
Figure 4.26 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$.



a)

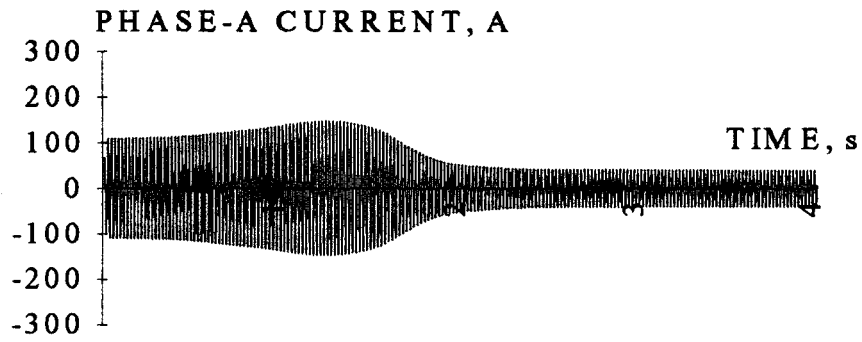


b)

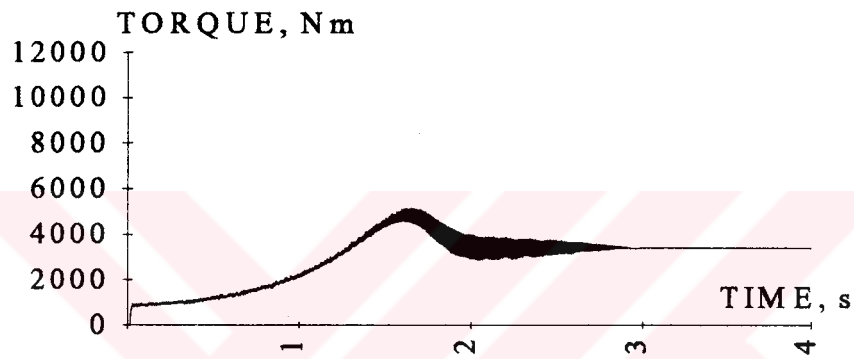


c)

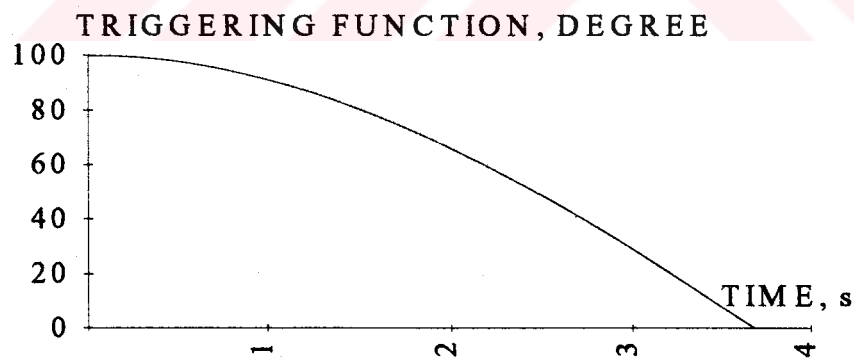
Figure 4.27 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here, $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=3.69s$.



a)

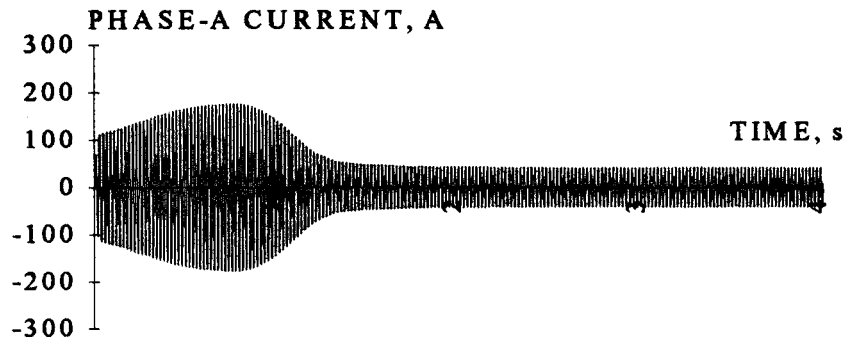


b)

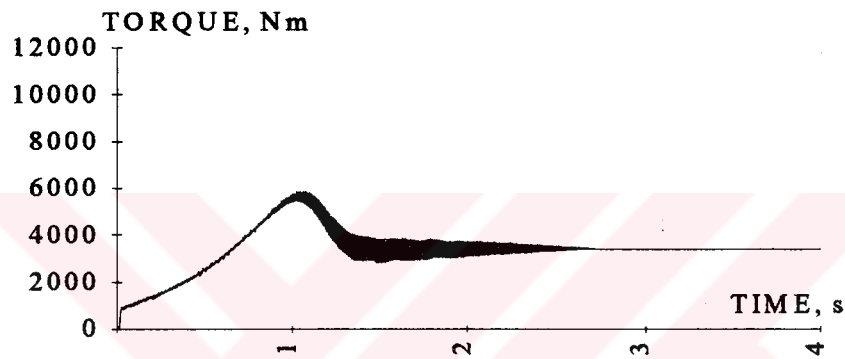


c)

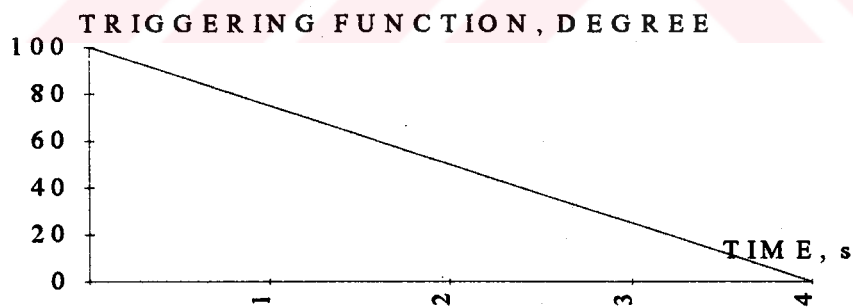
Figure 4.28 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here, $\alpha_s=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=3.69s$.



a)

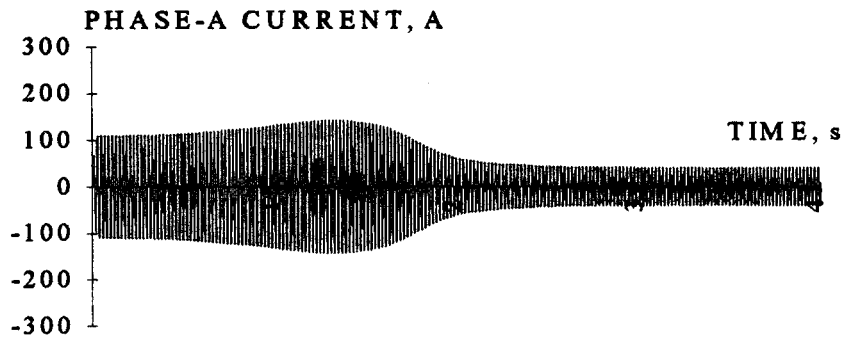


b)

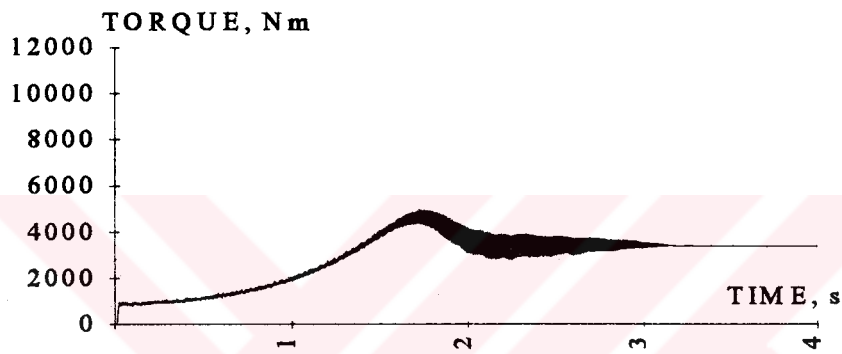


c)

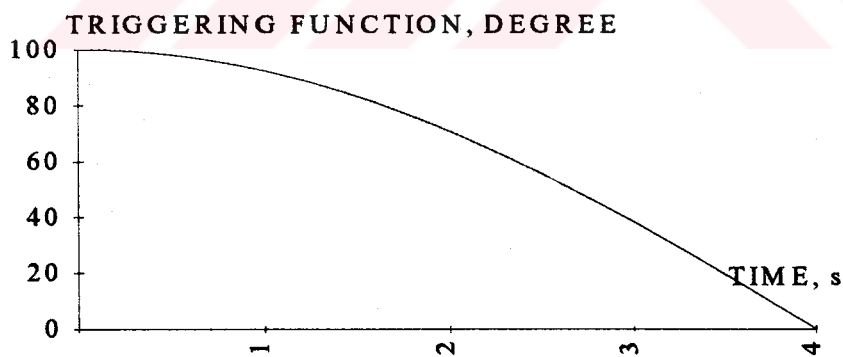
Figure 4.29 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a ramp triggering function. Here $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=4s$.



a)



b)



c)

Figure 4.30 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with a cosine triggering function. Here $\alpha_s=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=4s$.

2. The effects of increased ramp time on the system performance are reduced starting current and extending starting time (figures 4.23, 4.25, 4.27 and 4.29).

3. The effects of increased variation time for cosinusoidal triggering function on the system performance are reduced starting current and extending starting time (figures 4.24, 4.26, 4.28 and 4.30).

4. Cosinusoidal triggering function case results in a starting current waveform more approximated to a constant starting current waveform than ramp triggering case (figures 4.25 and 4.26, 4.27 and 4.28, 4.29 and 4.30).

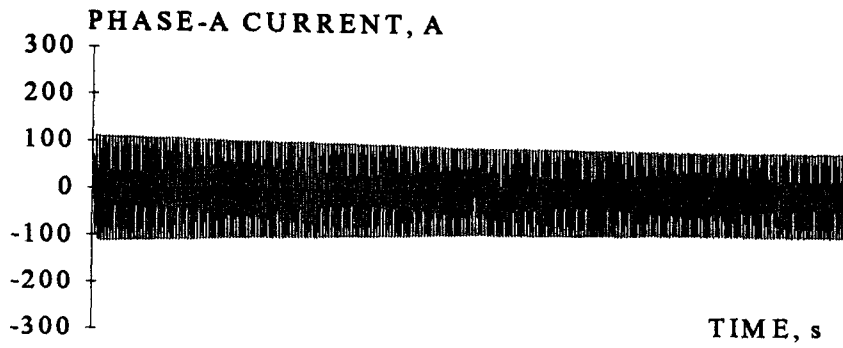
5. As the total variation time of either ramp or cosinusoidal function increases, the starting current waveform approximates more to a constant current waveform. The limit case would occur when $t_F - t_S$ goes to infinity. The associated waveforms are given in figure 4.31 but for that case, the motor reaches its steady state in an infinitely long time period.

6. For the same initial triggering angle value and total variation time value (figures 4.25 and 4.26, 4.27 and 4.28, 4.29 and 4.30) cosinusoidal triggering function case results in a longer acceleration time but reduced starting current for each case.

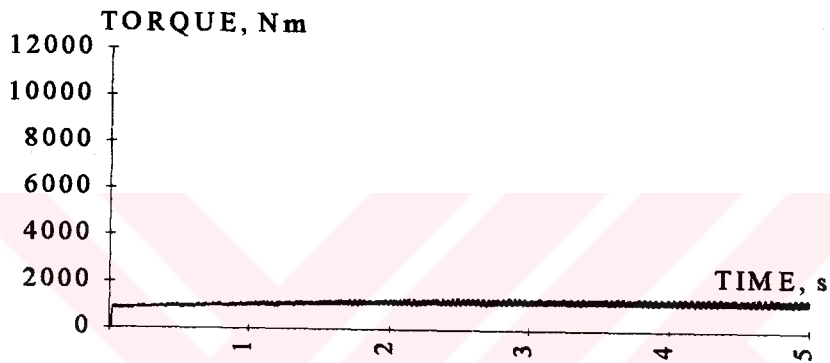
7. The overall performance of the open loop control strategy based on cosinusoidal triggering function is assessed to be better than those of ramp triggering function case, but none of these open loop control strategies are considered to be useful for implementation in practical applications.

For the cases in figures 4.23 and 4.24 the total variation period of α is adjusted to a lower value ($t_F - t_S = 0.5s$) than starting time of the motor when rated voltage is applied ($t_{STARTING} = 0.625s$ as shown in figure 4.22). For the cases in figures 4.25 and 4.26 the total variation period of α is adjusted to a slightly higher value ($t_F - t_S = 1s$) than starting time of the motor when rated voltage is applied. For the remaining cases, $\alpha(t)$ is adjusted much higher than this value.

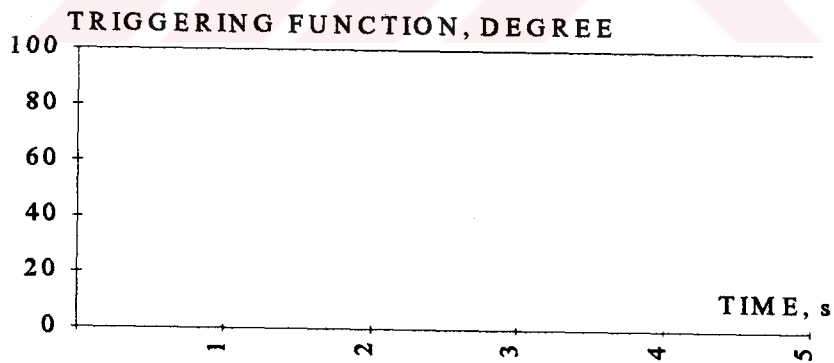
For the same initial value of triggering angle in figures 4.27 and 4.28, the response of the closed loop control strategy proposed in the thesis has also been



a)

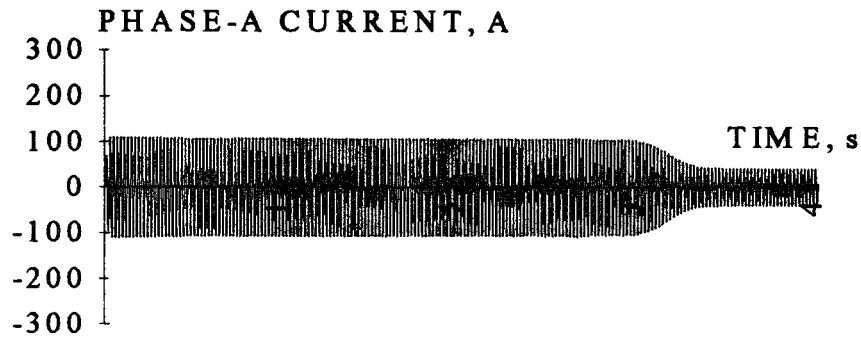


b)

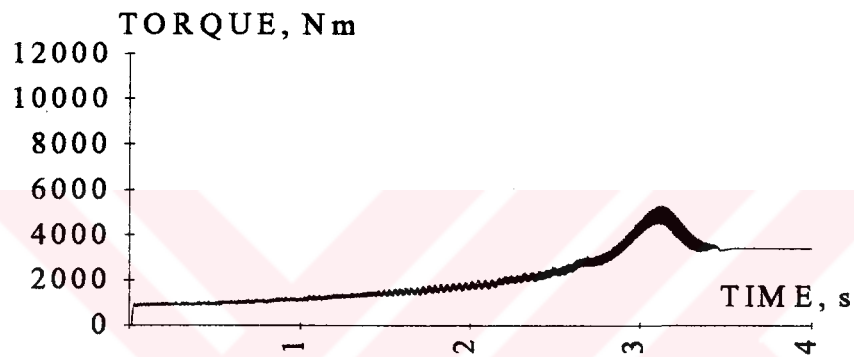


c)

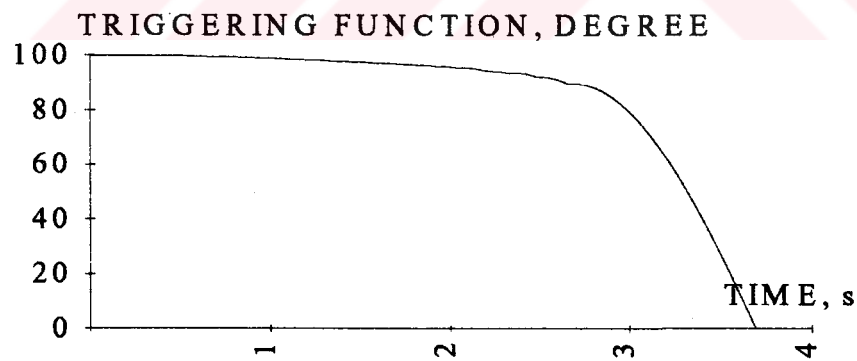
Figure 4.31 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with using the method in subsection 4.1.3 to minimize torque pulsations when $\alpha=100^\circ$.



a)



b)



c)

Figure 4.32 a) Phase-A current vs. time, b) electromagnetic torque vs. time, c) triggering function vs. time of motor-2 with the method used in the thesis . Here $\alpha_S=100^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.6 \cdot I_{NOMINAL}$.

obtained and presented in figure 4.32. A comparison of the associated waveforms shows us that the proposed closed loop control strategy for α control during starting gives quite accurate results in keeping starting current constant at this prespecified limit value ($2.6 \cdot I_{\text{NOMINAL}}$).

A comparison between figures 4.27, 4.28 and 4.32 shows us that the closed loop control strategy yields much lower starting current value with an extended starting period in comparison with those of open loop control strategies.

Adjusting the ramp time to value lower than or around the starting time does not yield us any benefit in limiting the starting current. On the other hand, a higher ramp time yields a lower k value for the current limit. Therefore, an optimum ramp time should be found by several trials made by the user in order not to allow the current to exceed a prespecified limit value.

The response of the softstarter-motor-load combination to various different set values of current limit during starting has been obtained for both motors for the proposed closed loop current limiting strategy. Some of these waveforms are shown in figures 4.33-4.48. For motor-2, limit value of the starting current has been adjusted to 2.5, 3.0 and 4.0 times the nominal value and the current, torque, α function and speed variations in time are obtained as in figures 4.33-4.36, 4.37-4.40 and 4.41-4.44 respectively. The waveforms in figures 4.45-4.48 show the response of the system for motor-1 when the set value of current limit is adjusted to 3 times the nominal value. As can be understood from these figures the performance of the closed loop current limiting strategy proposed in this thesis is quite satisfactory. Negligible fluctuations will take place in the envelope of the starting current waveform owing to the successive application of cosinusoidal-constant triggering angle functions as illustrated in figure 4.21. Another important observation is that, the acceleration of the motor-load combination is very smooth as can be understood from figures 4.36, 4.40, 4.44 and 4.48. Further than this, over a considerable portion of the starting period, acceleration may be assumed to be constant. This

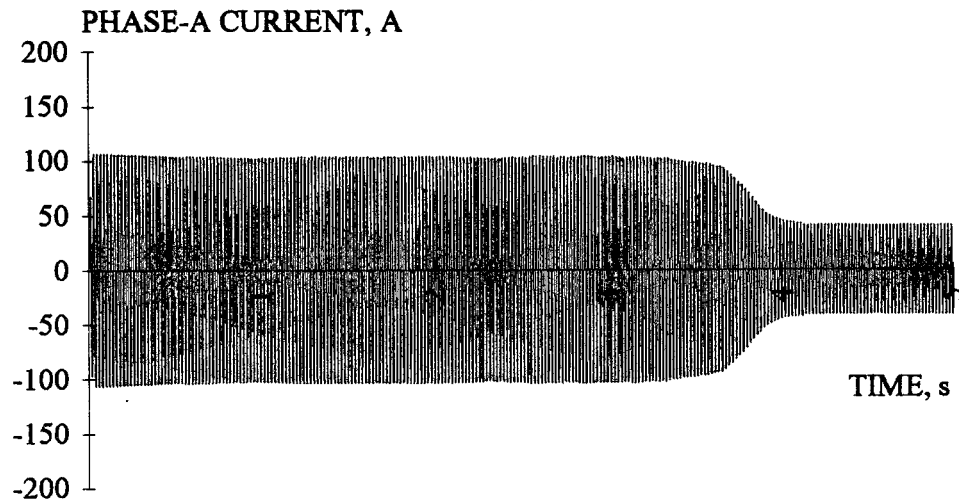


Figure 4.33 Current vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5 \cdot I_{NOMINAL}$.

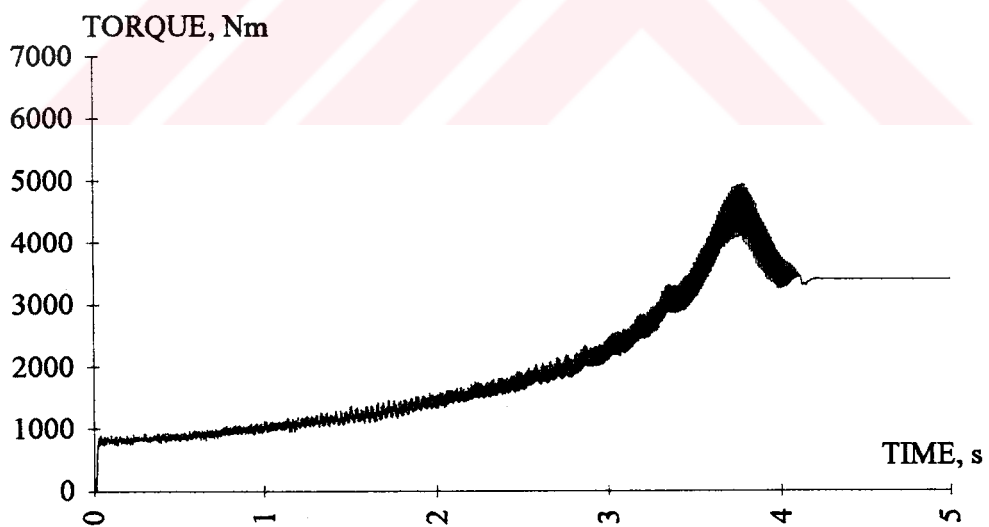


Figure 4.34 Electromagnetic torque vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5 \cdot I_{NOMINAL}$.

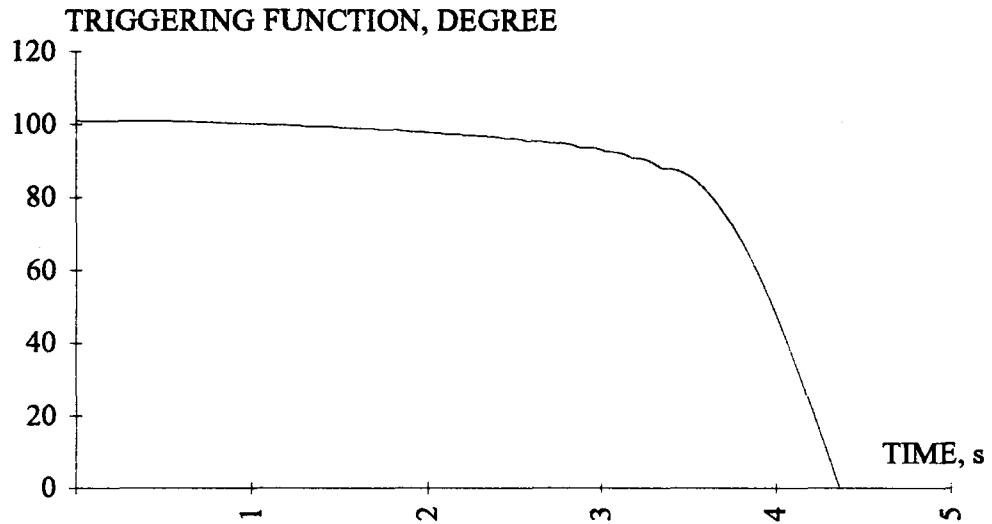


Figure 4.35 Triggering function vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5*I_{NOMINAL}$.

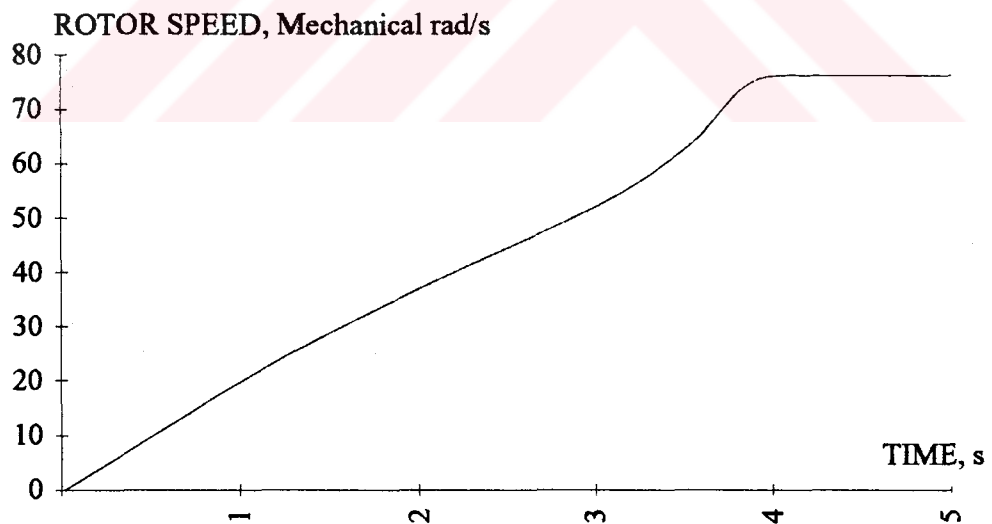


Figure 4.36 Rotor speed vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=101^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=2.5*I_{NOMINAL}$.

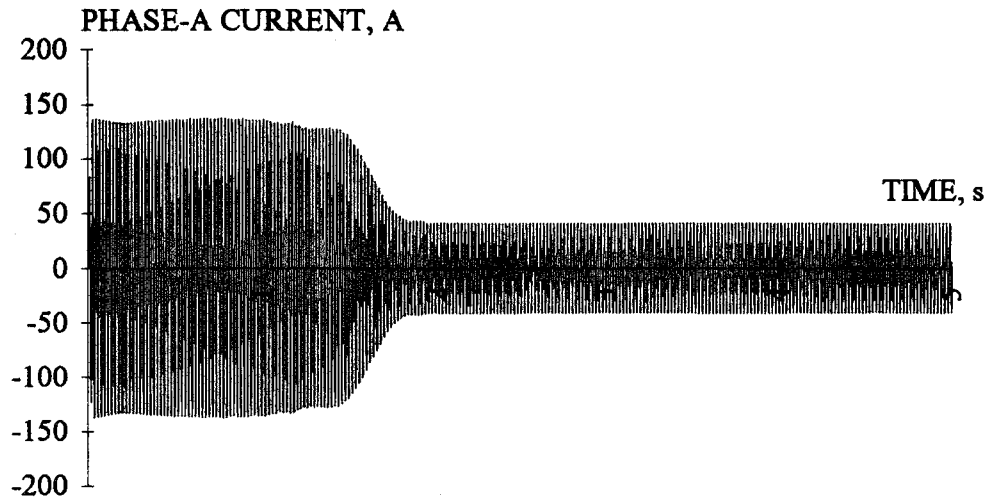


Figure 4.37 Current vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3*I_{NOMINAL}$.

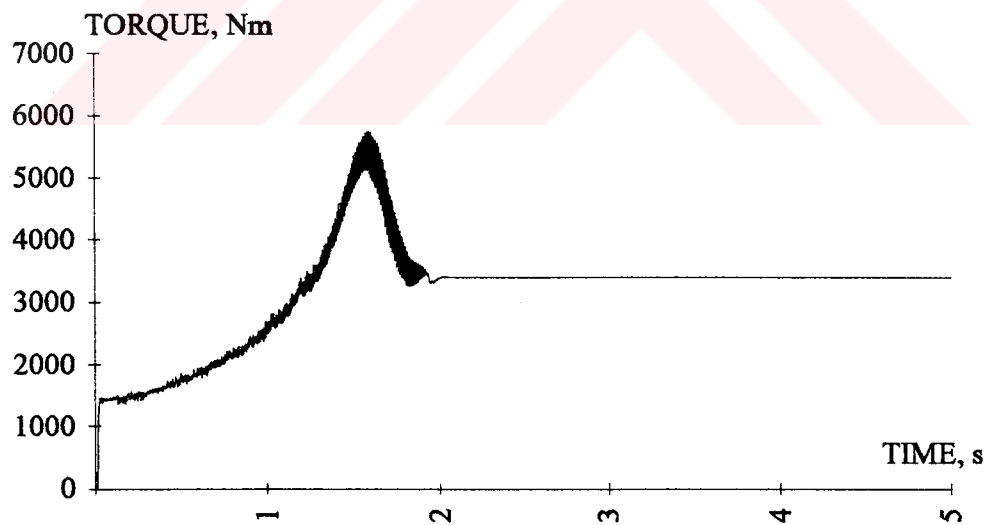


Figure 4.38 Electromagnetic torque vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3*I_{NOMINAL}$.

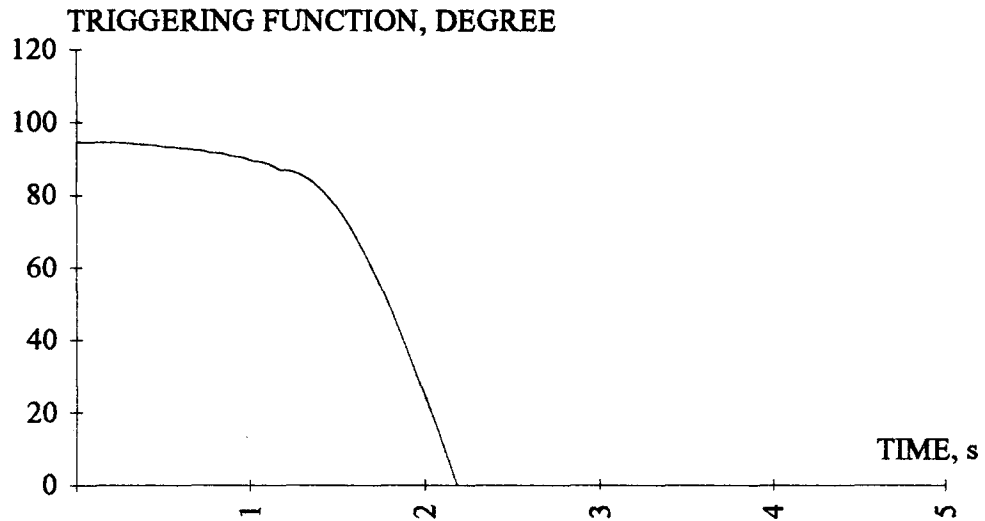


Figure 4.39 Triggering function vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3 \cdot I_{NOMINAL}$.

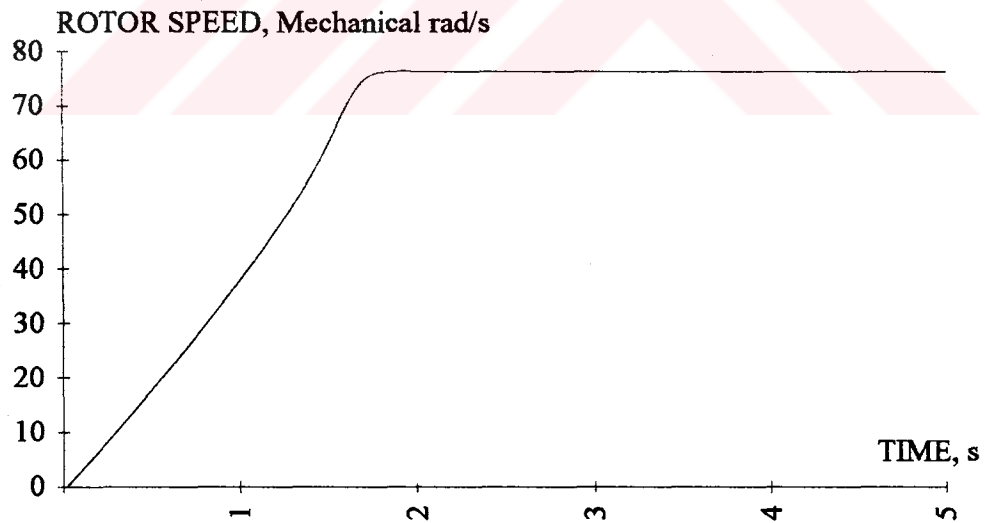


Figure 4.40 Rotor speed vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=94.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3.3 \cdot I_{NOMINAL}$.

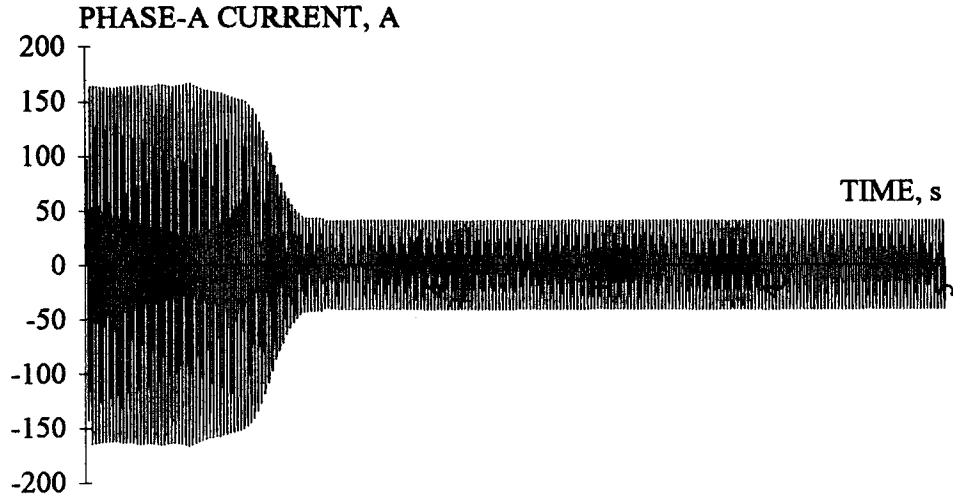


Figure 4.41 Current vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4 \cdot I_{NOMINAL}$.

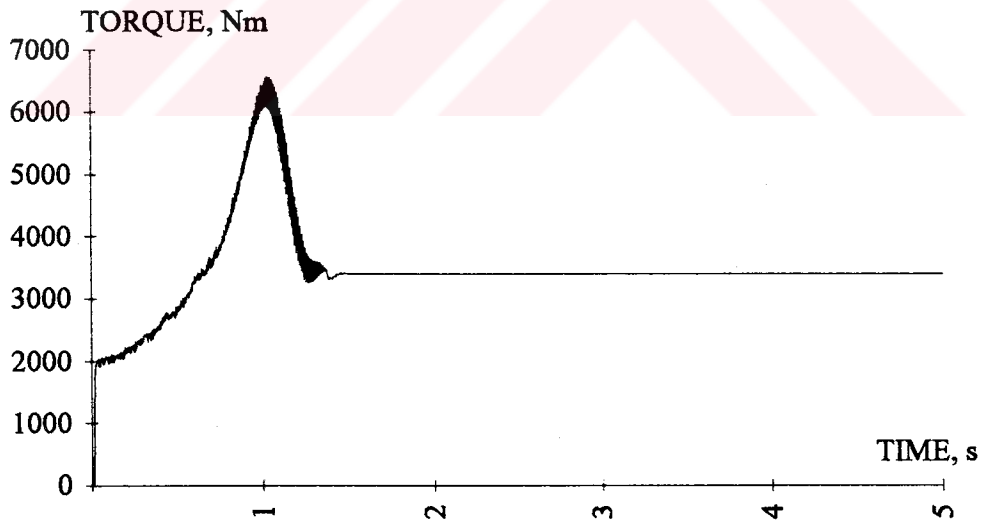


Figure 4.42 Electromagnetic torque vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4 \cdot I_{NOMINAL}$.

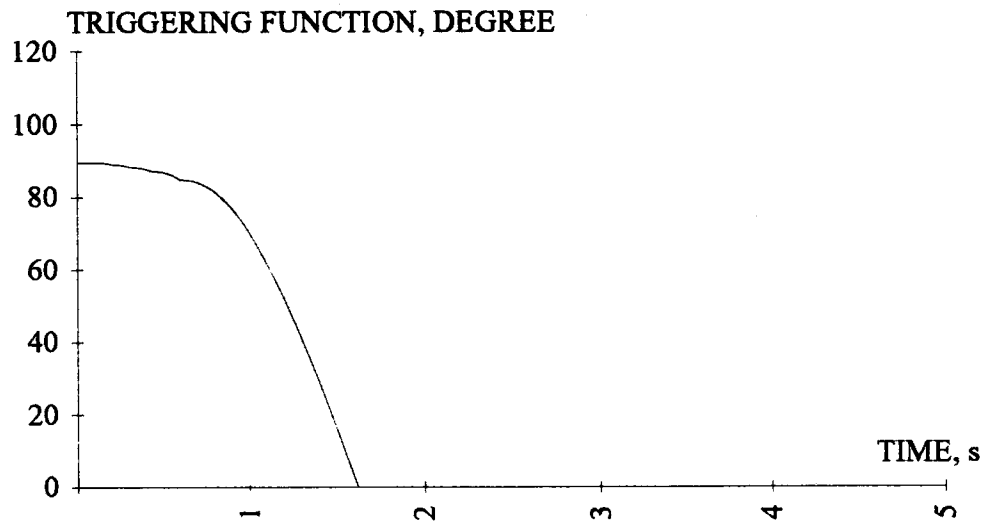


Figure 4.43 Triggering function vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4 \cdot I_{NOMINAL}$.

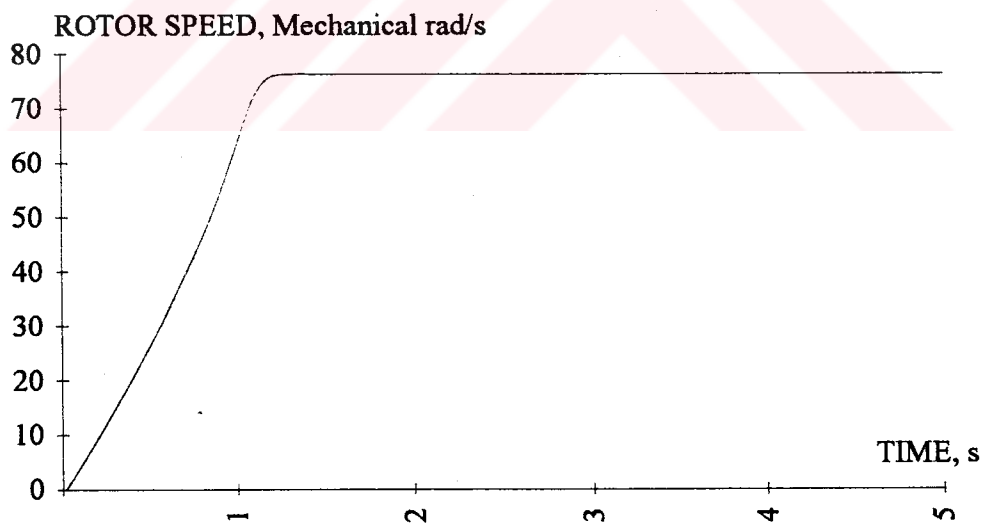


Figure 4.44 Rotor speed vs. time for motor-2 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=89.5^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=4 \cdot I_{NOMINAL}$.

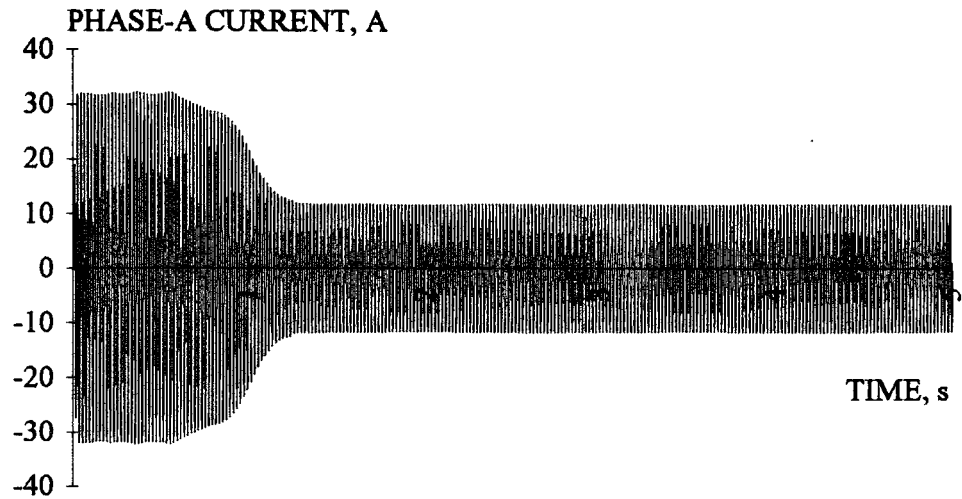


Figure 4.45 Current vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$.

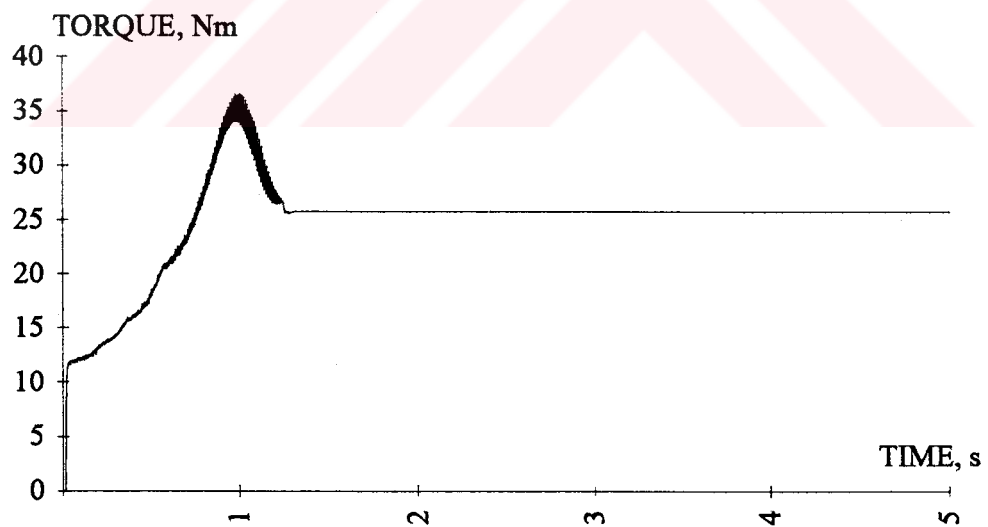


Figure 4.46 Electromagnetic torque vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_s=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$.

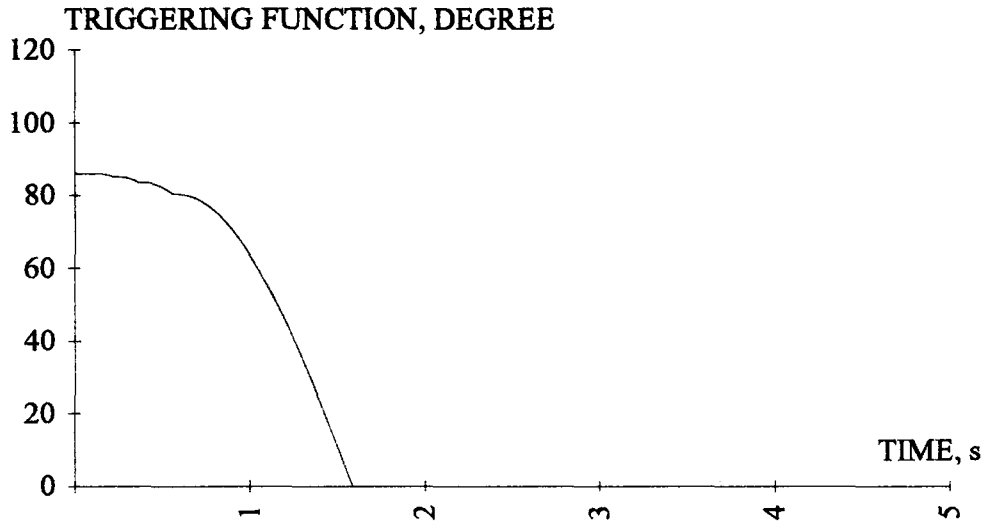


Figure 4.47 Triggering function vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$.

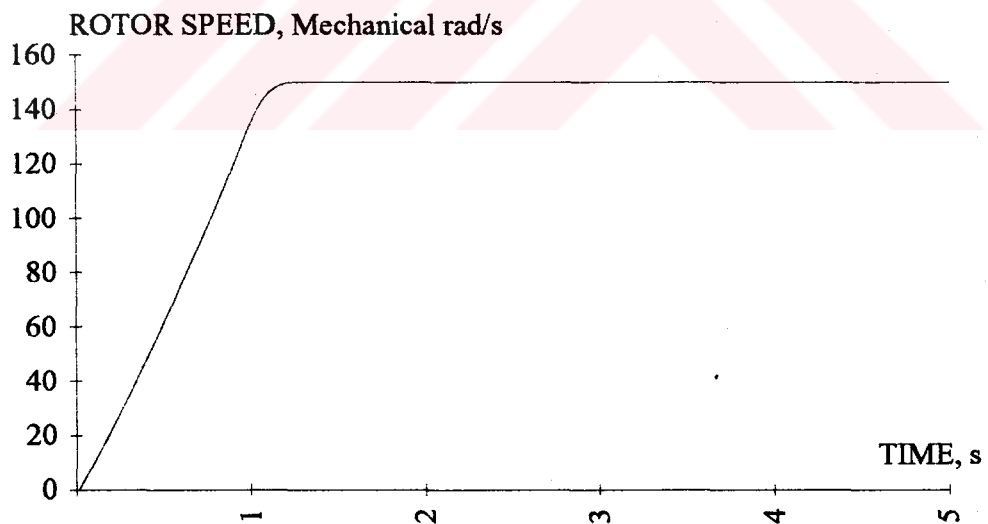


Figure 4.48 Rotor speed vs. time for motor-1 with the method described in section 4.2 to limit the current and with the method described in section 4.1.3 to minimize torque pulsations. Here, $\alpha_S=86^\circ$, $\alpha_F=0^\circ$, $t_F-t_S=1s$, $I_{PEAK}=3*I_{NOMINAL}$.

feature of the proposed control strategy is very important for some critical loads used in glass industry.

As can be understood from figures 4.33-4.34, 4.37-4.38, 4.41-4.42 and 4.45-4.46 the proposed method for the minimization of torque pulsations during starting matches very satisfactorily with the proposed current limiting strategy. For the operating conditions corresponding to the responses in figures 4.33, 4.37, 4.41 and 4.45, the current waveforms are being discontinuous over a considerable period of starting time. In spite of discontinuous motor current waveforms, very small pulsations will take place in electromechanical torque during starting. More discontinuous current waveform means a higher peak-to-peak torque pulsations. As the value of k factor is reduced, a more discontinuous stator current waveform arises.

Another important observation is that although the triggering angle control strategy is a closed loop control strategy, no stability problem arises as can be understood from the results of several runs for different operating conditions in the normal working range.

CHAPTER 5

CONCLUSIONS AND FURTHER WORK

In this thesis, analysis and performance optimization of a thyristorized induction motor softstarter using a hybrid model has been performed. This softstarting scheme will limit the current by voltage control by the variation of the thyristor firing angles. The main drawback of this method is that the motor torque reduces by the square of the voltage ratio. For the sake of generality, back to back connected thyristors are introduced into the three lines of the supply resulting in a universal system applicable to both wye and delta connected squirrel-cage induction motor systems.

First, a mathematical model for the induction motor has been developed and state-space representations of the softstarter system for disconnected, two-phase and three-phase operational modes have been deduced from the model for computer simulations. Conditions for transition between the operational modes have been determined and performance optimization of a thyristorized induction motor softstarter has been investigated.

The softstarter investigated in this thesis is a voltage controlled one. Voltage controlled softstarters are now commercially available. In these units, the main aim is to decrease the high starting current by using different techniques. However, they are not furnished with any facility for the minimization of torque pulsations during starting. In these softstarters only the peak of the transient torques are decreased by applying a lower voltage than the full supply voltage to the motor terminals.

Simultaneous or nonsimultaneous switching of induction motor terminals to the supply lines may cause severe torque pulsations. The magnitude of torque

pulsations can be minimized by applying proper firing pulses to the thyristors [17]. Three different firing strategies have been developed in the thesis to minimize torque pulsations in this thesis. Each triggering strategy can not be applied over the whole control range of α but in only one of the three α ranges as specified below. The strategies which minimize torque pulsations can be classified as follows according to the initial operating conditions.

1. Triggering strategy if all of the line currents are continuous;
2. Triggering strategy if at least one of the line currents is discontinuous with the triggering angle α less than the power factor angle at unity slip;
3. Triggering strategy if the triggering angle is greater than the power factor angle at unity slip.

If the firing angle α causes flow of continuous current through motor phases then the first triggering strategy should be used. In this triggering strategy, thyristors T1, T2, T3, T4, T5 and T6 (figure 2.3) should receive successively their firing pulses respectively at points α , 120° , $120^\circ+90^\circ$, $180^\circ+\alpha$, $240^\circ+\alpha$, $300^\circ+\alpha$ with respect to reference point of thyristor T1 firing angle (zero crossing point of phase-A voltage on ascending edge of positive half cycle) at the first period of starting (figure 4.2) and then all thyristors receive their firing pulses at their α 's.

Second type of triggering strategy will take place for a control range of $63^\circ < \alpha < 73^\circ$ for motor-1 and $65^\circ < \alpha < 75^\circ$ for motor-2 (appendix C). In these ranges, at least one of the phase current becomes discontinuous at the first period of the starting operation, then all currents become continuous and finally they turn back to discontinuous waveform. In this triggering strategy, thyristors T1, T2, T3, T4, T5 and T6 (figure 2.3) should receive successively their firing pulses respectively at points α , β_2 , $\beta_2+\beta_3$, $180^\circ+\alpha$, $240^\circ+\alpha$, $300^\circ+\alpha$ with respect to reference point of thyristor T1 firing angle at the first period of the starting (figure 4.9), where

$$\beta_2 = 1.75\alpha + 5.5 \text{ and}$$

$$\beta_3 = 90^\circ.$$

When the triggering angle α is greater than the power factor angle at unity slip, all line currents become discontinuous at every period of the starting and the third type triggering strategy should be used to minimize torque pulsations. In this method, thyristors T1, T2, T3, T4, T5 and T6 (figure 2.3) should receive successively their firing pulses respectively at points α , β_2 , $\beta_2+\beta_3$, $180^\circ+\alpha$, $240^\circ+\alpha$, $300^\circ+\alpha$ with respect to reference point of thyristor T1 firing angle at the first period of the operation and then all thyristors receive firing pulses at their α 's, where

$$\beta_2 = \alpha + 60^\circ \text{ and}$$

$$\beta_3 = -(19/30) * \alpha + 143.67.$$

Only a limited number of control strategies have been examined in this study for the purpose of keeping the starting current constant at the preset value. This is essential for the softstarters in order to minimize the disturbances exerted by the induction motors owing to the high currents during starting period. In this context, the performance of ramp and cosine triggering functions (open loop control strategies) are not found to be satisfactory. A novel closed loop control strategy in which the back to back connected thyristors are triggered into conduction by a triggering function composed of cosinusoidal and constant function segments has been developed in the study. The controller generates the above triggering function according to the value of feedback signal taken from the starting current of the induction motor. The results of the computer simulations have shown us that this closed loop control strategy gives quite satisfactory performance figures.

Following conclusions can be drawn related to the results found in the thesis:

1. This type of softstarters should be furnished with a control facility to minimize the electromechanical torque pulsations during starting.
2. Although the proposed triggering angle strategy is found to be quite satisfactory, there may be some other control strategies which are simpler, can give better results and provide ease in implementation.

3. The effect of motor parameter changes during starting need to be investigated experimentally after implementation of the system.

As a further work, the computer program can be brought to a more user-friendly form. The new form should provide to the user also other control strategies which can be applied in softstarters selected as inputs to the program making it more flexible.

Implementation of the control system both limiting the line currents and minimizing torque pulsations during starting as proposed in the thesis can also be performed. A look-up table for triggering angles can be prepared and used for controlling the firing instants of thyristors by a microprocessor.



REFERENCES

- [1] James T. Humphries, Leslie P. Sheets, "Industrial Electronics", Delmar Publishers Inc., Third Edition, 1989.
- [2] A. E. Fitzgerald, Charles Kingsley J.R., Alexander Kusko, "Electric Machinery", McGraw Hill Book Company, 1971.
- [3] "Drives and Servos Yearbook", Control Techniques, 1990-1.
- [4] Benjamin F. Bailey, James S. Gault, "Alternating-current Machinery", McGraw Hill Book Company, 1951.
- [5] L. X. Le, G. J. Berg, "Steady State Performance Analysis of SCR Controlled Induction Motors: A Closed Form Solution", IEEE Transactions on Power Apparatus and System, Vol. 103, No. 3, March 1984, pp. 601-611.
- [6] S. A. Hamed, B. J. Chalmers, "Analysis of Variable-Voltage Thyristor Controlled Induction Motors", IEE Proceedings, Vol. 137, Pt. B, No. 3, May 1990, pp. 184-193.
- [7] Patrick J. Colleran, William E. Rogers, "Controlled Starting of AC Induction Motors", IEEE Transactions on Industry Applications, Vol. 19, No. 6, November/December 1983, pp. 1014-1018.

- [8] Frank M. Bruce, "Reduced Voltage Starting of Squirrel-cage Induction Motors", IEEE Transactions on Industry Applications, Vol. 20, No. 1, January/February 1984, pp. 46-55.
- [9] S. Sreenivasa Murthy, G. J. Berg, "A New Approach to Dynamic Modelling and Transient Analysis of SCR-controlled Induction Motors", IEEE Transactions on Power Apparatus and Systems, Vol. 101, No. 9, September 1982, pp. 219-229.
- [10] Gautam Nath, Gunnar J. Berg, "Transient Analysis of Three-Phase SCR Controlled Induction Motors", IEEE Transactions on Industry Applications, Vol. 17, No. 2, March/April 1981, pp. 133-142.
- [11] H. Rehaoulia, "Transient Behavior of the Resultant Airgap Field During Run-up of an Induction Motor", IEEE Transactions on Energy Conversion, Vol. 1, No. 4, December 1986, pp. 92-98.
- [12] W. S. Wood, F. Flynn, A. Shanmugasundarain, "Transient Torques in Induction Motors, due to Switching of the Supply", Proc. IEE, Vol. 112, No. 7, July 1965, pp 1348-1354.
- [13] Werner Deleroi, Johan B. Woudstra, Azza A. Fahim, "Analysis and Application of Three-phase Induction Motor Voltage Controller with Improved Transient Performance", IEEE Transactions on Industry Applications, Vol. 25, No. 2, March/April 1989, pp. 280-286.
- [14] Jack Bowerfind, Sylvester J. Campbell, "Application of Solid-State AC Motor Starters in the Pulp and Paper Industry", IEEE Transactions on Industry Applications, Vol. 22, No. 1, January/February 1986, pp. 109-114.

- [15] John D. Robeck, "Fan Controlled for the Glass Industry Using Static Induction Motor Drives", IEEE Transactions on Industry Applications, Vol. 19, No. 1, January/February 1983, pp. 52-56.
- [16] C. V. Jones, "The Unified Theory of Electrical Machines", Butterworths, 1967.
- [17] "A 6.3 kV Thyristorized Switch for Direct-on Starting of Induction Motors", Master Thesis by Mahfujur Rahman, September 1991.
- [18] "A New Approach to Optimized Design of Induction Motors", Master Thesis by Cevdet Aykanat, August 1980.



APPENDIX A

COMPUTER PROGRAM

A.1 About the Computer Program

This program is written in FORTRAN computer language and computes the data, which are necessary to obtain current, torque, and speed simulations, and writes them to a data file. There are five subroutines in this program. These are ARB, RGKS, FCT, OUP, and FLWCRT. Before describing these subroutines it is better to know the important parameters used in the program.

X: Time

Y(1): Phase-A stator current

Y(2): Phase-B stator current

Y(3): Phase-q current referred to the stator.

Y(4): Phase-d current referred to the stator.

Y(5): Mechanical speed in rad/second.

DERY: Derivative vector of Y vector.

TE: Electromagnetic torque per pole pair.

TL: Load torque.

JJ: Inertia.

In the main program the subroutine ARB is called. Motor parameters and constants are written in this part of the program.

A.1.1 Subroutine ARB

This is the name of a subroutine which is called from the main program. Its parameter list must be X, Y, DERY, NDIM, and AUX. Initial values of input

vectors Y, and DERY and the values of PRMT vector are written in this subroutine. It calls subroutine RKGS and after subroutine RKGS returns, it writes an explanation into the data file whether there is any error or not.

A.1.2 Subroutine RKGS

This subroutine uses the Runge-Kutta method for the solution of initial-value problems.

The purpose of the Runge-Kutta method is to obtain an approximate solution of a system of first-order ordinary differential equations with given initial values. It is a fourth-order integration procedure which is stable and self-starting: that is, only the functional values at a single previous point are required to obtain the functional values ahead. For this reason it is easy to change the step size h at any step in the calculations. On the other hand, each Runge-Kutta step requires the evaluation of the right-hand side of the system four times, which is a great disadvantage compared with other methods of the same order of accuracy, especially predictor-control methods. Another disadvantage of the method is that neither the truncation nor estimates of them are obtained in the calculation procedure. Therefore, control of accuracy and adjustment of the step size h is done by comparison of the results due to double and single size $2h$ and h .

The entire input of the procedure is:

1. Lower and upper bound of the integration interval, initial increment of the independent variable, upper bound ε_2 of the local truncation error
2. Initial values of the dependent variables and weights for the local truncation errors in each component of the dependent variables
3. The number of differential equations in the system
4. As external subroutine subprograms, the computation of the right-hand side of the system of differential equations; for flexibility in output, an output subroutine

5. An auxiliary storage array named AUX with 8 rows and n columns

Output is done in the following way. If a set of approximations to the dependent variables $Y(X)$ is found to be sufficient accuracy, it is handed together with X , the derivative $F[X, Y(X)]$, the number of bisections of the initial increment, the number of differential equations, the lower and upper bound of the interval, the initial step size, error bound ε_2 , and a parameter for terminating subroutine RKGS to the output subroutine. Because of this output subroutine, the user has the opportunity to choose his own output format, to handle the output values as he wants, to change the upper error bound, and to terminate subroutine RKGS at any output point. In particular, the user is able to drop the output of some intermediate points, printing only the result values at the special points $X_0 + n.h (n=0,1,2,\dots)$. The user may also perform intermediate computation using integration results before continuing the process.

Description of parameters used in this subroutine is as follows:

PRMT: An input and output vector with dimension greater or equal to 5, which specifies the parameters of the interval and of accuracy and which serves for communication between output subroutine (furnished by the user) and subroutine RKGS. Except PRMT(5) the components are not destroyed by subroutine RKGS and they are:

PRMT(1): Lower bound of the interval (input),

PRMT(2): Upper bound of the interval (input),

PRMT(3): Initial increment of the independent variable (input),

PRMT(4): Upper error bound (input). If absolute error is greater than PRMT(4), increment is halved. If increment is less than PRMT(3) and absolute error less than $PRMT(4)/50$, increment gets doubled. The user may change PRMT(4) by means of his output subroutine.

PRMT(5): No input parameter. Subroutine RKGS initializes PRMT(5)=0. If the user wants to terminate subroutine RKGS at any output point, he has to change PRMT(5) to non-zero by means of subroutine OUTF.

Further components of vector PRMT are feasible if its dimension is greater than 5. However, subroutine RKGS does not require and change them. Nevertheless they may be useful for handing result values to the main program (calling RKGS) which are obtained by special manipulations with output data in subroutine OUTP.

Y: Input vector of initial values. (Destroyed) Later on Y is the resulting vector of dependent variables computed at intermediate points X.

DERY: Input vector of error weights. (Destroyed) The sum of its components must be equal to 1. Later on DERY is the vector of derivatives, which belong to function values Y at a point X.

NDIM: An input value, which specifies the number of equations in the system.

IHLF: An output value, which specifies the number of bisections of the initial increment. If IHLF gets greater than 10, subroutine RKGS returns with error message IHLF=11 into main program. Error message IHLF=12 or IHLF=13 appears in case $PRMT(3)=0$ or in case $SIGN(PRMT(3)).NE.SIGN(PRMT(2)-PRMT(1))$ respectively.

AUX: An auxiliary storage array with 8 rows and NDIM columns.

A.1.3 Subroutine FCT

Subroutine FCT is the name of an external subroutine used. This subroutine computes the right hand sides DERY of the system to given values X and Y. Its parameter list must be X, Y, and DERY. Subroutine FCT should not destroy X and Y.

This subroutine computes synchronous speed (WS), load torque (TL), slip (SLIP), effective value of phase-A voltage (VEFF), power factor (PF). Subroutine FCT also calls subroutine FLWCRT.

A.1.4 Subroutine FLWCRT

It is the name of an external subroutine used. This subroutine computes the ceasing or firing instants of the thyristors and finds the correct mode of operation. There are 18 different states in which different thyristors are active or passive.

This subroutine also determines the peak values of the phase-A current (IPEAK).

A.1.5 Subroutine OUTP

Subroutine OUTP is the name of an external subroutine used. Its parameter list must be X, Y, DERY, IHLF, NDIM, PRMT. None of these parameters (except, if necessary, PRMT(4), PRMT(5),...) should be changed to non-zero, subroutine RKGS is terminated.

Output data which are used to obtain simulations are written to a data file by means of this subroutine.

A.2 Calculation of the Simulation Data

To calculate the data to obtain the current, torque and speed simulations of an induction motor during starting, the program is run two times. Although the first and second program consists of the same subroutines mentioned above, there are some differences in ARB, FCT and OUTP subroutines because of the different functions of the programs.

The first program calculates the optimum starting firing angle α_0 which causes the current to start around the current limit level given by the user. To find the correct firing angle, triggering function is given as a ramp function with $\alpha_S=120^\circ$, $\alpha_F=70^\circ$, $t_S=0$, $t_F=1$ as shown in figure 4.19. Firing function is chosen as a ramp function instead of a cosine function because while the firing function

becomes closer to α_F , slope of the cosine function with same parameters has a larger slope than that of the ramp function, which increases the fault on α_0 . $\alpha_S=120^\circ$ because this angle is enough to limit the current to 1.0 pu. In fact, above 120° the torque produced becomes so smaller that motor needs very long starting time even in no-load condition, which can cause thermal problems for thyristors. In this condition motor may not start even if the load torque is not large. For $I_{peak}=1.0$ pu, the range of α_0 lies between 110° and 120° . This range appears to be acceptable for most motor parameters [13]. To limit the current below the direct-on-line starting level, α_0 should be above the power factor angle which is around 75° at standstill for induction motors so α_F is chosen as 70° . To decrease α_F towards 0° causes the increase of slope of the ramp function and this increases the fault during calculation. t_F is chosen as 1 second. When t_F decreases very much under 1s, current builds up faster and causes the miscalculation of α_0 .

The program starts to run at angle α_S and calculates peaks of the current phase-A until they are greater or equal to the starting current level. Then the program stops and writes the determined α_0 to a data file.

The second program determines the data which are necessary for current, torque, and speed simulations. At first, this program reads α_0 from the data file and begins the calculate results. To limit the current, α_S is set to α_0 and the method described in chapter 4 is used. Here, $\alpha_F=0^\circ$, $t_F=t_S+1$ seconds. At steady state power factor angle of an induction motor is around 20° so choosing α_F as 0° does not cause any important fault during calculation. t_F is chosen as t_S+1 seconds because as t_F becomes closer to t_S current develops rapidly. This causes the current to exceed the starting current level. If t_F is greater from this value, starting time will increase.

In subroutine FLWCRT active and passive thyristors are determined and output is sent to the subroutine FCT. In this subroutine suitable operation mode is chosen depending on the information which comes from the subroutine FLWCRT. After the right hand sides DERY of the system in subroutine FCT,

differential equations are solved in subroutine RGKS and step size h is adjusted according to the results. Results are written into a data file when subroutine OUTP is called by subroutine RKGS. Operations mentioned above continues until X reaches the value of PRMT(2). Results can be seen as a graphic form using a plotting program.

A.3 Computer Program Written in Fortran Computer Language

As mentioned in the above section to calculate the simulation data two computer programs are run successively. These are given below as their running order.

A.3.1 The first program

```
C*
C*
C*  THE FIRST PROGRAM
C*  THIS PROGRAM COMPUTES THE INITIAL TRIGGERING ANGLE
C*  FOR THE SECOND PROGRAM
C*  MAIN PROGRAM
  DIMENSION Y(10),DERY(10),AUX(20,20)
  REAL*8 R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI
  REAL*8 MM,PP,W0,F,X,Y,DERY,AUX,PRMT,VM
  REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
  REAL*8 IMAK,IPEAK,VVV,ISU
  REAL*8 VLL,TMAX
  INTEGER CONS,CCONS,PASS
  INTEGER K,MODE,ROW,J,NDIM
  INTEGER K1,K2,K3,K4,K5,K6
  INTEGER K11,K22,K44,K888
  COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
  COMMON K,MODE,J,ROW,CONS,CCONS,PASS
  COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
  COMMON/KTIMES/K1,K2,K3,K4,K5,K6
  COMMON/TLINE/TRIGS,TRIGF,TF,TS
  COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
  COMMON/VOLT/VR,VS,VT
  COMMON/TNN/T11,T22,T33,T44,T55,T66
```

```

COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM6/VLL,TMAX

```

```

PRINT*,'R1='
READ*,R1
PRINT*,'R2='
READ*,R2
PRINT*,'X1='
READ*,X1
PRINT*,'X2='
READ*,X2
PRINT*,'XM='
READ*,XM
PRINT*,'POLE PAIR='
READ*,PP
PRINT*,'INERTIA='
READ*,JJ
PRINT*,'LINE-TO-LINE VOLTAGE='
READ*,VLL
PRINT*,'CURRENT LIMIT='
READ*,ISU
PRINT*,'MAXIMUM STARTING TIME='
READ*,TMAX
PI=4.0D0*DATAN(1.0D0)
VM=VLL*DSQRT(2.0D0/3.0D0)

```

CCC MOTOR1 PARAMETERS CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

C   R1=0.9D0
C   R2=1.25D0
C   X1=3.45D0
C   X2=3.33D0
C   XM=50.0D0
C   PP=2.0D0
C   JJ=0.1D0
C   VM=380.0D0*DSQRT(2.0D0/3.0D0)
C   ISU=4.0D0*8.0D0*DSQRT(2.0D0)
C   TMAX=99.0D0

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCC MOTOR2 PARAMETERS CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

C   R1=1.84D0
C   R2=3.72D0

```

```

C  X1=10.05D0
C  X2=X1
C  XM=290.0D0
C  PP=4.0D0
C  JJ=40.0D0
C  VM=6300.0D0*DSQRT(2.0D0/3.0D0)
C  ISU=4.0D0*31.0D0*DSQRT(2.0D0)
C  TMAX=99.0D0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCC VARIABLES CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
  L1=(X1+XM)/(100.0D0*PI)
  L2=(X2+XM)/(100.0D0*PI)
  MM=XM/(100.0D0*PI)
  B=1.0D0/(2.0D0*L1-2.0D0*MM*MM/L2)
  A=-DSQRT(2.0D0)*B*MM/L2
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCC CONSTANTS CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
  F=50.0D0
  W0=2.0D0*PI*F
  J=0
  ROW=1
  NDIM=5
  K=1
  K1=0
  K2=0
  K3=0
  K4=0
  K5=0
  K6=0
  K11=0
  K22=0
  K44=0
  K888=0
  CONS=1
  CCONS=0
  PASS=0
  VVV=0.0D0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

OPEN(6,FILE='DAT1.DAT',STATUS='OLD')
CALL ARB(X,Y,DERY,NDIM,AUX)
STOP
END

```

C
C
C

```
SUBROUTINE ARB(X,Y,DERY,NDIM,AUX)
DIMENSION Y(NDIM),DERY(NDIM),AUX(8,NDIM),PRMT(5)
REAL*8 X,Y,DERY,AUX,PRMT,R1,R2,X1,X2,XM,L1,L2
REAL*8 JJ,A,B,PI,W0,VM,MM,PP
REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
REAL*8 IMAK,IPEAK,IN,ISL,ISU
REAL*8 TRIGS,TRIGF,TF,TS
INTEGER CONS,CCONS
EXTERNAL FCT,OUTP,FLWCRT
COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
COMMON K,MODE,J,ROW,CONS,CCONS,PASS
COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
COMMON/KTIMES/K1,K2,K3,K4,K5,K6
COMMON/TLINE/TRIGS,TRIGF,TF,TS
COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
COMMON/VOLT/VR,VS,VT
COMMON/TNN/T11,T22,T33,T44,T55,T66
COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM6/VLL,TMAX
```

```
CCC PRMT VECTOR CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
PRMT(1)=0.0D0
PRMT(2)=1.0D0
PRMT(3)=0.0001D0
PRMT(4)=0.0005D0
PRMT(5)=0.0D0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
CCC INITIAL VALUES OF Y AND DERY VECTORS CCCCCC
Y(1)=0.00001D0
Y(2)=0.0D0
Y(3)=0.0D0
Y(4)=0.0D0
Y(5)=0.0D0
DO 72 I=1,4
72 DERY(I)=0.0D0
DERY(5)=0.0D0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

CCC INITIAL VALUES OF THE TRIGGERING FUNCTION CCC

IPEAK=0.0D0

TRIGS=120.0D0

TRIGF=70.0D0

TS=0.0D0

TF=1.0D0+TS

T=0.02D0/360.0D0

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CALL RKGS(PRMT,Y,DERY,NDIM,IHLF,FCT,OUTP,AUX)

IF(IHLF-10) 520,520,550

520 WRITE(6,530)

530 FORMAT(1X,'INCREMENT IS OK AND SOLUTION ENDS')

RETURN

550 INDEX=IHLF-10

GO TO(560,580,600),INDEX

560 WRITE(6,531)

531 FORMAT(1X,'MORE THEN 10 BISECTIONS OF INITIAL
*INC. IS NECES.')

RETURN

580 WRITE(6,532)

532 FORMAT(1X,'INITIAL INC. IS ZERO')

RETURN

600 WRITE(6,533)

533 FORMAT(1X,'INITIAL INC. HAS WRONG SIGN')

RETURN

END

C

C

C

SUBROUTINE FLWCRT(X,Y)

DIMENSION Y(5),DERY(5)

REAL*8 X,Y,DERY

REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL

REAL*8 TRIGS,TRIGF,TRIG3,TF,TS

REAL*8 PI

REAL*8 IMAK,IPEAK,ISL,ISU

REAL*8 T11,T22,T33,T44,T55,T66

INTEGER CONS,CCONS,PASS

INTEGER ROW,MODE

INTEGER K1,K2,K3,K4,K5,K6

COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP

COMMON K,MODE,J,ROW,CONS,CCONS,PASS

COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL

COMMON/KTIMES/K1,K2,K3,K4,K5,K6

```

COMMON/TLINE/TRIGS,TRIGF,TF,TS
COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
COMMON/VOLT/VR,VS,VT
COMMON/TNN/T11,T22,T33,T44,T55,T66
COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM6/VLL,TMAX

```

```

CCC PEAK VALUE OF THE PHASE-A CURRENT CCCCCCCCCCCCCCCCCC

```

```

  IF(X.LT.0.01D0*CONS) THEN
  IF(ABS(Y(1)).GT.IMAK) IMAK=ABS(Y(1))
  ELSE
  IPEAK=IMAK
  IMAK=ABS(Y(1))
  CONS=CONS+1
  ENDIF

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCC TRIGGERING FUNCTION CCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

  IF(X.LE.TF) TRIG=((TRIGF-TRIGS)/TF)*X+TRIGS

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCC TRIGGERING INSTANTS OF THE THYRISTORS CCCCCCCCCCCCCC

```

```

  IF(X.LT.(300.0D0*T)) THEN
  IF(TRIG.GE.100.0D0) THEN
  TRIG3=80.0D0
  ELSE
  TRIG3=90.0D0
  ENDIF
  T1=TRIG*T
  T2=(TRIG+60.0D0)*T
  T3=(TRIG+60.0D0+TRIG3)*T
  T4=(TRIG+180.0D0)*T
  T5=(TRIG+240.0D0)*T
  T6=(TRIG+300.0D0)*T
  T11=T1
  T22=T2
  T33=T3
  T44=T4
  T55=T5
  T66=T6
  ELSE
  T1=(TRIG+360.0D0*K1)*T

```

```

T2=(TRIG+60.0D0+360.0D0*K2)*T
T3=(TRIG+120.0D0+360.0D0*K3)*T
T4=(TRIG+180.0D0+360.0D0*K4)*T
T5=(TRIG+240.0D0+360.0D0*K5)*T
T6=(TRIG+300.0D0+360.0D0*K6)*T
T11=T1-360.0D0*K1*T
T22=T2-360.0D0*K2*T
T33=T3-360.0D0*K3*T
T44=T4-360.0D0*K4*T
T55=T5-360.0D0*K5*T
T66=T6-360.0D0*K6*T
IF(X.GT.T1+0.01D0) K1=K1+1
IF(X.GT.T2+0.01D0) K2=K2+1
IF(X.GT.T3+0.01D0) K3=K3+1
IF(X.GT.T4+0.01D0) K4=K4+1
IF(X.GT.T5+0.01D0) K5=K5+1
IF(X.GT.T6+0.01D0) K6=K6+1
ENDIF

```

CCC TURN-ON AND TURN-OFF CONDITIONS OF THE THYRISTORS CC

```

GOTO (101,102,103,104,105,106,107,108,109,
*110,111,112,113,114,115,116,117,118),ROW
101 IF(X.LT.(TRIG+60.0D0)*T) THEN
  MODE=5
  ROW=1
  ELSEIF(Y(1).GT.0
*.AND.X.GE.T3) THEN
  MODE=0
  ROW=3
  ELSEIF(Y(1).GT.0.AND.X.LT.T3) THEN
  MODE=2
  ROW=1
  ELSEIF(Y(1).LE.0.AND.X.GE.T3) THEN
  MODE=3
  ROW=5
  ELSEIF(Y(1).LE.0.AND.X.LT.T3) THEN
  MODE=4
  ROW=2
  ENDIF
  GOTO 120
102 IF(X.LT.T3) THEN
  MODE=4
  ROW=2

```

```

ELSE
  MODE=3
  ROW=5
ENDIF
GOTO 120
103 IF(Y(1).GT.0) THEN
  MODE=0
  ROW=3
ELSEIF(Y(1).LE.0.AND.X.GE.T4) THEN
  MODE=0
  ROW=4
ELSEIF(Y(1).LE.0.AND.X.LT.T4) THEN
  MODE=3
  ROW=5
ENDIF
GOTO 120
104 IF(Y(1)+Y(2).GT.0) THEN
  MODE=0
  ROW=4
ELSEIF(Y(1)+Y(2).LE.0.AND.X.GE.T5) THEN
  MODE=0
  ROW=9
ELSEIF(Y(1)+Y(2).LE.0.AND.X.LT.T5) THEN
  MODE=1
  ROW=7
ENDIF
GOTO 120
105 IF(Y(1)+Y(2).LE.0.AND.X.GE.T4) THEN
  MODE=1
  ROW=7
ELSEIF(Y(1)+Y(2).LE.0.AND.X.LT.T4) THEN
  MODE=6
  ROW=6
ELSEIF(Y(1)+Y(2).GT.0.AND.X.GE.T4) THEN
  MODE=0
  ROW=4
ELSEIF(Y(1)+Y(2).GT.0.AND.X.LT.T4) THEN
  MODE=3
  ROW=5
ENDIF
GOTO 120
106 IF(X.GE.T4) THEN
  MODE=1
  ROW=7
ELSE

```

```

    MODE=6
    ROW=6
ENDIF
GOTO 120
107 IF(Y(2).LE.0.AND.X.GE.T5) THEN
    MODE=2
    ROW=11
ELSEIF(Y(2).LE.0.AND.X.LT.T5) THEN
    MODE=7
    ROW=8
ELSEIF(Y(2).GT.0.AND.X.GE.T5) THEN
    MODE=0
    ROW=9
ELSEIF(Y(2).GE.0.AND.X.LT.T5) THEN
    MODE=1
    ROW=7
ENDIF
GOTO 120
108 IF(X.GE.T5) THEN
    MODE=2
    ROW=11
ELSE
    MODE=7
    ROW=8
ENDIF
GOTO 120
109 IF(Y(2).LE.0.AND.X.GE.T6) THEN
    MODE=0
    ROW=10
ELSEIF(Y(2).LE.0.AND.X.LT.T6) THEN
    MODE=2
    ROW=11
ELSEIF(Y(2).GT.0) THEN
    MODE=0
    ROW=9
ENDIF
GOTO 120
110 IF(-Y(1).LE.0.AND.X.GE.T1) THEN
    MODE=0
    ROW=15
ELSEIF(-Y(1).LE.0.AND.X.LT.T1) THEN
    MODE=3
    ROW=13
ELSEIF(-Y(1).GT.0) THEN
    MODE=0

```

```

    ROW=10
ENDIF
GOTO 120
111 IF(-Y(1).LE.0.AND.X.GE.T6) THEN
    MODE=3
    ROW=13
ELSEIF(-Y(1).LE.0.AND.X.LT.T6) THEN
    MODE=8
    ROW=12
ELSEIF(-Y(1).GT.0.AND.X.GE.T6) THEN
    MODE=0
    ROW=10
ELSEIF(-Y(1).GT.0.AND.X.LT.T6) THEN
    MODE=2
    ROW=11
ENDIF
GOTO 120
112 IF(X.GE.T6) THEN
    MODE=3
    ROW=13
ELSE
    MODE=8
    ROW=12
ENDIF
GOTO 120
113 IF(-Y(1)-Y(2).LE.0.AND.X.GE.T1) THEN
    MODE=1
    ROW=17
ELSEIF(-Y(1)-Y(2).LE.0.AND.X.LT.T1) THEN
    MODE=9
    ROW=14
ELSEIF(-Y(1)-Y(2).GT.0.AND.X.GE.T1) THEN
    MODE=0
    ROW=15
ELSEIF(-Y(1)-Y(2).GT.0.AND.X.LT.T1) THEN
    MODE=3
    ROW=13
ENDIF
GOTO 120
114 IF(X.GE.T1) THEN
    MODE=1
    ROW=17
ELSE
    MODE=9
    ROW=14

```

```

ENDIF
GOTO 120
115 IF(-Y(1)-Y(2).LE.0.AND.X.GE.T2) THEN
    MODE=0
    ROW=16
ELSEIF(-Y(1)-Y(2).LE.0.AND.X.LT.T2) THEN
    MODE=1
    ROW=17
ELSEIF(-Y(1)-Y(2).GT.0) THEN
    MODE=0
    ROW=15
ENDIF
GOTO 120
116 IF(-Y(2).LE.0.AND.X.GE.T3) THEN
    MODE=0
    ROW=3
ELSEIF(-Y(2).LE.0.AND.X.LT.T3) THEN
    MODE=2
    ROW=1
ELSEIF(-Y(2).GT.0) THEN
    MODE=0
    ROW=16
ENDIF
GOTO 120
117 IF(-Y(2).LE.0.AND.X.GE.T2) THEN
    MODE=2
    ROW=1
ELSEIF(-Y(2).LE.0.AND.X.LT.T2) THEN
    MODE=5
    ROW=18
ELSEIF(-Y(2).GT.0.AND.X.GE.T2) THEN
    MODE=0
    ROW=16
ELSEIF(-Y(2).GT.0.AND.X.LT.T2) THEN
    MODE=1
    ROW=17
ENDIF
GOTO 120
118 IF(X.GE.T2) THEN
    MODE=2
    ROW=1
ELSE
    MODE=5
    ROW=18
ENDIF

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

120 RETURN

END

C
C
C

```
SUBROUTINE FCT(X,Y,DERY)
DIMENSION Y(5),DERY(5)
REAL*8 X,Y,DERY,Q,O,VA,VB,VC
REAL*8 VR,VS,VT
REAL*8 VAB,VAC,VBC,R1,R2,X1,X2,XM,L1,L2
REAL*8 JJ,A,B,PI,W0,VM,MM,PP,Y5,WS
REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
REAL*8 IMAK,IPEAK
REAL*8 ALFA1,ALFA2,ALFA22,ALFA4,TETA1,TETA2,VEFF,VVV
REAL*8 T11,T22,T33,T44,T55,T66
REAL*8 SLIP,PF
INTEGER CONS,CCONS,K,K1,K2,K3,K4,K5,K6
INTEGER K11,K22,K44
INTEGER INDX,MODE,K888
COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
COMMON K,MODE,J,ROW,CONS,CCONS,PASS
COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
COMMON/KTIMES/K1,K2,K3,K4,K5,K6
COMMON/TLINE/TRIGS,TRIGF,TF,TS
COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
COMMON/VOLT/VR,VS,VT
COMMON/TNN/T11,T22,T33,T44,T55,T66
COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM6/VLL,TMAX
```

CCC SUPPLY VOLTAGES CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```
VA=VM*DSIN(W0*X)
VB=VM*DSIN(W0*X-2.0D0*PI/3.0D0)
VC=VM*DSIN(W0*X-4.0D0*PI/3.0D0)
VAB=VA-VB
VAC=VA-VC
VBC=VB-VC
```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CALL FLWCRT(X,Y)

CCC LOAD TORQUE CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
 TL=0.0D0
 CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCC ROTOR SPEED IN ELECTRICAL RAD/S CCCCCCCCCCCCCCCCCCCCCC
 Y5=PP*Y(5)
 CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

VVV=VR
 INDX=MODE+1
 GO TO(11,12,13,14,15,16,17,18,19,20),INDX

CCC DIFFERENTIAL EQUATIONS SOLVED IN RKGS SUBROUTINE CC
 C FOR MODE 0

11 DERY(1)=(-2.0D0*B*R1-DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(1)+
 *(-2.0D0*DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(2)+
 *(2.0D0*DSQRT(6.0D0)/3.0D0*B*MM*Y5)*Y(3)+
 *(-2.0D0*DSQRT(3.0D0)/3.0D0*A*R2)*Y(4)+2.0D0/3.0D0*B*VAB+
 *2.0D0/3.0D0*B*VAC
 DERY(2)=(2.0D0*DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(1)+
 *(-2.0D0*B*R1+DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(2)+
 *(-A*R2-DSQRT(6.0D0)/3.0D0*B*MM*Y5)*Y(3)+
 *(DSQRT(3.0D0)/3.0D0*A*R2-DSQRT(2.0D0)*B*MM*Y5)*Y(4)+
 *(-4.0D0/3.0D0*B)*VAB+(2.0D0/3.0D0*B)*VAC
 DERY(3)=(-A*R1+DSQRT(6.0D0)/2.0D0*(A*A/B+
 *1.0D0/L2)*MM*Y5)*Y(1)+
 *(-2.0D0*A*R1)*Y(2)+(-A*A*R2/B-R2/L2)*Y(3)+
 *(-DSQRT(2.0D0)*A*MM*Y5+Y5)*Y(4)+(-A)*VAB+(A)*VAC
 DERY(4)=(A/2.0D0/B*Y5-DSQRT(3.0D0)*A*R1-DSQRT(2.0D0)/2.0D0*
 *A*A/B*MM*Y5)*Y(1)+(A/B*Y5-
 *DSQRT(2.0D0)*A*A/B*MM*Y5)*Y(2)+
 *(-Y5+DSQRT(2)*A*MM*Y5)*Y(3)+(-R2/L2-A*A/B*R2)*Y(4)+
 *(DSQRT(3.0D0)/3.0D0*A)*VAB+(DSQRT(3.0D0)/3.0D0*A)*VAC
 TE=-DSQRT(6.0D0)*MM*Y(1)*Y(3)/2.0D0+
 *DSQRT(2.0D0)*MM*Y(1)*Y(4)/2.0D0+DSQRT(2.0D0)*MM*Y(2)*Y(4)
 DERY(5)=(PP*TE-TL)/JJ
 VR=VA
 VS=VB
 VT=VC
 GO TO 61

C FOR MODE 1

12 DERY(1)=(-2.0D0*R1*B)*Y(1)+
 *(DSQRT(6.0D0)*MM*B*Y5+A*R2)*Y(3)/2.0D0+
 *(DSQRT(2.0D0)*MM*B*Y5-

```

*DSQRT(3.0D0)*A*R2)*Y(4)/2.0D0+(B)*VAB
DERY(2)=-DERY(1)
DERY(3)=(-DSQRT(3.0D0)*A/B*Y5/2.0D0+A*R1)*Y(1)+
*(-DSQRT(6.0D0)*MM*A*Y5/4.0D0-R2/L2-A*A*R2/B/4.0D0)*Y(3)+
*(-DSQRT(2.0D0)*A*MM*Y5/4.0D0+DSQRT(3.0D0)*A*A*R2/B/4.0D0+
*Y5)*Y(4)+(-A/2.0D0)*VAB
DERY(4)=(-A/2.0D0/B*Y5-DSQRT(3.0D0)*A*R1)*Y(1)+
*(DSQRT(3.0D0)*A*A*R2/B/4.0D0+
*DSQRT(2.0D0)*3.0D0*A*MM*Y5/4.0D0-
*Y5)*Y(3)+(DSQRT(6.0D0)*A*MM*Y5/4.0D0-
*3.0D0*A*A*R2/B/4.0D0-R2/L2)*Y(4)+
*(DSQRT(3.0D0)*A/2.0D0)*VAB
TE=-DSQRT(6.0D0)*MM*Y(1)*Y(3)/2.0D0-
*DSQRT(2.0D0)*MM*Y(1)*Y(4)/2.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=VA
VS=VB
VT=0.0D0
GO TO 61

```

C FOR MODE 2

```

13 DERY(1)=(-2.0D0*R1*B)*Y(1)+
*(DSQRT(6.0D0)*MM*B*Y5/2.0D0-A*R2/2.0D0)*Y(3)+
*(-DSQRT(3.0D0)*A*R2/2.0D0-
*DSQRT(2.0D0)*MM*B*Y5/2.0D0)*Y(4)+(B)*VAC
DERY(2)=0.0D0
DERY(3)=(-A*R1-DSQRT(3.0D0)*A/B*Y5/2.0D0)*Y(1)+
*(DSQRT(6.0D0)*A*MM*Y5/4.0D0-A*A*R2/B/4.0D0-R2/L2)*Y(3)+
*(-DSQRT(2.0D0)*MM*A*Y5/4.0D0-DSQRT(3.0D0)*A*A/B*R2/4.0D0+
*Y5)*Y(4)+(A/2.0D0)*VAC
DERY(4)=(-DSQRT(3.0D0)*A*R1+A*Y5/B/2.0D0)*Y(1)+
*(3.0D0/4.0D0*DSQRT(2.0D0)*A*MM*Y5-
*DSQRT(3.0D0)*A*A*R2/B/4.0D0-Y5)*Y(3)+
*(-DSQRT(6.0D0)*A*MM*Y5/4.0D0-0.75D0*A*A*R2/B-R2/L2)*Y(4)+
*(DSQRT(3.0D0)/2.0D0*A)*VAC
TE=-DSQRT(6.0D0)*MM*Y(1)*Y(3)/2.0D0+DSQRT(2.0D0)*MM*Y(1)*
*Y(4)/2.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=VA
VS=0.0D0
VT=VC
GO TO 61

```

C FOR MODE 3

```

14 DERY(1)=0.0D0

```

```

DERY(2)=(-2.0D0*R1*B)*Y(2)+(-A*R2)*Y(3)+
*(-DSQRT(2.0D0)*MM*B*Y5)*Y(4)+(B)*VBC
DERY(3)=(-2.0D0*R1*A)*Y(2)+(-A*A/B*R2-R2/L2)*Y(3)+
*(-DSQRT(2.0D0)*A*MM*Y5+Y5)*Y(4)+(A)*VBC
DERY(4)=(-DSQRT(2.0D0)*MM*Y5/L2)*Y(2)+
*(-Y5)*Y(3)+(-R2/L2)*Y(4)
TE=DSQRT(2.0D0)*MM*Y(2)*Y(4)
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=VB
VT=VC
GOTO 61

```

C FOR DISCONNECTED MODE

```

15 DERY(1)=0.0D0
   DERY(2)=0.0D0
   Y(1)=0.0D0
   Y(2)=0.0001D0
   DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
   DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
   TE=0.0D0
   DERY(5)=(PP*TE-TL)/JJ
   VR=0.0D0
   VS=0.0D0
   VT=0.0D0
   GOTO 61
16 DERY(1)=0.0D0
   DERY(2)=0.0D0
   Y(1)=0.0001D0
   Y(2)=0.0D0
   DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
   DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
   TE=0.0D0
   DERY(5)=(PP*TE-TL)/JJ
   VR=0.0D0
   VS=0.0D0
   VT=0.0D0
   GOTO 61
17 DERY(1)=0.0D0
   DERY(2)=0.0D0
   Y(1)=-0.0001D0
   Y(2)=0.0001D0
   DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
   DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
   TE=0.0D0

```

```

DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
18 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=-0.0001D0
Y(2)=0.0D0
DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
19 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=0.0D0
Y(2)=-0.0001D0
DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
20 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=0.0001D0
Y(2)=-0.0001D0
DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
61 IF(Y(5).LT.0.0D0) THEN
Y(5)=0.0D0
DERY(5)=0.0D0
ENDIF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

RETURN
END

C
C
C

```
SUBROUTINE OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
DIMENSION DERY(5),Y(5),PRMT(5)
REAL*8 X,Y,DERY,PRMT,VA,VB,VC,VAB,VAC,VBC,C
REAL*8 VR,VS,VT
REAL*8 R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP,O,Q,IND
REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
REAL*8 TRIGS,TRIGF,TF
REAL*8 IMAK,IPEAK,ISU,IN
REAL*8 ALFA1,ALFA2,ALFA22,ALFA4,TETA1,TETA2,VEFF,VVV
REAL*8 T11,T22,T33,T44,T55,T66
REAL*8 SLIP,PF
REAL*8 VLL,TMAX
INTEGER CONS,CCONS
INTEGER ROW,MODE,J
INTEGER K11,K22,K44,K888
COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
COMMON K,MODE,J,ROW,CONS,CCONS,PASS
COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
COMMON/KTIMES/K1,K2,K3,K4,K5,K6
COMMON/TLINE/TRIGS,TRIGF,TF,TS
COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
COMMON/VOLT/VR,VS,VT
COMMON/TNN/T11,T22,T33,T44,T55,T66
COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM6/VLL,TMAX

VA=VM*DSIN(W0*X)
VB=VM*DSIN(W0*X-2.0D0*PI/3.0D0)
VC=VM*DSIN(W0*X-4.0D0*PI/3.0D0)
VAB=VA-VB
VAC=VA-VC
VBC=VB-VC
C=-Y(1)-Y(2)

IF(IPEAK.GE.0.95D0*ISU) THEN
WRITE(6,71) R1
WRITE(6,72) R2
```

```

WRITE(6,73) X1
WRITE(6,74) X2
WRITE(6,75) XM
WRITE(6,76) PP
WRITE(6,77) JJ
WRITE(6,78) VLL
WRITE(6,79) ISU
WRITE(6,80) TMAX
WRITE(6,81) TRIG
71 FORMAT(2X,F10.4)
72 FORMAT(2X,F10.4)
73 FORMAT(2X,F10.4)
74 FORMAT(2X,F10.4)
75 FORMAT(2X,F10.4)
76 FORMAT(2X,F10.4)
77 FORMAT(2X,F10.4)
78 FORMAT(2X,F10.4)
79 FORMAT(2X,F10.4)
80 FORMAT(2X,F10.4)
81 FORMAT(2X,F10.4)
  PRMT(5)=1
  ENDIF
99 RETURN
  END
C
C
C
C*  $SET LIBRARY
SUBROUTINE RKGS(PRMT,Y,DERY,NDIM,IHLF,FCT,OUTP,AUX)
  DIMENSION Y(5),DERY(5),AUX(8,5),A(4),B(4),C(4),PRMT(5)
  REAL*8 X,Y,DERY,AUX,A,B,C,XEND,H,AJ,BJ,CJ,R1,R2,DELT,PRMT
  DO 1 I=1,NDIM
1  AUX(8,I)=.066666666666666667*DERY(I)
    X=PRMT(1)
    XEND=PRMT(2)
    H=PRMT(3)
    PRMT(5)=0.0
    CALL FCT(X,Y,DERY)
C*
C*  ERROR TEST
    IF (H*(XEND-X))38,37,2
C*
C*  PREPERATIONS FOR RUNGA KUTTA METHOD
2  A(1)=.5
    A(2)=.29289321881345248

```

```

A(3)=1.7071067811865475
A(4)=.16666666666666667
B(1)=2.
B(2)=1.
B(3)=1.
B(4)=2.
C(1)=.5
C(2)=.29289321881345248
C(3)=1.7071066666666667
C(4)=.5
C*
C*  PREPERATION FOR THE FIRST RUNGA-KUTTA STEP
DO 3 I=1,NDIM
  AUX(1,I)=Y(I)
  AUX(2,I)=DERY(I)
  AUX(3,I)=0.0
3  AUX(6,I)=0.0
  IREC=0
  H=H+H
  IHLF=-1
  ISTEP=0
  IEND=0
C*
C*
C*  START OF A RUNGA-KUTTA STEP
C*
4  IF((X+H-XEND)*H)7,6,5
5  H=XEND-X
6  IEND=1
C*
C*
C*  RECORDING OF INITIALS VALUES FOR THIS STEP
7  CALL OUTP(X,Y,DERY,IREC,NDIM,PRMT)
  IF(PRMT(5))40,8,40
8  ITEST=0
9  ISTEP=ISTEP+1
C*
C*
C*  START OF INNERMOST RUNGA KUTTA LOOP
  J=1
10 AJ=A(J)
  BJ=B(J)
  CJ=C(J)
  DO 11 I=1,NDIM
    R1=H*DERY(I)

```

```

      R2=AJ*(R1-BJ*AUX(6,I))
      Y(I)=Y(I)+R2
      R2=R2+R2+R2
11  AUX(6,I)=AUX(6,I)+R2-CJ*R1
      IF(J-4)12,15,15
12  J=J+1
      IF(J-3)13,14,13
13  X=X+.50*H
14  CALL FCT(X,Y,DERY)
      GOTO 10
C*
C*  END OF INNERMOST LOOP
C*
C*
C*  TEST IF ACCURACY
15  IF(ITEST)16,16,20
C*
C*
16  DO 17 I=1,NDIM
17  AUX(4,I)=Y(I)
      ITEST=1
      ISTEP=ISTEP+ISTEP-2
18  IHLF=IHLF+1
      X=X-H
      H=0.5*H
      DO 19 I=1,NDIM
        Y(I)=AUX(1,I)
        DERY(I)=AUX(2,I)
19  AUX(6,I)=AUX(3,I)
      GOTO 9
C*
C*
20  IMOD=ISTEP/2
      IF(ISTEP-IMOD-IMOD)21,23,21
21  CALL FCT(X,Y,DERY)
      DO 22 I=1,NDIM
        AUX(5,I)=Y(I)
22  AUX(7,I)=DERY(I)
      GOTO 9
C*
C*  COMPUTATION OF TEST VALUE DELT
23  DELT=0.0
      DO 24 I=1,NDIM
24  DELT=DELT+AUX(8,I)*DABS(AUX(4,I)-Y(I))
      IF(DELT-PRMT(4))28,28,25

```

```

C*
C*
25 IF(IHLF-10)26,36,36
26 DO 27 I=1,NDIM
27 AUX(4,I)=AUX(5,I)
  ISTEP=ISTEP+ISTEP-4
  X=X-H
  IEND=0
  GOTO 18
C*
C*
28 CALL FCT(X,Y,DERY)
  DO 29 I=1,NDIM
  AUX(1,I)=Y(I)
  AUX(2,I)=DERY(I)
  AUX(3,I)=AUX(6,I)
  Y(I)=AUX(5,I)
29 DERY(I)=AUX(7,I)
  CALL OUTP(X-H,Y,DERY,IHLF,NDIM,PRMT)
  IF(PRMT(5))40,30,40
30 DO 31 I=1,NDIM
  Y(I)=AUX(1,I)
31 DERY(I)=AUX(2,I)
  IREC=IHLF
  IF(IEND)32,32,39
C*
C*
C* INCREMENTS GET DOUBLED
32 IHLF=IHLF-1
  ISTEP=ISTEP/2
  H=H+H
  IF(IHLF)4,33,33
33 IMOD=ISTEP/2
  IF(ISTEP-IMOD-IMOD)4,34,4
34 IF(DELT-.02*PRMT(4))35,35,4
35 IHLF=IHLF-1
  ISTEP=ISTEP/2
  H=H+H
  GOTO 4
C*
C*
C* RETURNS TO CALLING PROGRAM
36 IHLF=11
  CALL FCT(X,Y,DERY)
  GOTO 39

```

```

37 IHLF=12
   GOTO 39
38 IHLF=13
39 CALL OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
40 RETURN
   END

```

A.3.2 The second program

```

C*
C*
C*  THE SECOND PROGRAM
C*  THIS PROGRAM COMPUTES OUPUT DATA OF
C*  THE MOTOR DURING STARTING PERIOD
C*  MAIN PROGRAM
  DIMENSION Y(10),DERY(10),AUX(20,20)
  REAL*8 R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI
  REAL*8 MM,PP,W0,F,X,Y,DERY,AUX,PRMT,VM
  REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
  REAL*8 IMAK,IPEAK,VVV,ISU
  REAL*8 TRIG3,SAYI
  REAL*8 VLL,TMAX
  INTEGER CONS,CCONS,PASS
  INTEGER K,MODE,ROW,J,NDIM
  INTEGER K1,K2,K3,K4,K5,K6
  INTEGER K11,K22,K44,K888
  INTEGER SABIT1,SABIT2,SABIT3
  INTEGER SON
  EXTERNAL ARB,FCT,FLWCRT,OUTP
  COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
  COMMON/K,MODE,J,ROW,CONS,CCONS,PASS
  COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
  COMMON/KTIMES/K1,K2,K3,K4,K5,K6
  COMMON/TLINE/TRIGS,TRIGF,TF,TS
  COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
  COMMON/VOLT/VR,VS,VT
  COMMON/TNN/T11,T22,T33,T44,T55,T66
  COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
  *TETA2,VEFF,VVV
  COMMON/COM2/K11,K22,K44,K888
  COMMON/COM3/SLIP,PF
  COMMON/COM4/ SABIT1,SABIT2,SABIT3

```

```

COMMON/COM5/ TRIG3,TRIGG
COMMON/COM6/ VLL,TMAX
COMMON/COM7/SON

```

```

OPEN(6,FILE='DAT1.DAT',STATUS='OLD')

```

```

CCC MOTOR PARAMETES AND REQUIRED DATA OF SOFTSTARTER
CCC ARE READ FROM THE DAT1.DAT FILE CCCCCCCCCCCCCCCCCC

```

```

READ(6,1) SAYI
READ(6,1) R1
READ(6,2) R2
READ(6,3) X1
READ(6,4) X2
READ(6,5) XM
READ(6,6) PP
READ(6,7) JJ
READ(6,8) VLL
READ(6,9) ISU
READ(6,10) TMAX
READ(6,11) TRIG
1 FORMAT(1X,F10.4)
2 FORMAT(1X,F10.4)
3 FORMAT(1X,F10.4)
4 FORMAT(1X,F10.4)
5 FORMAT(1X,F10.4)
6 FORMAT(1X,F10.4)
7 FORMAT(1X,F10.4)
8 FORMAT(1X,F10.4)
9 FORMAT(1X,F10.4)
10 FORMAT(1X,F10.4)
11 FORMAT(1X,F10.4)

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

OPEN(6,FILE='DAT.DAT',STATUS='OLD')
PI=4.0D0*DATAN(1.0D0)
VM=VLL*DSQRT(2.0D0/3.0D0)

```

```

CCC MOTOR1 PARAMETERS CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

C   R1=0.9D0
C   R2=1.25D0
C   X1=3.45D0
C   X2=3.33D0
C   XM=50.0D0
C   PP=2.0D0
C   JJ=0.1D0

```

```
C   VM=380.0D0*DSQRT(2.0D0/3.0D0)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
CCC MOTOR2 PARAMETERS CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
C   R1=1.84D0
C   R2=3.72D0
C   X1=10.05D0
C   X2=10.05D0
C   XM=290.0D0
C   PP=4.0D0
C   JJ=40.0D0
C   VM=6300.0D0*DSQRT(2.0D0/3.0D0)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
CCC VARIABLES CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
    L1=(X1+XM)/(100.0D0*PI)
    L2=(X2+XM)/(100.0D0*PI)
    MM=XM/(100.0D0*PI)
    B=1.0D0/(2.0D0*L1-2.0D0*MM*MM/L2)
    A=-DSQRT(2.0D0)*B*MM/L2
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
CCC CONSTANTS CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
    F=50.0D0
    W0=2.0D0*PI*F
    J=0
    MODE=0
    ROW=1
    NDIM=5
    K=1
    K1=0
    K2=0
    K3=0
    K4=0
    K5=0
    K6=0
    K11=0
    K22=0
    K44=0
    K888=0
    CONS=1
    CCONS=0
    PASS=0
    VVV=0.0D0
    SABIT1=1
```

```

SABIT2=0
SABIT3=0
SON=0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CALL ARB(X,Y,DERY,NDIM,AUX)
STOP
END
C
C
C
SUBROUTINE ARB(X,Y,DERY,NDIM,AUX)
DIMENSION Y(NDIM),DERY(NDIM),AUX(8,NDIM),PRMT(5)
REAL*8 X,Y,DERY,AUX,PRMT,R1,R2,X1,X2,XM,L1,L2
REAL*8 JJ,A,B,PI,W0,VM,MM,PP
REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TRIG3,TRIGG,TE,TL
REAL*8 IMAK,IPEAK,IN,ISU,ISL
REAL*8 TRIGS,TRIGF,TF,TS
INTEGER CONS,CCONS
INTEGER SON
EXTERNAL FCT,OUTP,FLWCRT
COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
COMMON K,MODE,J,ROW,CONS,CCONS,PASS
COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
COMMON/KTIMES/K1,K2,K3,K4,K5,K6
COMMON/TLINE/TRIGS,TRIGF,TF,TS
COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
COMMON/VOLT/VR,VS,VT
COMMON/TNN/T11,T22,T33,T44,T55,T66
COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM4/ SABIT1,SABIT2,SABIT3
COMMON/COM5/ TRIG3,TRIGG
COMMON/COM6/ VLL,TMAX
COMMON/COM7/SON

CCC PRMT VECTOR CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
PRMT(1)=0.0D0
PRMT(2)=1.0D0
PRMT(3)=0.000001D0
PRMT(4)=0.0005D0
PRMT(5)=0.0D0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

CCC INITIAL VALUES OF Y AND DERY VECTORS CCCCCCCCCCCCCC

Y(1)=0.00001D0

Y(2)=0.0D0

Y(3)=0.0D0

Y(4)=0.0D0

Y(5)=0.0D0

DO 72 I=1,4

72 DERY(I)=0.0D0

DERY(5)=0.0D0

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCC INITIAL VALUES OF THE TRIGGERING FUNCTION CCCCCCCCCC

C ISU=4.0D0*31.0D0*DSQRT(2.0D0)

C TRIG=80.0D0

IPEAK=0.0D0

TRIGG=TRIG

TRIGS=TRIG

TRIGF=0.0D0

TS=0.0D0

TF=1.0D0+TS

T=0.02D0/360.0D0

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CALL RKGS(PRMT,Y,DERY,NDIM,IHLF,FCT,OUTP,AUX)

IF(SON.EQ.1) GOTO 534

IF(IHLF-10) 520,520,550

520 WRITE(6,530)

530 FORMAT(1X,'INCREMENT IS OK AND SOLUTION ENDS')

RETURN

550 INDEX=IHLF-10

GO TO(560,580,600),INDEX

560 WRITE(6,531)

531 FORMAT(1X,'MORE THEN 10 BISECTIONS OF INITIAL

*INC. IS NECES.')

RETURN

580 WRITE(6,532)

532 FORMAT(1X,'INITIAL INC. IS ZERO')

RETURN

600 WRITE(6,533)

533 FORMAT(1X,'INITIAL INC. HAS WRONG SIGN')

534 RETURN

END

C

C

C

```

SUBROUTINE FLWCRT(X,Y)
DIMENSION Y(5),DERY(5)
REAL*8 X,Y,DERY
REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
REAL*8 TRIGS,TRIGF,TRIG3,TRIGG,TF,TS
REAL*8 PI
REAL*8 IMAK,IPEAK,ISU,ISL,IN
REAL*8 T11,T22,T33,T44,T55,T66
REAL*8 VLL,TMAX
INTEGER CONS,CCONS,PASS
INTEGER ROW,MODE
INTEGER K1,K2,K3,K4,K5,K6
INTEGER SIFIR
INTEGER SON
COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
COMMON K,MODE,J,ROW,CONS,CCONS,PASS
COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
COMMON/KTIMES/K1,K2,K3,K4,K5,K6
COMMON/TLINE/TRIGS,TRIGF,TF,TS
COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
COMMON/VOLT/VR,VS,VT
COMMON/TNN/T11,T22,T33,T44,T55,T66
COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
*TETA2,VEFF,VVV
COMMON/COM2/K11,K22,K44,K888
COMMON/COM3/SLIP,PF
COMMON/COM4/ SABIT1,SABIT2,SABIT3
COMMON/COM5/ TRIG3,TRIGG
COMMON/COM6/ VLL,TMAX
COMMON/COM7/SON

PI=4.0D0*DATAN(1.0D0)

CCC PEAK VALUE OF THE PHASE-A CURRENT CCCCCCCCCCCCCCCCCC
IF(X.LT.0.01D0*CONS) THEN
IF(ABS(Y(1)).GT.IMAK) IMAK=ABS(Y(1))
ELSE
IPEAK=IMAK
IMAK=ABS(Y(1))
CONS=CONS+1
ENDIF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCC TRIGGERING FUNCTION TO LIMIT THE STARTING CURRENT CC
IF(X.LT.TMAX) THEN

```

```

IF(IPEAK.GE.0.95D0*ISU) THEN
  TRIGS=TRIG
  TRIGF=0.0D0
  TS=X
  TF=1.0D0+TS
  ELSE
  TRIG=(TRIGS-TRIGF)*DCOS(PI/2.0D0/(TF-TS)*(X-TS))+TRIGF
  IF(TRIG.LE.0.0D0) SIFIR=1
  ENDIF
  ELSE
  SON=1
  ENDIF
  IF(SIFIR.EQ.1) TRIG=0.0D0
  CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCC TRIGGERING INSTANTS OF THE THYRISTORS
CCC TO MINIMIZE TORQUE PULSATIONS
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

  IF(X.LT.(300.0D0*T)) THEN
    TRIG3=(-19.0D0/30.0D0)*TRIGG+(19.0D0/30.0D0*80.0D0+93.0D0)
    T1=TRIG*T

```

```

C TRIGGERING STRATEGY DESCRIBED IN SECTION 4.1.1

```

```

C   T2=(120.0D0)*T
C   T3=(120.0D0+90.0D0)*T
CCCCCCCCCCCCCCCCCCCC

```

```

C TRIGGERING STRATEGY DESCRIBED IN SECTION 4.1.2

```

```

C   T2=(1.75D0*TRIGG+5.5D0)*T
C   T3=T2+90.0D0*T
CCCCCCCCCCCCCCCCCCCC

```

```

C TRIGGERING STRATEGY DESCRIBED IN SECTION 4.1.3

```

```

  T2=(TRIG+60.0D0)*T
  T3=(TRIG+60.0D0+TRIG3)*T
CCCCCCCCCCCCCCCCCCCC

```

```

  T4=(TRIG+180.0D0)*T
  T5=(TRIG+240.0D0)*T
  T6=(TRIG+300.0D0)*T

```

```

  T11=T1
  T22=T2
  T33=T3
  T44=T4
  T55=T5
  T66=T6

```

```

  ELSE
  T1=(TRIG+360.0D0*K1)*T
  T2=(TRIG+60.0D0+360.0D0*K2)*T

```

```

T3=(TRIG+120.0D0+360.0D0*K3)*T
T4=(TRIG+180.0D0+360.0D0*K4)*T
T5=(TRIG+240.0D0+360.0D0*K5)*T
T6=(TRIG+300.0D0+360.0D0*K6)*T
T11=T1-360.0D0*K1*T
T22=T2-360.0D0*K2*T
T33=T3-360.0D0*K3*T
T44=T4-360.0D0*K4*T
T55=T5-360.0D0*K5*T
T66=T6-360.0D0*K6*T
IF(X.GT.T1+0.01D0) K1=K1+1
IF(X.GT.T2+0.01D0) K2=K2+1
IF(X.GT.T3+0.01D0) K3=K3+1
IF(X.GT.T4+0.01D0) K4=K4+1
IF(X.GT.T5+0.01D0) K5=K5+1
IF(X.GT.T6+0.01D0) K6=K6+1
ENDIF

```

```

GOTO (101,102,103,104,105,106,107,108,109,
*110,111,112,113,114,115,116,117,118),ROW
CCC TURN-ON AND TURN-OFF CONDITIONS OF THE THYRISTORS CC
101 IF(X.LT.360.0D0*T.AND.X.LT.T2) THEN
    MODE=5
    ROW=1
ELSEIF(Y(1).GT.0
*.AND.X.GE.T3) THEN
    MODE=0
    ROW=3
ELSEIF(Y(1).GT.0.AND.X.LT.T3) THEN
    MODE=2
    ROW=1
ELSEIF(Y(1).LE.0.AND.X.GE.T3) THEN
    MODE=3
    ROW=5
ELSEIF(Y(1).LE.0.AND.X.LT.T3) THEN
    MODE=4
    ROW=2
ENDIF
GOTO 120
102 IF(X.LT.T3) THEN
    MODE=4
    ROW=2
ELSE
    MODE=3
    ROW=5

```

```

ENDIF
GOTO 120
103 IF(Y(1).GT.0) THEN
    MODE=0
    ROW=3
ELSEIF(Y(1).LE.0.AND.X.GE.T4) THEN
    MODE=0
    ROW=4
ELSEIF(Y(1).LE.0.AND.X.LT.T4) THEN
    MODE=3
    ROW=5
ENDIF
GOTO 120
104 IF(Y(1)+Y(2).GT.0) THEN
    MODE=0
    ROW=4
ELSEIF(Y(1)+Y(2).LE.0.AND.X.GE.T5) THEN
    MODE=0
    ROW=9
ELSEIF(Y(1)+Y(2).LE.0.AND.X.LT.T5) THEN
    MODE=1
    ROW=7
ENDIF
GOTO 120
105 IF(Y(1)+Y(2).LE.0.AND.X.GE.T4) THEN
    MODE=1
    ROW=7
ELSEIF(Y(1)+Y(2).LE.0.AND.X.LT.T4) THEN
    MODE=6
    ROW=6
ELSEIF(Y(1)+Y(2).GT.0.AND.X.GE.T4) THEN
    MODE=0
    ROW=4
ELSEIF(Y(1)+Y(2).GT.0.AND.X.LT.T4) THEN
    MODE=3
    ROW=5
ENDIF
GOTO 120
106 IF(X.GE.T4) THEN
    MODE=1
    ROW=7
ELSE
    MODE=6
    ROW=6
ENDIF

```

```

GOTO 120
107 IF(Y(2).LE.0.AND.X.GE.T5) THEN
    MODE=2
    ROW=11
ELSEIF(Y(2).LE.0.AND.X.LT.T5) THEN
    MODE=7
    ROW=8
ELSEIF(Y(2).GT.0.AND.X.GE.T5) THEN
    MODE=0
    ROW=9
ELSEIF(Y(2).GE.0.AND.X.LT.T5) THEN
    MODE=1
    ROW=7
ENDIF
GOTO 120
108 IF(X.GE.T5) THEN
    MODE=2
    ROW=11
ELSE
    MODE=7
    ROW=8
ENDIF
GOTO 120
109 IF(Y(2).LE.0.AND.X.GE.T6) THEN
    MODE=0
    ROW=10
ELSEIF(Y(2).LE.0.AND.X.LT.T6) THEN
    MODE=2
    ROW=11
ELSEIF(Y(2).GT.0) THEN
    MODE=0
    ROW=9
ENDIF
GOTO 120
110 IF(-Y(1).LE.0.AND.X.GE.T1) THEN
    MODE=0
    ROW=15
ELSEIF(-Y(1).LE.0.AND.X.LT.T1) THEN
    MODE=3
    ROW=13
ELSEIF(-Y(1).GT.0) THEN
    MODE=0
    ROW=10
ENDIF
GOTO 120

```

```

111 IF(-Y(1).LE.0.AND.X.GE.T6) THEN
    MODE=3
    ROW=13
ELSEIF(-Y(1).LE.0.AND.X.LT.T6) THEN
    MODE=8
    ROW=12
ELSEIF(-Y(1).GT.0.AND.X.GE.T6) THEN
    MODE=0
    ROW=10
ELSEIF(-Y(1).GT.0.AND.X.LT.T6) THEN
    MODE=2
    ROW=11
ENDIF
GOTO 120
112 IF(X.GE.T6) THEN
    MODE=3
    ROW=13
ELSE
    MODE=8
    ROW=12
ENDIF
GOTO 120
113 IF(-Y(1)-Y(2).LE.0.AND.X.GE.T1) THEN
    MODE=1
    ROW=17
ELSEIF(-Y(1)-Y(2).LE.0.AND.X.LT.T1) THEN
    MODE=9
    ROW=14
ELSEIF(-Y(1)-Y(2).GT.0.AND.X.GE.T1) THEN
    MODE=0
    ROW=15
ELSEIF(-Y(1)-Y(2).GT.0.AND.X.LT.T1) THEN
    MODE=3
    ROW=13
ENDIF
GOTO 120
114 IF(X.GE.T1) THEN
    MODE=1
    ROW=17
ELSE
    MODE=9
    ROW=14
ENDIF
GOTO 120
115 IF(-Y(1)-Y(2).LE.0.AND.X.GE.T2) THEN

```

```

    MODE=0
    ROW=16
ELSEIF(-Y(1)-Y(2).LE.0.AND.X.LT.T2) THEN
    MODE=1
    ROW=17
ELSEIF(-Y(1)-Y(2).GT.0) THEN
    MODE=0
    ROW=15
ENDIF
GOTO 120
116 IF(-Y(2).LE.0.AND.X.GE.T3) THEN
    MODE=0
    ROW=3
ELSEIF(-Y(2).LE.0.AND.X.LT.T3) THEN
    MODE=2
    ROW=1
ELSEIF(-Y(2).GT.0) THEN
    MODE=0
    ROW=16
ENDIF
GOTO 120
117 IF(-Y(2).LE.0.AND.X.GE.T2) THEN
    MODE=2
    ROW=1
ELSEIF(-Y(2).LE.0.AND.X.LT.T2) THEN
    MODE=5
    ROW=18
ELSEIF(-Y(2).GT.0.AND.X.GE.T2) THEN
    MODE=0
    ROW=16
ELSEIF(-Y(2).GT.0.AND.X.LT.T2) THEN
    MODE=1
    ROW=17
ENDIF
GOTO 120
118 IF(X.GE.T2) THEN
    MODE=2
    ROW=1
ELSE
    MODE=5
    ROW=18
ENDIF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
120 RETURN

```

```

END
C
C
C
SUBROUTINE FCT(X,Y,DERY)
  DIMENSION Y(5),DERY(5)
  REAL*8 X,Y,DERY,Q,O,VA,VB,VC
  REAL*8 VR,VS,VT
  REAL*8 VAB,VAC,VBC,R1,R2,X1,X2,XM,L1,L2
  REAL*8 JJ,A,B,PI,W0,VM,MM,PP,Y5,WS
  REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
  REAL*8 IMAK,IPEAK
  REAL*8 ALFA1,ALFA2,ALFA22,ALFA4,TETA1,TETA2,VEFF,VVV
  REAL*8 T11,T22,T33,T44,T55,T66
  REAL*8 SLIP,PF
  REAL*8 RAD
  REAL*8 TRIG3
  INTEGER CONS,CCONS,K,K1,K2,K3,K4,K5,K6
  INTEGER K11,K22,K44
  INTEGER INDX,MODE,K888
  INTEGER SABIT1,SABIT2,SABIT3
  COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP
  COMMON K,MODE,J,ROW,CONS,CCONS,PASS
  COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
  COMMON/KTIMES/K1,K2,K3,K4,K5,K6
  COMMON/TLINE/TRIGS,TRIGF,TF,TS
  COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN
  COMMON/VOLT/VR,VS,VT
  COMMON/TNN/T11,T22,T33,T44,T55,T66
  COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,
  *TETA2,VEFF,VVV
  COMMON/COM2/K11,K22,K44,K888
  COMMON/COM3/SLIP,PF
  COMMON/COM4/ SABIT1,SABIT2,SABIT3
  COMMON/COM5/ TRIG3,TRIGG
  COMMON/COM6/ VLL,TMAX
  COMMON/COM7/SON

  PI=4.0D0*DATAN(1.0D0)
  RAD=PI/180.0D0

CCC SUPPLY VOLTAGES CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
  VA=VM*DSIN(W0*X)
  VB=VM*DSIN(W0*X-2.0D0*PI/3.0D0)
  VC=VM*DSIN(W0*X-4.0D0*PI/3.0D0)

```

```

VAB=VA-VB
VAC=VA-VC
VBC=VB-VC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CALL FLWCRT(X,Y)

```

```

CCC SYNCHRONOUS SPEED IN MECHANICAL RAD/S CCCCCCCCCCCC
WS=100.0D0*PI/PP
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C LOAD TORQUE FOR MOTOR1
C TL=0.00113506*Y(5)*Y(5)+0.00113506*Y(5)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C LOAD TORQUE FOR MOTOR2
C TL=0.57561818*Y(5)*Y(5)+0.57561818*Y(5)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

CCC ROTOR SPEED IN ELECTRICAL RAD/S CCCCCCCCCCCCCCCCCCCC
Y5=PP*Y(5)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

VVV=VR
INDX=MODE+1
GO TO(11,12,13,14,15,16,17,18,19,20),INDX

```

```

CCC DIFFERENTIAL EQUATIONS SOLVED IN RKGS SUBROUTINE CC
C FOR MODE 0

```

```

11 DERY(1)=(-2.0D0*B*R1-DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(1)+
* (-2.0D0*DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(2)+
* (2.0D0*DSQRT(6.0D0)/3.0D0*B*MM*Y5)*Y(3)+
* (-2.0D0*DSQRT(3.0D0)/3.0D0*A*R2)*Y(4)+2.0D0/3.0D0*B*VAB+
* 2.0D0/3.0D0*B*VAC
DERY(2)=(2.0D0*DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(1)+
* (-2.0D0*B*R1+DSQRT(6.0D0)/3.0D0*A*MM*Y5)*Y(2)+
* (-A*R2-DSQRT(6.0D0)/3.0D0*B*MM*Y5)*Y(3)+
* (DSQRT(3.0D0)/3.0D0*A*R2-DSQRT(2.0D0)*B*MM*Y5)*Y(4)+
* (-4.0D0/3.0D0*B)*VAB+(2.0D0/3.0D0*B)*VAC
DERY(3)=(-A*R1+DSQRT(6.0D0)/2.0D0*(A*A/B+
* 1.0D0/L2)*MM*Y5)*Y(1)+
* (-2.0D0*A*R1)*Y(2)+(-A*A*R2/B-R2/L2)*Y(3)+
* (-DSQRT(2.0D0)*A*MM*Y5+Y5)*Y(4)+(-A)*VAB+(A)*VAC

```

```

DERY(4)=(A/2.0D0/B*Y5-DSQRT(3.0D0)*A*R1-DSQRT(2.0D0)/2.0D0*
*A*A/B*MM*Y5)*Y(1)+(A/B*Y5-
*DSQRT(2.0D0)*A*A/B*MM*Y5)*Y(2)+
*(-Y5+DSQRT(2)*A*MM*Y5)*Y(3)+(-R2/L2-A*A/B*R2)*Y(4)+
*(DSQRT(3.0D0)/3.0D0*A)*VAB+(DSQRT(3.0D0)/3.0D0*A)*VAC
TE=-DSQRT(6.0D0)*MM*Y(1)*Y(3)/2.0D0+
*DSQRT(2.0D0)*MM*Y(1)*Y(4)/2.0D0+DSQRT(2.0D0)*MM*Y(2)*Y(4)
DERY(5)=(PP*TE-TL)/JJ
VR=VA
VS=VB
VT=VC
GO TO 61

```

C FOR MODE 1

```

12 DERY(1)=(-2.0D0*R1*B)*Y(1)+(DSQRT(6.0D0)*MM*B*Y5+
*A*R2)*Y(3)/2.0D0
*+(DSQRT(2.0D0)*MM*B*Y5-
*DSQRT(3.0D0)*A*R2)*Y(4)/2.0D0+(B)*VAB
DERY(2)=-DERY(1)
DERY(3)=(-DSQRT(3.0D0)*A/B*Y5/2.0D0+A*R1)*Y(1)+
*(-DSQRT(6.0D0)*MM*A*Y5/4.0D0-R2/L2-A*A*R2/B/4.0D0)*Y(3)+
*(-DSQRT(2.0D0)*A*MM*Y5/4.0D0+DSQRT(3.0D0)*A*A*R2/B/4.0D0+
*Y5)*Y(4)+(-A/2.0D0)*VAB
DERY(4)=(-A/2.0D0/B*Y5-DSQRT(3.0D0)*A*R1)*Y(1)+
*(DSQRT(3.0D0)*A*A*R2/B/4.0D0+
*DSQRT(2.0D0)*3.0D0*A*MM*Y5/4.0D0-Y5)*Y(3)+
*(DSQRT(6.0D0)*A*MM*Y5/4.0D0-3.0D0*A*A*R2/B/4.0D0-
*R2/L2)*Y(4)+(DSQRT(3.0D0)*A/2.0D0)*VAB
TE=-DSQRT(6.0D0)*MM*Y(1)*Y(3)/2.0D0-
*DSQRT(2.0D0)*MM*Y(1)*Y(4)/2.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=VA
VS=VB
VT=0.0D0
GO TO 61

```

C FOR MODE 2

```

13 DERY(1)=(-2.0D0*R1*B)*Y(1)+
*(DSQRT(6.0D0)*MM*B*Y5/2.0D0-A*R2/2.0D0)*Y(3)+
*(-DSQRT(3.0D0)*A*R2/2.0D0-
*DSQRT(2.0D0)*MM*B*Y5/2.0D0)*Y(4)+(B)*VAC
DERY(2)=0.0D0
DERY(3)=(-A*R1-DSQRT(3.0D0)*A/B*Y5/2.0D0)*Y(1)+
*(DSQRT(6.0D0)*A*MM*Y5/4.0D0-A*A*R2/B/4.0D0-R2/L2)*Y(3)+
*(-DSQRT(2.0D0)*MM*A*Y5/4.0D0-

```

```

*DSQRT(3.0D0)*A*A/B*R2/4.0D0+Y5)*Y(4)
*+(A/2.0D0)*VAC
DERY(4)=(-DSQRT(3.0D0)*A*R1+A*Y5/B/2.0D0)*Y(1)+
*(3.0D0/4.0D0*DSQRT(2.0D0)*A*MM*Y5-
*DSQRT(3.0D0)*A*A*R2/B/4.0D0-Y5)*Y(3)+
*(-DSQRT(6.0D0)*A*MM*Y5/4.0D0-0.75D0*A*A*R2/B-R2/L2)*Y(4)+
*(DSQRT(3.0D0)/2.0D0*A)*VAC
TE=-DSQRT(6.0D0)*MM*Y(1)*Y(3)/2.0D0+DSQRT(2.0D0)*MM*Y(1)*
*Y(4)/2.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=VA
VS=0.0D0
VT=VC
GO TO 61

```

C FOR MODE 3

```

14 DERY(1)=0.0D0
DERY(2)=(-2.0D0*R1*B)*Y(2)+(-A*R2)*Y(3)+
*(-DSQRT(2.0D0)*MM*B*Y5)*Y(4)+(B)*VBC
DERY(3)=(-2.0D0*R1*A)*Y(2)+(-A*A/B*R2-R2/L2)*Y(3)+
*(-DSQRT(2.0D0)*A*MM*Y5+Y5)*Y(4)+(A)*VBC
DERY(4)=(-DSQRT(2.0D0)*MM*Y5/L2)*Y(2)+
*(-Y5)*Y(3)+(-R2/L2)*Y(4)
TE=DSQRT(2.0D0)*MM*Y(2)*Y(4)
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=VB
VT=VC
GOTO 61

```

C FOR DISCONNECTED MODE

```

15 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=0.0D0
Y(2)=0.0001D0
DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
16 DERY(1)=0.0D0
DERY(2)=0.0D0

```

```

Y(1)=0.0001D0
Y(2)=0.0D0
DERY(3)=- (R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=- Y5*Y(3)- (R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
17 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=-0.0001D0
Y(2)=0.0001D0
DERY(3)=- (R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=- Y5*Y(3)- (R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
18 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=-0.0001D0
Y(2)=0.0D0
DERY(3)=- (R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=- Y5*Y(3)- (R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
GOTO 61
19 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=0.0D0
Y(2)=-0.0001D0
DERY(3)=- (R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=- Y5*Y(3)- (R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0

```

```

GOTO 61
20 DERY(1)=0.0D0
DERY(2)=0.0D0
Y(1)=0.0001D0
Y(2)=-0.0001D0
DERY(3)=-(R2/L2)*Y(3)+Y5*Y(4)
DERY(4)=-Y5*Y(3)-(R2/L2)*Y(4)
TE=0.0D0
DERY(5)=(PP*TE-TL)/JJ
VR=0.0D0
VS=0.0D0
VT=0.0D0
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

61 IF(Y(5).LT.0.0D0) THEN
Y(5)=0.0D0
DERY(5)=0.0D0
ENDIF

CCC POWER FACTOR ANGLE IN RAD/S AND SLIP CCCCCCCCCCCCCCCC
SLIP=(WS-Y(5))/WS
PF=DATAN((X2*XM*(X2+XM)+(XM+X1)*(R2/SLIP)*(R2/SLIP)+
*X1*(X2+XM)*(X2+XM))/(XM*XM*(R2/SLIP)+
*R1*(R2/SLIP)*(R2/SLIP)+R1*(X2+XM)*(X2+XM)))
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

CCC PHASE-A EFFECTIVE VOLTAGE OF THE MOTOR CCCCCCCCCCCCC
IF(X.GE.T22+0.02D0*(SABIT1-1)) THEN
SABIT2=0
SABIT3=0
IF(X.GE.(TRIG+60.0D0+360.0D0)*T) THEN
VEFF=VM*DSQRT((1.0D0/(2.0D0*(ALFA22-ALFA2)*RAD)))*
*(TETA1+TETA2+ALFA22-ALFA1-
*ALFA2-ALFA4)*RAD+(1.0D0/2.0D0)*
*(DSIN(2.0D0*ALFA1*RAD)+DSIN(2.0D0*ALFA2*RAD)+
*DSIN(2.0D0*ALFA4*RAD)-DSIN(2.0D0*TETA1*RAD)-
*DSIN(2.0D0*TETA2*RAD)-DSIN(2.0D0*ALFA22*RAD))))
ENDIF
ALFA1=(T1+0.02D0)/T-360.0D0*(SABIT1-1)
ALFA2=T2/T-360.0D0*(SABIT1-1)
ALFA22=ALFA2+360.0D0
ALFA4=T4/T-360.0D0*(SABIT1-1)
SABIT1=SABIT1+1
ENDIF
IF(X.LT.(ALFA4*T+0.02D0*(SABIT1-2))).

```

```

*AND.X.GE.(ALFA2*T+0.02D0*(SABIT1-2))) THEN
IF(SABIT2.EQ.0) THEN
IF(VVV.EQ.0.0D0.AND.VR.EQ.0.0D0) THEN
TETA1=(X-0.02D0*(SABIT1-2))/T
SABIT2=1
ELSE
TETA1=ALFA4
ENDIF
ENDIF
ENDIF
IF(X.LT.ALFA1*T+(0.02D0*(SABIT1-2))).
*AND.X.GE.ALFA4*T+(0.02D0*(SABIT1-2))) THEN
IF(SABIT3.EQ.0) THEN
IF(VVV.EQ.0.0D0.AND.VR.EQ.0.0D0) THEN
TETA2=(X-0.02D0*(SABIT1-2))/T
SABIT3=1
ELSE
TETA2=ALFA1
ENDIF
ENDIF
ENDIF
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
RETURN
END
C
C
C
SUBROUTINE OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
DIMENSION DERY(5),Y(5),PRMT(5)
REAL*8 X,Y,DERY,PRMT,VA,VB,VC,VAB,VAC,VBC,C
REAL*8 VR,VS,VT
REAL*8 R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP,O,Q,IND
REAL*8 T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL
REAL*8 TRIGS,TRIGF,TF
REAL*8 IMAK,IPEAK,IN,RAD,ISU
REAL*8 ALFA1,ALFA2,ALFA22,ALFA4,TETA1,TETA2,VEFF,VVV
REAL*8 T11,T22,T33,T44,T55,T66
REAL*8 SLIP,PF
REAL*8 TRIG3,TRIGG
REAL*8 VLL,TMAX
INTEGER CONS,CCONS
INTEGER ROW,MODE,J
INTEGER K11,K22,K44,K888
INTEGER SABIT1,SABIT2,SABIT3

```

INTEGER SON

COMMON/PAR/R1,R2,X1,X2,XM,L1,L2,JJ,A,B,PI,W0,VM,MM,PP

COMMON K,MODE,J,ROW,CONS,CCONS,PASS

COMMON/TRGRNG/T,T1,T2,T3,T4,T5,T6,TETA,TRIG,TE,TL

COMMON/KTIMES/K1,K2,K3,K4,K5,K6

COMMON/TLINE/TRIGS,TRIGF,TF,TS

COMMON/PEAK/IMAK,IPEAK,ISU,ISL,IN

COMMON/VOLT/VR,VS,VT

COMMON/TNN/T11,T22,T33,T44,T55,T66

COMMON/COM1/ALFA1,ALFA2,ALFA22,ALFA4,TETA1,

*TETA2,VEFF,VVV

COMMON/COM2/K11,K22,K44,K888

COMMON/COM3/SLIP,PF

COMMON/COM4/ SABIT1,SABIT2,SABIT3

COMMON/COM5/ TRIG3,TRIGG

COMMON/COM6/ VLL,TMAX

COMMON/COM7/SON

RAD=PI/180.0D0

IND=MODE+1

VA=VM*DSIN(W0*X)

VB=VM*DSIN(W0*X-2.0D0*PI/3.0D0)

VC=VM*DSIN(W0*X-4.0D0*PI/3.0D0)

VAB=VA-VB

VAC=VA-VC

VBC=VB-VC

C=-Y(1)-Y(2)

IF(SON.EQ.1) THEN

WRITE(6,777)

WRITE(6,778)

WRITE(6,779)

777 FORMAT(1X,'ERROR')

778 FORMAT(5X,'INCREASE MAXIMUM STARTING TIME OR')

779 FORMAT(5X,'INCREASE CURRENT LIMIT')

PRMT(5)=1.0D0

GOTO 99

ENDIF

IF(X.GT.0.0D0) THEN

IF(J.EQ.25) THEN

J=0

GO TO 88

ENDIF

J=J+1

GO TO 99

```

ELSE
GOTO 99
ENDIF

CCC REQUIRED DATA ARE WRITTEN IN THE FILE DAT.DAT CCCCCC
88 WRITE(6,77) X,Y(1),Y(5),PP*TE,TL,PF*180.0D0/PI,SLIP,
  *TRIG,VEFF,IPEAK
77 FORMAT(2X,F10.2,2X,F15.5,2X,F15.5,
  *2X,F15.5,2X,F15.5,2X,F15.5,2X,F15.5,2X,F15.5,2X,F15.5,
  *2X,F15.5)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
99 RETURN
END

C
C
C
C* $SET LIBRARY
SUBROUTINE RKGS(PRMT,Y,DERY,NDIM,IHLF,FCT,OUTP,AUX)
DIMENSION Y(5),DERY(5),AUX(8,5),A(4),B(4),C(4),PRMT(5)
REAL*8 X,Y,DERY,AUX,A,B,C,XEND,H,AJ,BJ,CJ,R1,R2,DELT,PRMT
DO 1 I=1,NDIM
1  AUX(8,I)=.066666666666666667*DERY(I)
  X=PRMT(1)
  XEND=PRMT(2)
  H=PRMT(3)
  PRMT(5)=0.0
  CALL FCT(X,Y,DERY)
C*
C* ERROR TEST
  IF (H*(XEND-X))38,37,2
C*
C* PREPERATIONS FOR RUNGA KUTTA METHOD
2  A(1)=.5
  A(2)=.29289321881345248
  A(3)=1.7071067811865475
  A(4)=.16666666666666667
  B(1)=2.
  B(2)=1.
  B(3)=1.
  B(4)=2.
  C(1)=.5
  C(2)=.29289321881345248
  C(3)=1.7071066666666667
  C(4)=.5
C*

```

```

C*  PREPERATION FOR THE FIRST RUNGA-KUTTA STEP
      DO 3 I=1,NDIM
        AUX(1,I)=Y(I)
        AUX(2,I)=DERY(I)
        AUX(3,I)=0.0
      3  AUX(6,I)=0.0
        IREC=0
        H=H+H
        IHLF=-1
        ISTEP=0
        IEND=0
C*
C*
C*  START OF A RUNGA-KUTTA STEP
C*
      4  IF((X+H-XEND)*H)7,6,5
      5  H=XEND-X
      6  IEND=1
C*
C*
C*  RECORDING OF INITIALS VALUES FOR THIS STEP
      7  CALL OUTP(X,Y,DERY,IREC,NDIM,PRMT)
        IF(PRMT(5))40,8,40
      8  ITEST=0
      9  ISTEP=ISTEP+1
C*
C*
C*  START OF INNERMOST RUNGA KUTTA LOOP
      J=1
    10  AJ=A(J)
        BJ=B(J)
        CJ=C(J)
        DO 11 I=1,NDIM
          R1=H*DERY(I)
          R2=AJ*(R1-BJ*AUX(6,I))
          Y(I)=Y(I)+R2
          R2=R2+R2+R2
    11  AUX(6,I)=AUX(6,I)+R2-CJ*R1
        IF(J-4)12,15,15
    12  J=J+1
        IF(J-3)13,14,13
    13  X=X+.50*H
    14  CALL FCT(X,Y,DERY)
        GOTO 10
C*

```

```

C*  END OF INNERMOST LOOP
C*
C*
C*  TEST IF ACCURACY
  15 IF(ITEST)16,16,20
C*
C*
  16 DO 17 I=1,NDIM
  17 AUX(4,I)=Y(I)
    ITEST=1
    ISTEP=ISTEP+ISTEP-2
  18 IHLF=IHLF+1
    X=X-H
    H=0.5*H
    DO 19 I=1,NDIM
    Y(I)=AUX(1,I)
    DERY(I)=AUX(2,I)
  19 AUX(6,I)=AUX(3,I)
    GOTO 9
C*
C*
  20 IMOD=ISTEP/2
    IF(ISTEP-IMOD-IMOD)21,23,21
  21 CALL FCT(X,Y,DERY)
    DO 22 I=1,NDIM
    AUX(5,I)=Y(I)
  22 AUX(7,I)=DERY(I)
    GOTO 9
C*
C*  COMPUTATION OF TEST VALUE DELT
  23 DELT=0.0
    DO 24 I=1,NDIM
  24 DELT=DELT+AUX(8,I)*DABS(AUX(4,I)-Y(I))
    IF(DELT-PRMT(4))28,28,25
C*
C*
  25 IF(IHLF-10)26,36,36
  26 DO 27 I=1,NDIM
  27 AUX(4,I)=AUX(5,I)
    ISTEP=ISTEP+ISTEP-4
    X=X-H
    IEND=0
    GOTO 18
C*
C*

```

```

28 CALL FCT(X,Y,DERY)
   DO 29 I=1,NDIM
     AUX(1,I)=Y(I)
     AUX(2,I)=DERY(I)
     AUX(3,I)=AUX(6,I)
     Y(I)=AUX(5,I)
29 DERY(I)=AUX(7,I)
   CALL OUTP(X-H,Y,DERY,IHLF,NDIM,PRMT)
   IF(PRMT(5))40,30,40
30 DO 31 I=1,NDIM
   Y(I)=AUX(1,I)
31 DERY(I)=AUX(2,I)
   IREC=IHLF
   IF(IEND)32,32,39
C*
C*
C* INCREMENTS GET DOUBLED
32 IHLF=IHLF-1
   ISTEP=ISTEP/2
   H=H+H
   IF(IHLF)4,33,33
33 IMOD=ISTEP/2
   IF(ISTEP-IMOD-IMOD)4,34,4
34 IF(DELT-.02*PRMT(4))35,35,4
35 IHLF=IHLF-1
   ISTEP=ISTEP/2
   H=H+H
   GOTO 4
C*
C*
C* RETURNS TO CALLING PROGRAM
36 IHLF=11
   CALL FCT(X,Y,DERY)
   GOTO 39
37 IHLF=12
   GOTO 39
38 IHLF=13
39 CALL OUTP(X,Y,DERY,IHLF,NDIM,PRMT)
40 RETURN
   END

```

APPENDIX B

TRANSFORMATION MATRICES

1. The Phase Transformation

$$\mathbf{C}_1 = (\sqrt{2}/\sqrt{3})$$

	0	α	β
a	$1/\sqrt{2}$	1	0
b	$1/\sqrt{2}$	-1/2	$\sqrt{3}/2$
c	$1/\sqrt{2}$	-1/2	$\sqrt{3}/2$

2. The Commutator Transformation

$$\mathbf{C}_2 =$$

	0	d	q
0	1	0	0
α	0	$\cos\Phi$	$\sin\Phi$
β	0	$\sin\Phi$	$-\cos\Phi$

APPENDIX C

MOTOR PARAMETERS AND SPECIFICATIONS

1. Motor-1

Machine specifications

Power, kW	4
Voltage, V	380
Stator current, A	8
Frequency, c/s	50
Power factor	0.75
Rotational speed (synchronous), rpm	1500

Machine parameters

$$\begin{aligned}R_1 &= 0.9 \, \Omega \\R_2 &= 1.25 \, \Omega \\X_1 &= 3.45 \, \Omega \\X_2 &= 3.33 \, \Omega \\X_M &= 50 \, \Omega\end{aligned}$$

2. Motor-2

Machine specifications

Power, kW	250
Voltage, V	6000
Stator current, A	31
Frequency, c/s	50
Power factor	0.82
Rotational speed (synchronous), rpm	750

Machine parameters

$$\begin{aligned}R_1 &= 1.84 \, \Omega \\R_2 &= 3.72 \, \Omega \\X_1 &= X_2 = 10.05 \, \Omega \\X_M &= 290 \, \Omega\end{aligned}$$

APPENDIX D

LOAD TORQUES OF THE MOTORS USED IN THE THESIS

1. Load torque for motor-1:

$$T_L = 1.14 \cdot 10^{-3} \cdot w_r^2 + 1.14 \cdot 10^{-3} \cdot w_r$$

where,

w_r : Rotor speed in mechanical rad/s.

2. Load torque for motor-2:

$$T_L = 0.58 \cdot w_r^2 + 0.58 \cdot w_r$$