DUAL WOUND SYNCHRONOUS MACHINE AS A DC CONVERTER FOR REMOTE LOADS

BY

MOHAMMAD R. AGHA EBRAHIMI

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Winnipeg, Manitoba

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Abstract

Supplying the remote communities with electric energy, even in a developed country like Canada, has a great importance from several points of view. Some benefits include improving the life–style of such communities, and preparing the conditions for establishment of more industrial enterprises in such locations through the continuous supply of reliable, non–limited volumes of cheap energy.

DC transmission can be an economical way of supplying energy to remote loads. In this case, the problem of inversion of DC power to AC at the load location and the necessary commutation techniques must be well addressed.

The dual wound synchronous machine is a suitable means for this purpose. It provides AC voltages through the motor action to perform commutation on the inverter. And it supplies electric energy to the load through the generator action, taking place within the single machine.

In the current study, the dual wound synchronous machine is studied, and a digital model is developed to simulate the transient and the steady state operation of the machine in conjunction with EMTDC program.

Operation of a system consisting of the machine, the inverter, and the rectifier, separated by a long, monopolar DC transmission line is simulated. The results indicate that the machine successfully performs commutation on the inverter, that the machine can be started from standstill by Static Variable Frequency Starting techniques, i.e., by pulsing the rectifier on and off at low frequencies, and that the machine can be brought to rated speed by a proper closed–loop control system.

بسم الله الرحمن الرحیم

به پدر و مادرم :

به خاطر رنجهای فزون از شمارشان ،

و به پاس دریائی از عشق و تشویق ،

که همواره در آن غوطه‌ور بوده‌ام .

To my parents;

for their countless sufferings,

and for the ocean of love and encouragement,

which has always been surrounding me.

Acknowledgement

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Table of Contents

List of Figures

Figure	Page

List of Tables

List of Symbols

a, b, c, x, y, z	phase sequence
C_a	capacitance
C	transformation matrix
D	damping coefficient
E, V_{dc}	DC voltage
f	frequency
F	field winding
i_a	instantaneous current in phase a
I_a	phasor current in phase a
I_{dc}	DC current
I	current matrix
J	moment of inertia
KD	direct–axis damper winding
KQ	quadrature–axis damper winding
L_a	inductance
M_{ab}	mutual inductance between phase a and phase b
p	number of machine poles
p	time–derivative operator
P	real power
Q	reactive power
Q_1 , Q_2 , etc.	thyristors
R_a	resistance
S	complex power
t	time
T_{em}	electromagnetic torque

T_{mech}	mechanical torque
v_a	instantaneous phase a voltage
V_a	phasor phase a voltage
V_L	line–to–line voltage
$\mathbf{V}$	voltage matrix
x_a	inductive reactance
$\mathbf{Z}$	impedance matrix
α	firing angle
β	advance angle
γ	displacement angle between machine winding sets
γ	turn–off angle
δ	rotor load angle
θ	rotor position
λ_{d1}	flux linkage
μ	overlap angle
ϕ	power angle
ω	angular frequency

Chapter One

Introduction

1.1 – Remote Loads

There are many remote loads far from a source of AC generation in Manitoba, currently being supplied by diesel generation. As the loads grow, the desirability of connecting these loads to the AC system increases [1].

Rural electrification is of great economic and social significance in both developing and developed countries. Many isolated communities however are still lacking unrestricted low cost electricity. In Canada for example, about one percent of the national population or over 200,000 people are without access to services and amenities most Canadians take for granted. One problem facing the residents of these communities is how to supply themselves with energy for their daily needs. Their communities are not connected to electrical grids and natural gas networks. Oil, for heating and diesel, whether trucked, barged, or flown into the villages and homes, is expensive [2].

In some parts of the Northwest Territories, electricity costs 70 cents per KWh. In southern Canada, electric energy consumers typically pay well under 10 cents per KWh. Electrical services in isolated locations can be limited to levels sufficient only for a radio and a few light bulbs [2].

High cost electrical supply at limited levels discourages commercial and industrial enterprises. Consequently jobs and income levels are restricted. Inadequate energy supplies also cause hardship for individuals and communities in matters of health, safety, comfort and convenience. Normal community services and infrastructure, such as sanitation, lighting, education and transportation can be maintained only with difficulty. In short, the lack of a secure energy supply is a major impediment to individual and community development [2].

The long distances, difficult terrain and small loads are not attractive for establishing conventional transmission line connections to the main electrical grids. However, emerging technologies offer lower cost options for realistically extending rural electrification programs to service isolated loads [2].

In the current study, proven technology in the field of power electronics will be used for a new application, i.e. supplying remote loads with electric energy, using DC transmission.

Although neither the transmission distance nor the power to be transmitted to remote loads can be regarded as advantageous for DC transmission, nevertheless other constraints tend to favor DC transmission. The line costs for a monopolar line at relatively low voltages are cheaper than a three phase line. Generally, the rectifier stations for the DC transmission can be constructed at existing stations, using existing DC collector systems including filters and earth electrodes [1]. Besides, the ever–decreasing costs of semiconductor devices, further improve the possibility of economically justifiable use of DC transmission for the current purpose.

1.2 – Review of Literature

In this section a quick review of literature, regarding those concepts needed for the current study, will be made. Detailed discussions are to be pursued in references, as well as other related sources.

1.2.1 – DC Transmission

Over the last two decades there has been an increase in acceptance of DC systems for power transmission. There is a variety of reasons for this trend: DC systems are useful for power transmission over long distances from remote energy sources; they can be used for interconnecting major AC systems; they can be used for improving the stability of existing AC systems; they can be used for controlling MVA short circuit capacities or they can be used for crossing bodies of water. And there is a variety of other reasons [4].

The main motivation behind the choosing DC transmission for the current purpose is the fact that transmission line costs must be kept to a minimum where small loads are to be electrically serviced over long distances. The conventional approach to transmission is the three phase AC transmission line. However, the use of single wire line with ground return is one cost–effective option worthy of consideration. The single–wire line could be excited at 60 Hz or with DC voltage. For AC case, separate reservations, regarding VAR compensation at the receiving end, must be considered [2].

1.2.2 – Semiconductor Valve Groups and Commutation

The function of converting AC to DC or DC to AC power can be achieved by valve groups generally known as converters. These valve groups are formed by connecting a number of semiconductor devices called thyristors to each other.

Thyristors can be defined as controllable switches with two states of conducting and blocking. In order to turn on a thyristor, when its positive terminal, the anode, is positive, compared to its negative terminal, the cathode, a control signal must be given to its gate terminal.

Turning off a thyristor, when it is conducting, is possible only if the current passing through it is brought to zero. A reverse bias across the thyristor will then be necessary to help the thyristor regain its blocking ability [5].

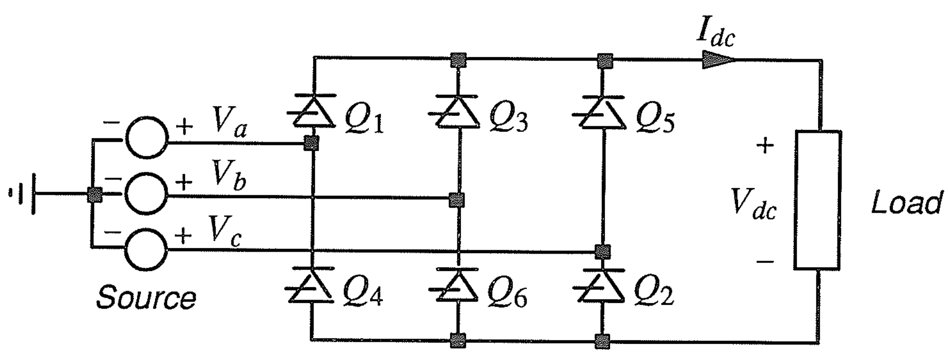
Converters, based on the direction of conversion between AC and DC, are divided to two categories. The ones which converts AC to DC, or rectifiers, and the ones which convert DC to AC or inverters [6]. One of the popular valve groups, used in different applications, is the three phase Graetz bridge.

The Three Phase, Six Pulse Bridge Rectifiers

The bridge is shown in Fig. 1.1. At each specific instant one thyristor in the upper group and one thyristor in the lower group is conducting. At $\omega t = 30^o$ (Fig. 1.2), where V_a starts to become "more positive" than V_c, the control signal can be given to the gate of Q_1. In this case, the current passing through Q_5 will shift to Q_1, and the reverse voltage imposed on Q_5 drives it to the blocking state. This phenomenon is called natural or line commutation. Sending the control signal, or the firing signal as it is frequently called, however can be delayed for some limited time. The delay angle, α, then plays an important role in determining the shape of output voltage, as well as its mean or DC value. The mathematical relationship between DC voltage and the delay angle can be showed to be as follows:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \tag{1.1}$$

V_L being the AC line–to–line voltage. In order to have proper rectification, the range of variations of α must be confined between 0^o and 90^o [6].



$$V_a = \sin(\omega t)$$
$$V_b = sin(\omega t - 120^o)$$
$$V_c = \sin(\omega t + 120^o)$$

Fig. 1.1 – Three phase, six pulse bridge rectifier

Fig. 1.2 shows the input and output voltages for $\alpha = 0^o$ (i.e., the firing signal has been given exactly at the point of natural commutation). In Fig. 1.3, the same voltages are shown for $\alpha = 25^o$. Note that the DC voltage is the difference between the AC voltage related to the conducting thyristor in the upper group and that of the conducting thyristor in the lower group.

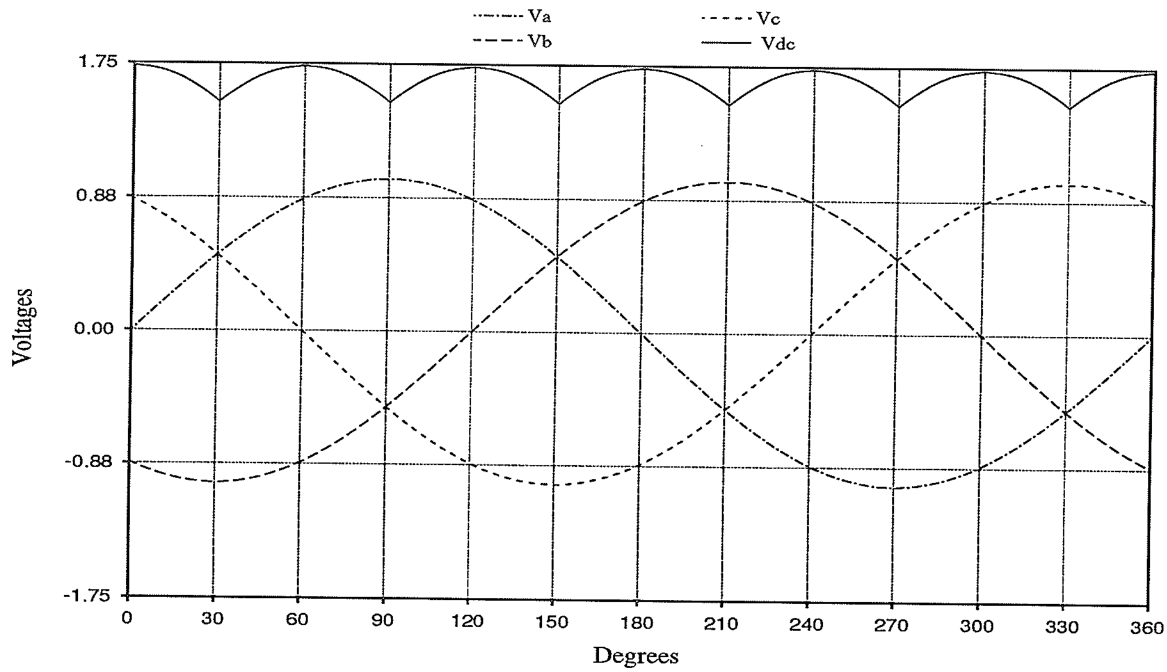


Fig. 1.2 – Voltages for $\alpha = 0^o$

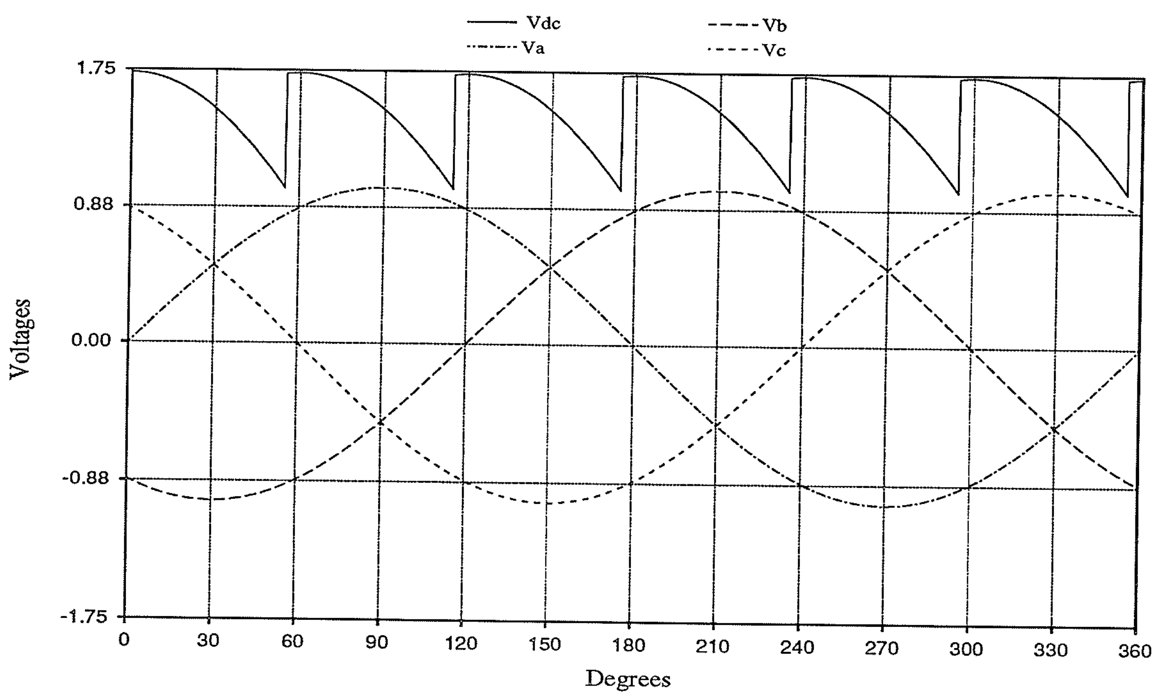
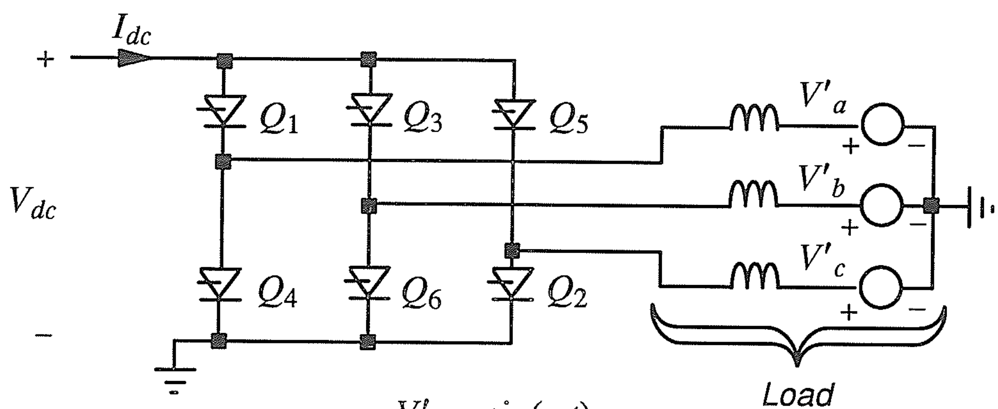


Fig. 1.3 – Voltages for $\alpha = 25^o$

The Three Phase Inverters

As it was stated before, the class of converters which convert the DC power to AC power are called inverters. Based on the nature of their input, the inverters are divided to two categories. The ones with a stiff DC voltage as input, or Voltage Source Inverters (VSI), and the ones with a stiff DC current as input, or Current Source Inverters (CSI). The output of these inverters is AC voltage or current, respectively, with a variable frequency, determined by the speed at which the thyristors are fired.

The configuration is basically the same as that of the bridge rectifier, and is shown in Fig. 1.4.



$$V'_a = \sin(\omega t)$$
$$V'_b = sin(\omega t - 120^o)$$
$$V'_c = \sin(\omega t + 120^o)$$

Fig. 1.4 – Three phase inverter

The relationship between the DC voltage, AC voltage, and α is the same as (1.1), but to make the inversion happen, i.e., to make the active power flow to the AC part from the DC part, α must be between 90^o and 180^o [6]. The inverter input and output voltages are shown in Fig. 1.5 for $\alpha = 170^o$.

As it may be clear from the above diagram, for a n–phase inverter to work properly, there must be a system of n–phase AC voltages generated in the load system to make the commutation between thyristors possible. If such voltages do not exist, auxiliary circuits and devices

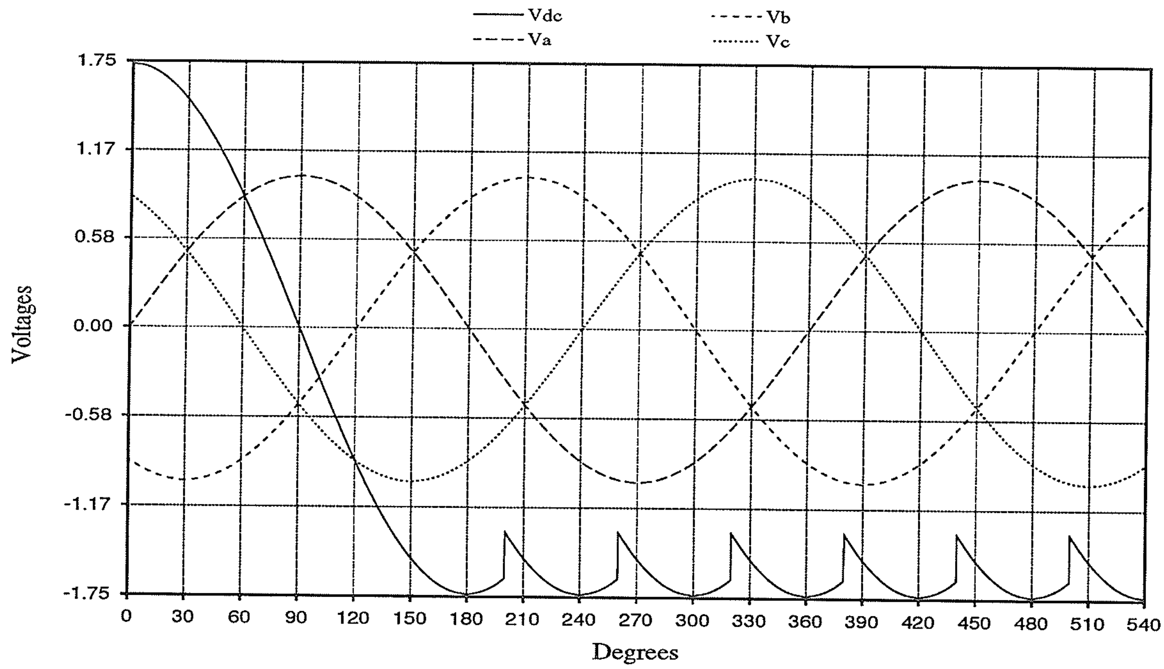


Fig. 1.5 – Voltages for $\alpha = 170^o$

will be needed to perform " Forced Commutation" on the inverter. In fact, the problem of commutation in inverters is one the most important problems to be considered and solved before any successful design and implementation can be achieved.

The dual wound synchronous machine, to be studied later, has the ability to create necessary voltages on the load side, and to successfully perform commutation on the inverter.

Before closing this section, one important point regarding α must be discussed. Because of the presence of high inductances in the circuits, the current in an out–going thyristor can not be brought to zero instantaneously. This is also the case with the increasing current in the in–coming thyristor. Therefore, for a period of time the current in the out–going thyristor decreases exponentially, while the current in the in–coming thyristor increases exponentially. The sum of of these two currents is always equal to the DC current. During this period of time, which is called the overlap angle and is shown by μ , the output voltage is equal to the mean value of the voltages related to the commutating thyristors.

Also, before a thyristor can completely gain its blocking ability, a negative voltage must be applied on its terminals and the voltage must remain negative for a specific period of time. This period of time is called the turn–off angle and is shown by γ .

Therefore, although it was previously stated that for inversion to take place, α must be between 90^o and 180^o, practically α can not be larger than $180^o - \beta$. β , which is called the advance angle, is :

$$\beta = \gamma + \mu \tag{1.2}$$

Fig. 1.6 shows the voltages of upper and lower thyristor groups in an inverter, while α is equal to $180^o - \beta$, $\mu = 10^o$, and $\gamma = 10^o$. Typically the β angle is limited to 10^o to 15^o [6].

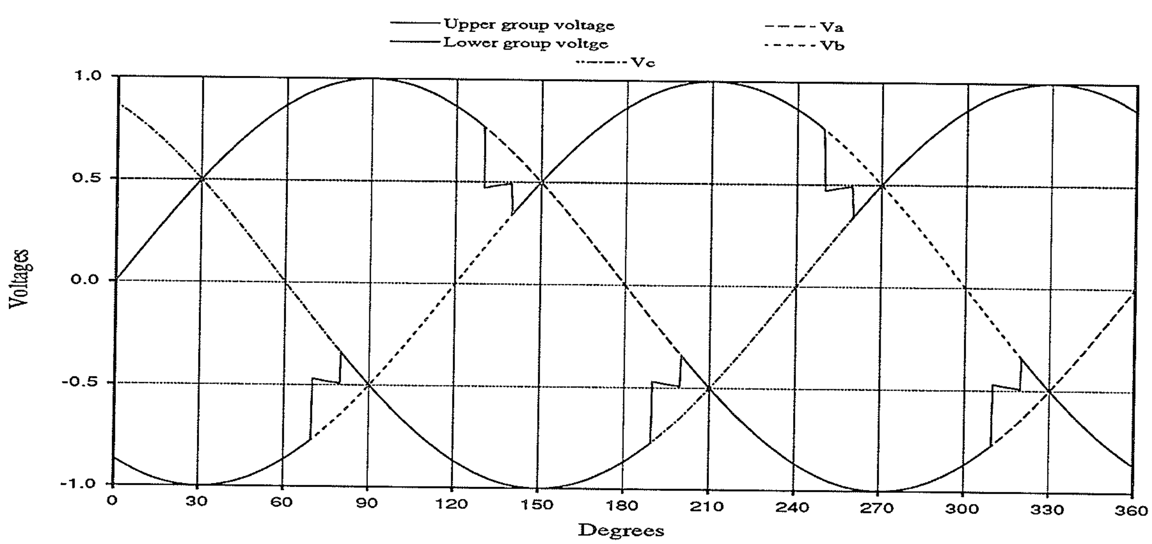


Fig. 1.6 – Voltages for $\alpha = 180^o - \beta$

1.2.3 – Synchronous Machines

Synchronous machine is one of the most known and utilized types of the extended family of electric machines. From huge nuclear power plants, where tremendous amounts of electric energy is produced by synchronous generators, to small industrial workshops, in which constant speed for assembly lines is gained from synchronous motors, this kind of electric machine is present. Other applications of synchronous machines include speed control by variable frequency sources, production (or consumption) of reactive power for voltage control (known as synchronous condenser), etc.

The machine is divided to two main parts; armature, which delivers or receives AC power, and field, which receives DC power and is responsible for producing the necessary electromagnetic field in the air–gap of the machine as a medium for conversion between electric and mechanical energy. Besides these two parts, there are certain iron bars, embodied in the moving part of the machine, the rotor, which help the machine accelerate faster during start–ups, or dampen the oscillations of the rotor during transient disturbances. These components are known as damper windings.

Except for large turbine–generators, designed to work at high speeds of 3600 rpm or 3000 rpm (60 Hz and 50 Hz respectively), at nuclear or thermal power plants, and therefore having cylindrical rotors, most synchronous machines have salient pole rotors, i.e., in certain parts of the rotor, the air–gap between rotor and the fixed part of the machine, stator, is considerably less than the air–gap in the other parts. This difference in the air–gap causes variations of electromagnetic reluctance in the space between rotor and stator, and consequently the reactance of windings mounted on different parts of stator will be dependent on the position of the rotor. Thus, in order to be able to analyze the performance of the machine effectively, one has to somehow distinguish between different parts of the rotor. This distinction is very well done by defining two axes on the rotor, namely the direct axis, on which the air–gap is at its least possible magnitude, and the quadrature axis, on which the air–gap is maximum. As it may be evident from the above terminology, these two axes are perpendicular to each other, i.e., they are displaced by 90 electrical degrees.

In ordinary synchronous machines, in which the current in armature is considerably higher than that of the field, the armature winding (three similarly wound coils and displaced by

120^o) is mounted on the stator to avoid the problem of transmission of high currents through the slip–rings. The field winding, in order to have the most effective electromagnetic field, is mounted on the direct axis of the rotor. And finally for most applications, it is enough to simulate the effects of damper bars in the rotor by considering two short–circuited windings, with their own resistance and inductances, each mounted on one of the rotor axes. These two fictitious, but important, windings are known as KD and KQ windings, for direct and quadrature axes respectively. The other windings are named as: a, b, and c, for three–phase armature windings, and F for field winding.

The steady state and transient performance of ordinary synchronous machines, including electromagnetic theory, voltage and torque production, mechanical dynamics, and design reservations are discussed in the literature in detail and will not be repeated here. Further details could be found, for example, in references [7,8,9].

1.3 – The Proposed Scheme

The proposed scheme to be studied, consists of a rectifier, low voltage DC line (22.5 KV) with a load commutated current source inverter (CSI) and a dual wound synchronous machine (SM) at the receiving end as shown in Fig. 1.7 .

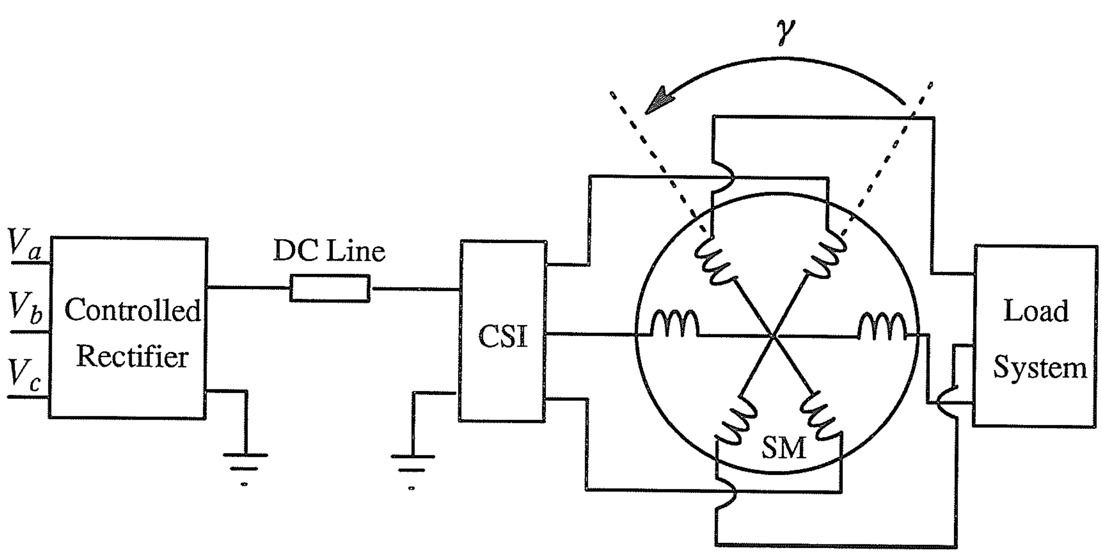


Fig. 1.7 – The proposed scheme

Commutation in the CSI is achieved at very low frequency by pulsing the DC current, i.e., turning on and off the rectifier. As soon as the synchronous machine starts to rotate, the field circuit is energized and the generated emf's in the machine will perform commutation on the inverter.

The advantages of the proposed scheme are [3]:

a) The cost is low; estimated at \$200 – \$250/KW for the complete system, apart from the transmission line;

b) An AVR can be used on the synchronous machine for load voltage control;

c) Filters may not be required on the load system;

d) The synchronous machine will provide continuity of supply during short faults on the transmission system or converters. The CSI can be blocked or bypassed and resynchronized to the machine very quickly; and,

e) Since the electrical load is supplied by the synchronous machine, instead of the inverter, the conventional control and protection devices, used on diesel generator, can be used in this system as well.

1.4 – Scope of the Project

The project will consist of the following tasks:

a) Study of the dual wound synchronous machine.

The machine will be studied from the circuit point of view, and general equations representing the behavior of the machine, as well as the equivalent circuits for the machine will be derived.

b) Modelling of the dual wound synchronous machine.

The machine will be digitally simulated with a variable displacement angle, γ, between the windings. The program will be a compatible subroutine for the EMTDC program.

c) System studies.

Some operating aspects of the system, including starting and accelerating the machine will be examined. The main objective will be to examine the possibility of using Static Variable Frequency System (SVFS) techniques to start the synchronous machine, as well as bringing it to rated speed, in the presence of a long transmission line.

Chapter Two

Theory of the Dual Wound Synchronous Machine

2.1 – Introduction

Of special interest in the current study is the dual wound synchronous machine. This type of synchronous machine is designed basically like an ordinary synchronous machine. The only difference, compared to common type of synchronous machine, is that in the dual wound synchronous machine, there are two sets of armature windings in the stator, each set consisting of three identical coils, displaced by 120 electrical degrees. The two sets are mounted in the same slots on the stator, but the magnetic axis of each coil in one set is displaced by an angle, say γ , with respect to its counterpart in the other set. For instance, if the three coils in first set are named as a, b, and c, and the three coils in the second set as x, y, and z, then a and x, b and y, and c and z are displaced by γ. The addition of the second set of windings results in the complication of relationships between existing coils in the machine, i.e., there are not only certain interactions between each set of armature windings and the rotor windings, but also between the two sets of windings themselves. Based on the interaction between these two sets, if one of them is connected to a three–phase AC source, a three–phase voltage system will be generated in the other one. The magnitude of generated voltage will be dependent on the turns ratio of the two windings, and it will be displaced by γ, compared to the source voltage. This transformation characteristic of the dual wound synchronous machine is the reason why it has been chosen for the proposed scheme.

Considering the above definitions and using a single coil placed on the magnetic axis of each actual coil, the diagram of a dual wound synchronous machine, consisting of six armature coils, one field coil on direct axis, and two damper coils on direct and quadrature axes, is shown in Fig. 2.1.

As it can be seen from the Fig. 2.1, the quadrature axis is assumed to be leading the direct axis. The set x,y, and z leads the set a, b, and c by γ . And finally θ is the angle between the electromagnetic axis of the coil a and the direct axis. Damper windings KD and KQ are short–circuited, as there is no access to them and there is no voltage source in their circuits.

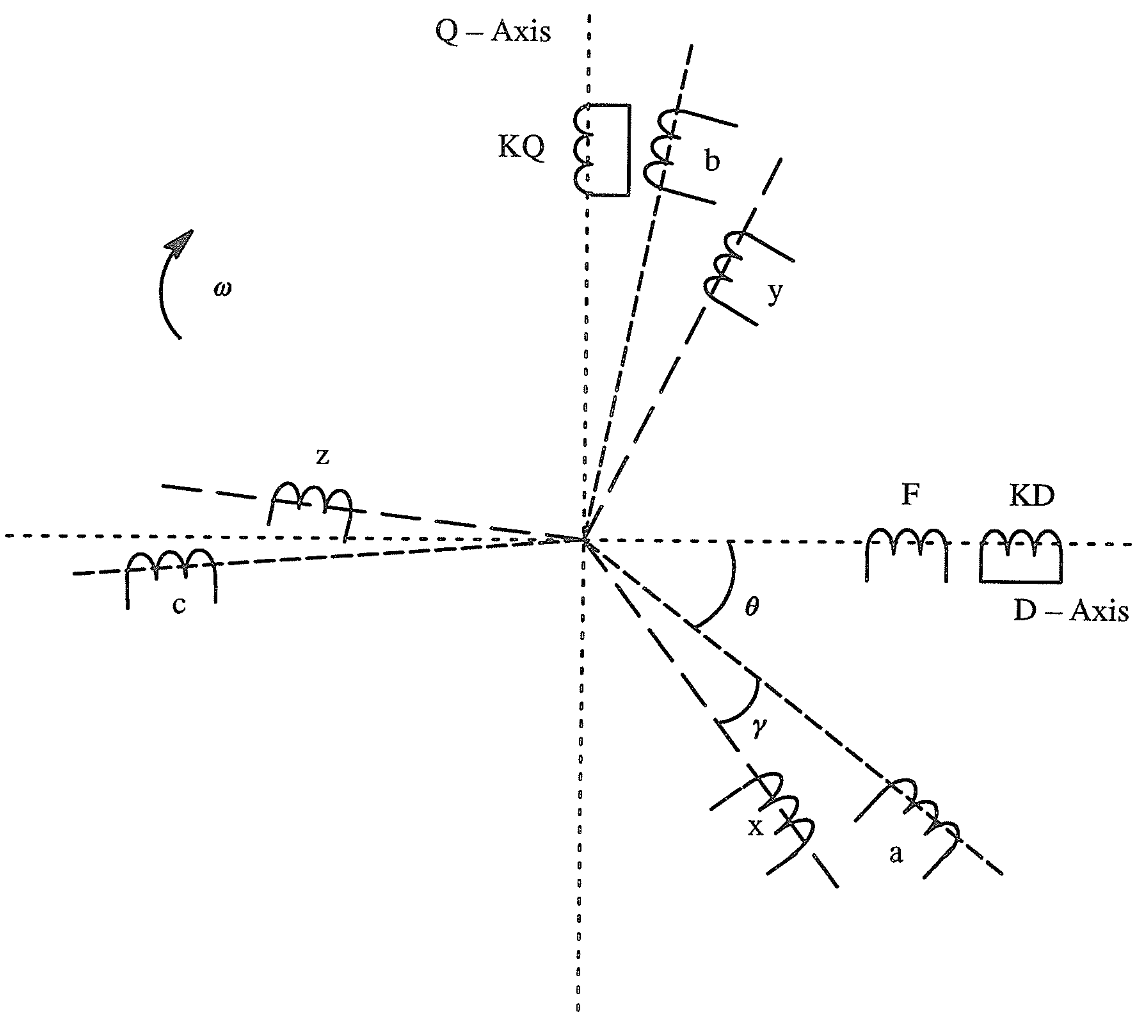


Fig. 2.1 – Diagram of a Dual Wound Synchronous Machine

It may be noteworthy that there is a certain relationship between electrical degrees and mechanical degrees, i.e., the electrical degree is $\frac{p}{2}$ times the mechanical degree, p being the number of magnetic poles. From this point, the electrical degree will be simply referred to as degree, unless otherwise stated. Also from now on "machine" will be used instead of "dual wound synchronous machine", unless otherwise stated.

In the next sections of this chapter the general equations governing the electrical and mechanical behavior of synchronous machine will be considered. Relationships between currents and voltages, equations for power and torque and equivalent circuits for machine will be derived. Finally, some experimental observations, regarding some of the parameters of a synchronous machine will be presented.

2.2 – *The Unified Theory of Electric Machines*

In this section the unified theory of electric machines will be introduced. This method of analyzing machines, briefly, considers each and every machine as a set of coupled coils, whose inductances vary with rotor position. The spirit of this theory is that "The performance of any machine under any condition of operation may be analyzed or predetermined in terms of measurements made solely at the terminals and shaft of the machine when machine is stationary" [7] . The outcome of this approach could be summarized by saying that "The performance of any type of machine under any condition is governed by a single voltage equation and a single torque equation" [7] .This method is concerned exclusively with the circuit theory of machines, i.e., measurements are made only at terminals and the shaft, and machine is analyzed solely in terms of quantities derived from these measurements. The measured quantities are primarily voltage, current, power, torque, and speed and derived quantities are resistance and various types of inductance. No attention is paid to the form of internal construction (the number and distribution of turns, the length of the air–gap and so on) to produce the circuit effects at terminals, or to the quantities like magnetomotive force, current density, flux density, flux linkage, and permeance [7] .

Various aspects and advantages of this method, along with the results of comparison between analytical and experimental observations, are discussed in different sources, especially in reference [7] .

2.3 – General Equations

Following the discussion in the previous section, one quickly finds that the dual wound synchronous machine can be regarded as an assemblage of nine coupled coils, each consisting of a resistance and a self–inductance, coupled with other coils by certain mutual inductances. As it was pointed out in Section 2.1, the coils will be named as : a, b, and c for the first set of armature windings, x, y, and z for the second set of armature windings, F for the field winding and KD and KQ for damper windings. Before introducing the equations, however, it must be noted that the mutual coupling between damper coils is zero [7] .

In this step a current and an applied voltage is assigned to each coil and simple and well–known equations governing the relationship between these parameters along with coil resistances, self–inductances, and couplings will be written. Using matrix form, the following equation holds:

$$\mathbb{V} = \mathbb{Z} \, . \, \mathbb{I}, \tag{2.1}$$

in which :

$$\mathbb{V} = \begin{bmatrix} v_f \\ v_{kd} \\ v_{kq} \\ v_a \\ v_b \\ v_c \\ v_x \\ v_y \\ v_z \end{bmatrix}, \qquad \text{and,} \qquad \mathbb{I} = \begin{bmatrix} i_f \\ i_{kd} \\ i_{kq} \\ i_a \\ i_b \\ i_c \\ i_x \\ i_y \\ i_z \end{bmatrix},$$

and $\mathbb{Z}$ is :

$$\begin{bmatrix} R_f+L_fp & M_{fd}p & 0 & pM_{af} & pM_{bf} & pM_{cf} & pM_{xf} & pM_{yf} & pM_{zf} \\ M_{fd}p & R_{kd}+L_{kd}p & 0 & pM_{ad} & pM_{bd} & pM_{cd} & pM_{xd} & pM_{yd} & pM_{zd} \\ 0 & 0 & R_{kq}+L_{kq}p & pM_{aq} & pM_{bq} & pM_{cq} & pM_{xq} & pM_{yq} & pM_{zq} \\ pM_{af} & pM_{ad} & pM_{aq} & R_a+pL_a & pM_{ab} & pM_{ac} & pM_{ax} & pM_{ay} & pM_{az} \\ pM_{bf} & pM_{bd} & pM_{bq} & pM_{ab} & R_b+pL_b & pM_{bc} & pM_{bx} & pM_{by} & pM_{bz} \\ pM_{cf} & pM_{cd} & pM_{cq} & pM_{ac} & pM_{bc} & R_c+pL_c & pM_{cx} & pM_{cy} & pM_{cz} \\ pM_{xf} & pM_{xd} & pM_{xq} & pM_{ax} & pM_{bx} & pM_{cx} & R_x+pL_x & pM_{xy} & pM_{xz} \\ pM_{yf} & pM_{yd} & pM_{yq} & pM_{ay} & pM_{by} & pM_{cy} & pM_{xy} & R_y+pL_y & pM_{yz} \\ pM_{zf} & pM_{zd} & pM_{zq} & pM_{az} & pM_{bz} & pM_{cz} & pM_{xz} & pM_{yz} & R_z+pL_z \end{bmatrix}$$

In the above $\mathbb{Z}$ matrix, p is the time derivative operand and is used instead of $\frac{d}{dt}$. As it can be seen, the mutual inductances between F or KD and KQ are entered as zero. Also the p operates on all mutual and self–inductances as they vary with the position of the rotor and therefore with time, except for those of the rotor windings, because of their constancy regardless of the position of rotor.

For the sake of convenience, $\mathbb{Z}$ will be partitioned to nine 3*3 matrices, and then each one of them will be considered separately. The result is:

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}_{00} & \mathbb{Z}_{01} & \mathbb{Z}_{02} \\ \mathbb{Z}_{10} & \mathbb{Z}_{11} & \mathbb{Z}_{12} \\ \mathbb{Z}_{20} & \mathbb{Z}_{21} & \mathbb{Z}_{22} \end{bmatrix} \qquad \text{and,} \qquad \begin{cases} \mathbb{Z}_{01} = \mathbb{Z}_{10}^t \\ \mathbb{Z}_{02} = \mathbb{Z}_{20}^t \\ \mathbb{Z}_{12} = \mathbb{Z}_{21}^t \end{cases} \qquad (2.2)$$

a. $\mathbb{Z}_{00}$:

This matrix contains the parameters concerning the coils on the rotor and their interactions with each other. All the parameters are constant and do not vary with the position of the rotor. all parameters in $\mathbb{Z}_{00}$ are the same as those in (2.1).

b. $\mathbb{Z}_{10}$:

This matrix contains the mutual inductances between the coils in set number one on the stator and the coils on the rotor. The coupling between a coil on stator and a coil on the rotor is maximum when their axes are aligned, is zero when their axes are perpendicular, and is minimum (or negative) when their axes are aligned on a direct line but with opposite directions. Knowing the above and remembering that: i) When a and F are aligned, θ is zero, ii) b and c are lagging a by 120^o and 240^o, respectively, the formulas for parameters in $\mathbb{Z}_{10}$ can be written as follows :

$$M_{af} = M_{1f} \cos\theta \quad , \quad M_{ad} = M_{1d} \cos\theta \quad , \quad M_{aq} = -M_{1q} \sin\theta$$

$$M_{bf} = M_{1f} \cos(\theta - 120^o), \quad M_{bd} = M_{1d} \cos(\theta - 120^o), \quad M_{bq} = -M_{1q} \sin(\theta - 120^o)$$

$$M_{cf} = M_{1f} \cos(\theta + 120^o), \quad M_{cd} = M_{1d} \cos(\theta + 120^o), \quad M_{cq} = -M_{1q} \sin(\theta + 120^o)$$

in which :

M_{1f} : Mutual inductance between coils in set number one and the field winding, when their axes are aligned,

M_{1d} : Mutual inductance between coils in set number one and the direct axis damper, when their axes are aligned,

M_{1q} : Mutual inductance between coils in set number one and the quadrature axis damper, when their axes are aligned.

c. $\mathbb{Z}_{20}$:

This matrix contains the mutual inductances between coils in set number 2 on the stator and coils on the rotor. All discussions for $\mathbb{Z}_{10}$ are valid here, except that, since set number 2 is leading set number 1 by γ , the effect of γ must be considered. If the angle between coil x and the direct axis is called α , then :

$$\alpha = \theta + \gamma \tag{2.3}$$

therefore it is enough to replace θ in $\mathbb{Z}_{10}$ by $\theta + \gamma$. Also, since the formulas are being developed in a general manner, i.e., there is room for possible differences between the two sets of windings in the armature (e.g. turns ratio not equal to one), the constants in formulas for $\mathbb{Z}_{10}$ will be replaced with new proper constants. Therefore the equations for $\mathbb{Z}_{20}$ are as follows:

$$M_{xf} = M_{2f}\cos(\theta+\gamma) \quad , \quad M_{xd} = M_{2d}\cos(\theta+\gamma) \quad , \quad M_{xq} = -M_{2q}\sin(\theta+\gamma)$$

$$M_{yf} = M_{2f}\cos(\theta+\gamma-120^o), M_{yd} = M_{2d}\cos(\theta+\gamma-120^o), M_{yq} = -M_{2q}\sin(\theta+\gamma-120^o)$$

$$M_{zf} = M_{2f}\cos(\theta+\gamma+120^o), M_{zd} = M_{2d}\cos(\theta+\gamma+120^o), M_{zq} = -M_{2q}\sin(\theta+\gamma+120^o)$$

where the definition of M_{2f} , M_{2d} *,and* M_{2q} is the same as M_{1f} , M_{1d} *,and* M_{1q} respectively.

d. $\mathbb{Z}_{11}$:

This matrix contains the parameters concerning the coils in set number 1 on the stator and the interactions between them. The resistances are constant and since the coils in each set are identical, the resistances are the same, or :

$$R_a = R_b = R_c = R_1 .$$

Self–inductances of the coils vary with the position of the rotor. When the axis of each coil is aligned with d–axis, the flux linkage is maximum, because the magnetic path shows least possible reluctance, therefore the coil self–inductance will be maximum at such a position. But because of the shape of the rotor, consider for example coil a, this situation happens on $\theta = 0^o$ and $\theta = 180^o$, thus the coil self–inductance is a function of 2θ instead of θ . It can be shown that the self–inductance of each coil is always positive. This fact leads to the assumption that the self–inductance of each coil on the stator consists of two parts. The first part is a positive constant and the second part is dependent on 2θ . Therefore the self–inductances for the set number 1 are as follows:

$$L_a = L_{01} + L_{21}\cos 2\theta ,$$

$$L_b = L_{01} + L_{21} \cos 2(\theta - 120^o)\,,$$

$$L_c = L_{01} + L_{21} \cos 2(\theta + 120^o)\,.$$

To find the proper formulas for the mutual inductances between coils in each set, consider coils a and b. These parameters too, consist of two parts. One part is constant and does not vary with θ. The other part varies with θ, but like the self–inductance, this variation is dependent on 2θ. The magnetic path between phase a and b has a minimum reluctance when $\theta = 60^o$, i.e., when the d–axis is exactly at the mid–way between the axes of the two coils, therefore at $\theta = 60^o$ the mutual inductance between a and b is maximum. The constant part in mutual inductance, however, is negative, because all coils are displaced with respect to each other by angles greater than 90^o, i.e., 120^o. Considering above discussion, the mutual inductions in $\mathbb{Z}_{11}$ are:

$$M_{ab} = -M_{01} + M_{21} \cos(2\theta - 120^o)\,,$$

$$M_{ac} = -M_{01} + M_{21} \cos(2\theta + 120^o)\,,$$

$$M_{bc} = -M_{01} + M_{21} \cos 2\theta\,.$$

The results of experimental observations done on a dual wound synchronous machine for M_{ab}, presented in Section 2.9, shows good accordance with the above formulas.

e. $\mathbb{Z}_{22}$:

This matrix is the same as $\mathbb{Z}_{11}$, except that it is concerning the second set of windings on the stator. All the discussions, and therefore formulas, for $\mathbb{Z}_{11}$ are still valid, the only difference being that one must replace constants properly, and replace θ by $\theta + \gamma$. The formulas are as follows:

$$R_x = R_y = R_z = R_2\,,$$

and:

$$L_x = L_{02} + L_{22} \cos 2(\theta + \gamma),$$

$$L_y = L_{02} + L_{22} \cos 2(\theta + \gamma - 120^o),$$

$$L_z = L_{02} + L_{22} \cos 2(\theta + \gamma + 120^o),$$

and:

$$M_{xy} = -M_{02} + M_{22} \cos[2(\theta + \gamma) - 120^o],$$

$$M_{xz} = -M_{02} + M_{22} \cos[2(\theta + \gamma) + 120^o],$$

$$M_{yz} = -M_{02} + M_{22} \cos 2(\theta + \gamma).$$

f. $\mathbb{Z}_{21}$:

This last, but not least, matrix contains the mutual inductances between the coils in set number 1 and the coils in set number 2. Here, again, the couplings consist of two parts. One part which is not dependent on the position of rotor, and therefore constant from the point of view of θ , but is dependent on the angle between the axes of the two coils in question. In other words, consider for example coils a and x, as the angle γ decreases, the flux linkage and therefore the mutual inductance between these two coils increases and vice–versa. This phenomenon can be shown by multiplying the constant part of the mutual inductance by $\cos\gamma$, for a and x, and by the cosine of proper angle for other couples. The second part which varies with θ , also obeys the same rule, mentioned for the constant part.

To find the proper expression for variations of parameters with θ , the following case will be considered. For coils a and x, the magnetic path has its least possible reluctance, or the largest possible permeance, when the d–axis is exactly at the mid–way between the axes of a and x, or when :

$$\theta = -\frac{\gamma}{2}.$$

It is concluded that M_{ax} is maximum when $2\theta + \gamma = 0$. This is the case also for M_{bz} and

M_{cy}. Therefore the second part of these three couplings are multiplied by $\cos(2\theta+\gamma)$. It can be easily shown that this relationship is $\cos(2\theta+\gamma-120^o)$ for M_{ay}, M_{bx}, and M_{cz}, and $\cos(2\theta+\gamma+120^o)$ for M_{az}, M_{by}, and M_{cy}.

Before writing the formulas, one last point must be considered. The constant part in mutual inductances between the coils of two sets is positive for those coils which are displaced by angles less than 90^o, and is negative for those coils which are displaced by angles greater than that.

From the above discussions, we are in a position to write the formulas for parameters in $\mathbb{Z}_{21}$, and thus complete the definition of parameters in $\mathbb{Z}$. Here they are :

$$M_{ax} = M_0 \cos\gamma + M_2 \cos\gamma \;\; . \;\; \cos(2\theta+\gamma),$$

$$M_{ay} = -M_0 \cos(\gamma+60^o) + M_2 \cos(\gamma+60^o) \;\; . \;\; \cos(2\theta+\gamma-120^o),$$

$$M_{az} = -M_0 \cos(\gamma-60^o) + M_2 \cos(\gamma-60^o) \;\; . \;\; \cos(2\theta+\gamma+120^o),$$

$$M_{bx} = -M_0 \cos(\gamma-60^o) + M_2 \cos(\gamma-60^o) \;\; . \;\; \cos(2\theta+\gamma-120^o),$$

$$M_{by} = M_0 \cos\gamma + M_2 \cos\gamma \;\; . \;\; \cos(2\theta+\gamma+120^o),$$

$$M_{bz} = -M_0 \cos(\gamma+60^o) + M_2 \cos(\gamma+60^o) \;\; . \;\; \cos(2\theta+\gamma),$$

$$M_{cx} = -M_0 \cos(\gamma+60^o) + M_2 \cos(\gamma+60^o) \;\; . \;\; \cos(2\theta+\gamma+120^o),$$

$$M_{cy} = -M_0 \cos(\gamma-60^o) + M_2 \cos(\gamma-60^o) \;\; . \;\; \cos(2\theta+\gamma),$$

$$M_{cz} = M_0 \cos\gamma + M_2 \cos\gamma \;\; . \;\; \cos(2\theta+\gamma-120^o).$$

Again, the results of experimental observations for M_{ax} and M_{az}, presented in Section 2.9, show very good accordance with above expressions.

2.4 – The dqo Transformation

Up to this point, the formulas by which one can write complete relationships between all existing coils in the machine were developed. But, as is obvious from the first glance, these are complex equations so that obtaining solutions for different modes of operation of the machine is difficult. The main difficulty arises from the fact that the differential equation derived for each coil has coefficients which are functions of θ, while θ itself is a function of time.

The above problem can be solved very effectively by the well–known active transformation called the dqo transformation. In fact this transformation not only eliminates θ from differential equations, but also achieves one other important goal ,i.e. , it makes it possible to transform all different types of electric machines to a single DC machine model, in which there are two perpendicular coils on the stator and two perpendicular coils on the rotor. This transformation is discussed in detail in the majority of electric machinery sources, and is presented completely in reference [7], from which the necessary techniques will be taken.

Transformation is done in two steps. First the three–phase machine with coils a, b, and c will be transformed to a two–phase machine with coils α and β and a zero sequence coil called 0, and then the two–phase machine will be transformed to a DC machine with two perpendicular coils d and q and the zero sequence coil. The first step is called phase transformation, for it transforms a three–phase machine to a two phase one. The second step is called the commutator transformation., as it transforms the two phase machine to a DC machine whose coils on the rotor are made fixed via four commutators. The two steps can be accomplished in one single step, and that is what is called dqo–transformation.

The phase transformation is achieved by the following transformation:

$$C_1 = \sqrt{\frac{2}{3}}\; \begin{array}{c|ccc} & 0 & \alpha & \beta \\ \hline a & 1/\sqrt{2} & 1 & 0 \\ b & 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ c & 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{array} ,$$

and the commutator transformation is achieved by :

$$C_2 = \begin{array}{c|ccc} & 0 & q & d \\ \hline 0 & 1 & 0 & 0 \\ \alpha & 0 & \sin\theta & \cos\theta \\ \beta & 0 & \cos\theta & -\sin\theta \end{array} .$$

It can be shown that both C_1 and C_2 are orthogonal transformations, meaning that :

$$C_1 . C_1^t = \mathbb{1}, \qquad \text{and,} \qquad C_2 . C_2^t = \mathbb{1},$$

in which C_1^t and C_2^t are transposed matrices of C_1 and C_2, respectively, and $\mathbb{1}$ is the unit matrix. Therefore the multiplication of these matrices is also orthogonal. In other words if:

$$C = C_1 . C_2 , \tag{2.4}$$

then :

$$C . C^t = \mathbb{1}. \tag{2.5}$$

The reason for orthogonality being a necessity can be found from the following equations. It was shown that for each machine :

$$V = Z . I ,$$

therefore :

$$C^t . V = C^t . Z . I .$$

Now, if $C . C^t = \mathbb{1}$, it can be written that :

$$C^t . V = C^t . Z . C . C^t . I ,$$

by which, the transformed form of machine matrices are found. If $\mathbb{V}'$, $\mathbb{I}'$, and $\mathbb{Z}'$ are the transformed forms of $\mathbb{V}$, $\mathbb{I}$, and $\mathbb{Z}$, respectively, it is obvious that :

$$\mathbb{V}' = \mathbb{C}^t \, . \, \mathbb{V} \, , \tag{2.6}$$

$$\mathbb{I}' = \mathbb{C}^t \, . \, \mathbb{I} \, , \tag{2.7}$$

and,

$$\mathbb{Z}' = \mathbb{C}^t \, . \, \mathbb{Z} \, . \, \mathbb{C} \, . \tag{2.8}$$

Finally, the dqo–transformation $\mathbb{C}$, the multiplication of $\mathbb{C}_1$ and $\mathbb{C}_2$ as it was pointed out before, is :

$$\mathbb{C}^t = \sqrt{\frac{2}{3}} \begin{array}{c} \\ \mathrm{d} \\ \mathrm{q} \\ 0 \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{a} & \mathrm{b} & \mathrm{c} \end{array} \\ \begin{bmatrix} \cos\theta & \cos(\theta - 120^o) & \cos(\theta + 120^o) \\ -\sin\theta & -\sin(\theta - 120^o) & -\sin(\theta + 120^o) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \end{array} \tag{2.9}$$

The negative signs before parameters in the second row of $\mathbb{C}^t$ arise from the fact that q–axis has been assumed to be leading d–axis.

Before starting to use the above transformation, one important point must be considered. Suppose that a, b, and c in the above transformation are representing a balanced three–phase (sinosoidal) voltage system. It is easy to verify that 0 component will be equal to zero. The results of tests on synchronous machines show that the effect of zero–sequence row and column in the transformed impedance matrix is so small that it is quite legitimate to omit these rows and columns from the matrix [7] .

In order to transform $\mathbb{Z}$ properly, special transformations must be assigned for each set of the windings, i.e., coils on the rotor, set number 1, and set number 2, on the stator, have their own special transformations. Since the coils on the rotor are already on d and q axes, there is no need to further transform them. Coils in the set number 1 will be transformed by $\mathbb{C}_a^t$, $\mathbb{C}_a^t$ being identical to above $\mathbb{C}^t$. $\mathbb{C}_x^t$ which transforms set number 2, however, differs with $\mathbb{C}_a^t$ in the way that θ in $\mathbb{C}_a^t$ has been replaced by $\theta + \gamma$ in it. Therefore $\mathbb{C}^t$ can be written as:

$$\mathbf{C}^t = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mathbf{C}_a^t & 0 \\ 0 & 0 & \mathbf{C}_x^t \end{bmatrix} ,$$

in which :

$$\mathbb{1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} ,$$

and :

$$\mathbf{C}_a^t = \begin{array}{c} \\ d_1 \\ q_1 \\ o_1 \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{a} & \mathrm{b} & \mathrm{c} \end{array} \\ \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ -\sin\theta & -\sin(\theta - 120^\circ) & -\sin(\theta + 120^\circ) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \end{array} \tag{2.10}$$

and :

$$\mathbf{C}_x^t = \begin{array}{c} \\ d_2 \\ q_2 \\ o_2 \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{x} & \mathrm{y} & \mathrm{z} \end{array} \\ \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta + \gamma) & \cos(\theta + \gamma - 120^\circ) & \cos(\theta + \gamma + 120^\circ) \\ -\sin(\theta + \gamma) & -\sin(\theta + \gamma - 120^\circ) & -\sin(\theta + \gamma + 120^\circ) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \end{array} . \tag{2.11}$$

Recalling the first partitioning which was made in $\mathbf{Z}$, and using the formulas derived previously for transforming it, the process of transformation is as follows :

$$\mathbf{Z}' = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mathbf{C}_a^t & 0 \\ 0 & 0 & \mathbf{C}_x^t \end{bmatrix} \begin{bmatrix} \mathbf{Z}_{00} & \mathbf{Z}_{01} & \mathbf{Z}_{02} \\ \mathbf{Z}_{10} & \mathbf{Z}_{11} & \mathbf{Z}_{12} \\ \mathbf{Z}_{20} & \mathbf{Z}_{21} & \mathbf{Z}_{22} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mathbf{C}_a & 0 \\ 0 & 0 & \mathbf{C}_x \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{Z}'_{00} & \mathbf{Z}'_{01} & \mathbf{Z}'_{02} \\ \mathbf{Z}'_{10} & \mathbf{Z}'_{11} & \mathbf{Z}'_{12} \\ \mathbf{Z}'_{20} & \mathbf{Z}'_{21} & \mathbf{Z}'_{22} \end{bmatrix} .$$

Consequently :

$$\mathbf{Z}'_{00} = \mathbf{Z}_{00} \quad , \quad \mathbf{Z}'_{01} = \mathbf{Z}_{01}\mathbf{C}_a \quad , \quad \mathbf{Z}'_{02} = \mathbf{Z}_{02}\mathbf{C}_x ,$$

$$\mathbf{Z}'_{10} = \mathbf{C}_a^t\mathbf{Z}_{10} \quad , \quad \mathbf{Z}'_{11} = \mathbf{C}_a^t\mathbf{Z}_{11}\mathbf{C}_a \quad , \quad \mathbf{Z}'_{12} = \mathbf{C}_a^t\mathbf{Z}_{12}\mathbf{C}_x ,$$

$$\mathbf{Z}'_{20} = \mathbf{C}_x^t\mathbf{Z}_{20} \quad , \quad \mathbf{Z}'_{21} = \mathbf{C}_x^t\mathbf{Z}_{21}\mathbf{C}_a \quad , \quad \mathbf{Z}'_{22} = \mathbf{C}_x^t\mathbf{Z}_{22}\mathbf{C}_x .$$

Note that :

$$\mathbf{Z}'_{01} \neq \mathbf{Z}''^{t}_{10} \quad , \quad \mathbf{Z}'_{02} \neq \mathbf{Z}''^{t}_{20} \quad , \quad \mathbf{Z}'_{12} \neq \mathbf{Z}''^{t}_{21} \ .$$

Each partition of $\mathbf{Z}'$, after applying corresponding transformations, will be as follows :

a. $\mathbf{Z}'_{00} = \mathbf{Z}_{00}$.

b. $\mathbf{Z}'_{01} = \mathbf{Z}_{01}\mathbf{C}_a$

$$= \sqrt{\frac{3}{2}} \begin{bmatrix} M_{1f}\,p & 0 & 0 \\ M_{1d}\,p & 0 & 0 \\ 0 & M_{1q}\,p & 0 \end{bmatrix}$$

c. $\mathbf{Z}'_{02} = \mathbf{Z}_{02}\mathbf{C}_x$

$$= \sqrt{\frac{3}{2}} \begin{bmatrix} M_{2f}\,p & 0 & 0 \\ M_{2d}\,p & 0 & 0 \\ 0 & M_{2q}\,p & 0 \end{bmatrix}$$

d. $\mathbf{Z}'_{10} = \mathbf{C}^t_a\mathbf{Z}_{10}$

$$= \sqrt{\frac{3}{2}} \begin{bmatrix} M_{1f}\,p & M_{1d}\,p & -M_{1q}\,\omega \\ M_{1f}\,\omega & M_{1d}\,\omega & M_{1q}\,p \\ 0 & 0 & 0 \end{bmatrix}$$

e. $\mathbf{Z}'_{20} = \mathbf{C}^t_x\mathbf{Z}_{20}$

$$= \sqrt{\frac{3}{2}} \begin{bmatrix} M_{2f}\,p & M_{2d}\,p & -M_{2q}\,\omega \\ M_{2f}\,\omega & M_{1d}\,\omega & M_{2q}\,p \\ 0 & 0 & 0 \end{bmatrix}$$

f. $\mathbf{Z}'_{11} = \mathbf{C}^t_a\mathbf{Z}_{11}\mathbf{C}_a$

$$= \begin{bmatrix} R_1 + L_{d1}p & -\omega L_{q1} & 0 \\ \omega L_{d1} & R_1 + L_{q1}p & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

where :

$$L_{d1} = L_{01} + M_{01} + \frac{1}{2} L_{21} + M_{21},$$

and

$$L_{q1} = L_{01} + M_{01} - \frac{1}{2} L_{21} - M_{21}.$$

g. $\mathbf{Z}'_{22} = \mathbf{C}_x^t \mathbf{Z}_{22} \mathbf{C}_x$

$$= \begin{bmatrix} R_2 + L_{d2}p & -\omega L_{q2} & 0 \\ \omega L_{d2} & R_2 + L_{q2}p & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

where, by analogy :

$$L_{d2} = L_{02} + M_{02} + \frac{1}{2} L_{22} + M_{22},$$

$$L_{d2} = L_{02} + M_{02} - \frac{1}{2} L_{22} - M_{22}.$$

h. $\mathbf{Z}'_{21} = \mathbf{C}_x^t \mathbf{Z}_{21} \mathbf{C}_a$

$$= \begin{bmatrix} M_{dd}\, p & -\omega\, M_{dq} & 0 \\ \omega\, M_{dd} & M_{dq}\, p & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where :

$$M_{dd} = \frac{3}{2} M_0 + M_2 \cos\gamma,$$

and,

$$M_{dq} = \frac{3}{2} M_0 - M_2 \cos\gamma.$$

i. $\mathbf{Z}'_{12} = \mathbf{C}_a^t \mathbf{Z}_{12} \mathbf{C}_x$

$$= \begin{bmatrix} M_{dd}p & -\omega M_{dq} & 0 \\ \omega M_{dd} & M_{dq}p & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

M_{dd} and M_{dq} are the same as in $\mathbb{Z}'_{21}$. Note that contrary to what was seen before, these last two matrices are identical.

With all partitions of $\mathbb{Z}'$ being derived, the final matrix consisting of relationships between voltages, currents, and impedances of all coils, transformed to d and q axes, is now ready. Although deriving this matrix is somewhat tedious, obviously because of the amount of mathematical work involved, the final form is simple and needs only be calculated once. The final transformed equations are as follows:

$$\mathbb{V}' = \mathbb{Z}'.\mathbb{I}' \tag{2.12}$$

in which:

$$\mathbb{V}' = \begin{bmatrix} v_f \\ v_{kd} \\ v_{kq} \\ v_{d1} \\ v_{q1} \\ v_{d2} \\ v_{q2} \end{bmatrix}, \qquad \mathbb{I}' = \begin{bmatrix} i_f \\ i_{kd} \\ i_{kq} \\ i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix},$$

and :

$$\mathbb{Z}' = \begin{bmatrix} R_f + L_f\, p & M_{fd}\, p & 0 & \sqrt{3/2}\,M_{1f}\, p & 0 & \sqrt{3/2}\,M_{2f}\, p & 0 \\ M_{fd}\, p & R_{Kd} + L_{kd}\, p & 0 & \sqrt{3/2}\,M_{1d}\, p & 0 & \sqrt{3/2}\,M_{2d}\, p & 0 \\ 0 & 0 & R_{kq} + L_{kq}\, p & 0 & \sqrt{3/2}\,M_{1q}\, p & 0 & \sqrt{3/2}\,M_{2q}\, p \\ \sqrt{3/2}\,M_{1f}\, p & \sqrt{3/2}\,M_{1d}\, p & -\sqrt{3/2}\,M_{1q}\, \omega & R_1 + L_{d1}p & -\omega L_{q1} & M_{dd}\, p & -\omega M_{dq} \\ \sqrt{3/2}\,M_{1f}\, \omega & \sqrt{3/2}\,M_{1d}\, \omega & \sqrt{3/2}\,M_{1q}\, p & \omega L_{d1} & R_1 + L_{q1}\, p & \omega M_{dd} & M_{dq}\, p \\ \sqrt{3/2}\,M_{2f}\, p & \sqrt{3/2}\,M_{df}\, p & -\sqrt{3/2}\,M_{2q}\, \omega & M_{dd}\, p & -\omega M_{dq} & R_2 + L_{d2}\, p & -\omega L_{q2} \\ \sqrt{3/2}\,M_{2f}\, \omega & \sqrt{3/2}\,M_{2d}\, \omega & \sqrt{3/2}\,M_{2q}\, p & \omega M_{dd} & M_{dq}\, p & \omega L_{kd2} & R_2 + L_{q2}\, p \end{bmatrix}$$

It is clear that the application of the dqo transformation on the original impedance matrix eliminates the rows and columns representing the zero sequences. Therefore, although under some special circumstances, the zero sequence currents may be present in the machine, the zero sequence voltages do not appear in the equations, and thus, the rank of the final matrices has been reduced from 9 to 7.

2.5 – *Real and Reactive Powers*

In a system with voltage $V \measuredangle 0^\circ$ and current $I \measuredangle -\phi^\circ$, V and I being the peak values of sine waves, the real and reactive powers, P and Q respectively, are found by following relationships:

$$P = \frac{1}{2} VI \cos\phi \ ,$$

and,

$$Q = \frac{1}{2} VI \sin\phi \ .$$

Considering the per–unit values of V_1 , V_2 , I_1 , and I_2 , in dq system, and assuming that both currents are lagging their corresponding voltages by ϕ_1 and ϕ_2 , respectively, the formulas for P and Q in dq system can be derived from the phasor diagram in Fig. 2.2.

Knowing that :

$$P_1 = \frac{1}{2} V_1 I_1 \cos\phi_1 \quad , \quad Q_1 = \frac{1}{2} V_1 I_1 \sin\phi_1 ,$$

and

$$P_2 = \frac{1}{2} V_2 I_2 \cos\phi_2 \quad , \quad Q_2 = \frac{1}{2} V_2 I_2 \sin\phi_2 ,$$

and using the following trigonometric equations:

$$\cos\phi_1 = \cos\theta \cos(\theta - \phi_1) + \sin\theta \sin(\theta - \phi_1) ,$$

$$\sin\phi_1 = \sin\theta \cos(\theta - \phi_1) - \cos\theta \sin(\theta - \phi_1) ,$$

$$\cos\phi_2 = \cos(\theta + \gamma) \cos(\theta + \gamma - \phi_2) + \sin(\theta + \gamma) \sin(\theta + \gamma - \phi_2) ,$$

and

$$\sin\phi_2 = \sin(\theta + \gamma) \cos(\theta + \gamma - \phi_2) - \cos(\theta + \gamma) \sin(\theta + \gamma - \phi_2) ,$$

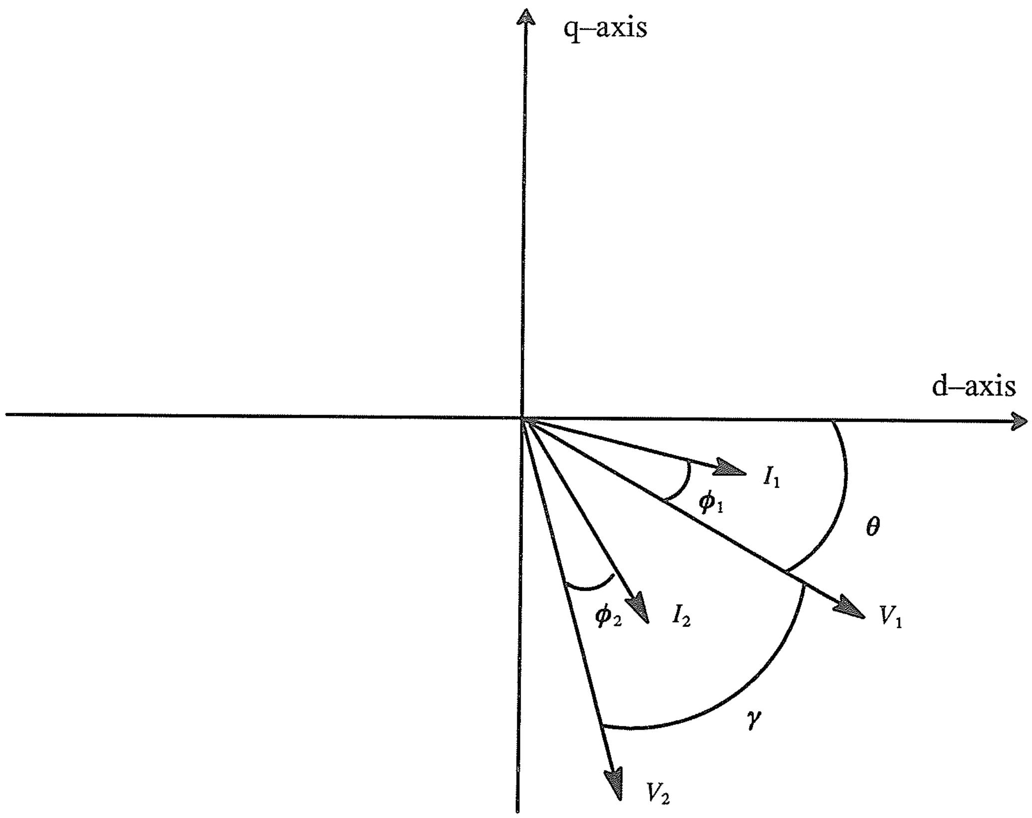


Fig. 2.2 – Phasor diagram of voltages and currents in dq system

the equations for powers could be re–written as follows:

$$P_1 = \frac{1}{2} V_1 I_1 \ [\ \cos\theta \cos(\theta - \phi_1) + \sin\theta \sin(\theta - \phi_1)\ ]$$

$$= \frac{1}{2} [V_1 \cos\theta \ \ I_1 \cos(\theta - \phi_1) + V_1 \sin\theta \ \ I_1 \sin(\theta - \phi_1)]$$

$$= \frac{1}{2} [V_{d1} I_{d1} + V_{q1} I_{q1}] , \tag{2.13}$$

and by the same approach (using proper trigonometric equation from above) ,

$$Q_1 = \frac{1}{2} [V_{q1} I_{d1} - V_{d1} I_{q1}] \tag{2.14}$$

$$P_2 = \frac{1}{2} [V_{d2} I_{d2} + V_{q2} I_{q2}] , \tag{2.15}$$

and finally,

$$Q_2 = \frac{1}{2} [V_{q2} I_{d2} - V_{d2} I_{q2}] . \tag{2.16}$$

2.6 – *Electromechanical Torque*

There is another way to derive the equations for different powers in the machine, by which the equations for the machine torque will be found. In this method total power in the machine is divided to three parts, namely, ohmic loss in the windings, stored energy in machine electromagnetic field, and electromechanical power. The latter could be used to derive the equations for electromechanical torque.

As it was shown before, machine equations can be written in the following form:

$$\mathbf{V} = \mathbf{Z} \,.\, \mathbf{I} \,,$$

it can be shown that the total power in machine is equal to :

$$\mathbf{P} = \mathbf{I}^t \,.\, \mathbf{V} = \mathbf{I}^t \,.\, \mathbf{Z} \,.\, \mathbf{I} \,,$$

in which $\mathbf{I}^t$ is transposed matrix of $\mathbf{I}$. For more convenience, $\mathbf{Z}$ matrix (here $\mathbf{Z}$ is the transformed impedance matrix, as it is the case with $\mathbf{V}$ and $\mathbf{I}$) will be divided to three different matrices, namely:

$$\mathbf{Z} = \mathbf{R} + p\mathbf{M} + \omega \;\mathbf{G} \,,$$

in which:

$$\mathbf{R} = \begin{bmatrix} R_f & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_{kd} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{kq} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_2 \end{bmatrix} ,$$

and:

$$\mathbf{M} = \begin{bmatrix} L_f & M_{fd} & 0 & \sqrt{3/2}M_{1f} & 0 & \sqrt{3/2}M_{2f} & 0 \\ M_{fd} & L_{kd} & 0 & \sqrt{3/2}M_{1d} & 0 & \sqrt{3/2}M_{2d} & 0 \\ 0 & 0 & L_{kq} & 0 & \sqrt{3/2}M_{1q} & 0 & \sqrt{3/2}M_{2q} \\ \sqrt{3/2}M_{1f} & \sqrt{3/2}M_{1d} & 0 & L_{d1} & 0 & M_{dd} & 0 \\ 0 & 0 & \sqrt{3/2}M_{1q} & 0 & L_{q1} & 0 & M_{dq} \\ \sqrt{3/2}M_{2f} & \sqrt{3/2}M_{2k} & 0 & M_{dd} & 0 & L_{d2} & 0 \\ 0 & 0 & \sqrt{3/2}M_{2q} & 0 & M_{dq} & 0 & L_{q2} \end{bmatrix} ,$$

and finally :

$$
\mathbf{G} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\sqrt{3/2}M_{1q} & 0 & -L_{q1} & 0 & -M_{dq} \\
\sqrt{3/2}M_{1f} & \sqrt{3/2}M_{1d} & 0 & L_{d1} & 0 & M_{dd} & 0 \\
0 & 0 & -\sqrt{3/2}M_{2q} & 0 & -M_{dq} & 0 & -L_{q2} \\
\sqrt{3/2}M_{2f} & \sqrt{3/2}M_{2d} & 0 & M_{dd} & 0 & L_{d2} & 0
\end{bmatrix}.
$$

Therefore the total power is:

$$
\mathbf{P} = \mathbf{I}^t \,.\, \mathbf{V} = \mathbf{I}^t \,.\, \mathbf{Z} \,.\, \mathbf{I} \,. = \mathbf{I}^t.\mathbf{R}.\mathbf{I} + \mathbf{I}^t.p\mathbf{M}.\mathbf{I} + \mathbf{I}^t.\omega\ \mathbf{G}\,.\mathbf{I}.
$$

The above power components are:

$\mathbf{I}^t.\mathbf{R}.\mathbf{I}$: Ohmic losses in the machine,

$\mathbf{I}^t.p\mathbf{M}.\mathbf{I}$: Stored energy in the electromagnetic field,

$\mathbf{I}^t.\omega\ \mathbf{G}\,.\mathbf{I}$: Electromechanical power.

Using the following mechanical equation:

$$
T_{em} = \frac{P_{em}}{\omega},
$$

electromechanical torque , T_{em} , will be:

$$
T_{em} = \frac{\mathbf{I}^t.\omega\ \mathbf{G}.\mathbf{I}}{\omega} = \mathbf{I}^t \,.\, \mathbf{G} \,.\, \mathbf{I} \,.
$$

G being defined in above, and knowing that:

$$
\mathbf{I}^t = \begin{bmatrix} i_f & i_{kd} & i_{kq} & i_{d1} & i_{d2} & i_{q1} & i_{q2} \end{bmatrix},
$$

the result of multiplication is:

$$
T_{em} = \mathbf{I}^t \,.\, \mathbf{G}\,.\mathbf{I}
$$

$$
= -i_{d1}[\ \sqrt{3/2}M_{1q}\ i_{kq} + L_{q1}i_{q1} + M_{dq}\ i_{q2}]
$$

$$
+\, i_{q1}[\ \sqrt{3/2}M_{1f}\ i_f + \sqrt{3/2}M_{1d}\ i_{kd} + L_{d1}\ i_{d1} + M_{dd}\ i_{d2}]
$$

$$-i_{d2}[\sqrt{3/2}M_{2q}\ i_{kq}+M_{dq}\ i_{q1}+L_{q2}\ i_{q2}]$$

$$+i_{q2}[\sqrt{3/2}M_{2f}\ i_f+\sqrt{3/2}M_{2d}\ i_{kd}+M_{dd}\ i_{d1}+L_{d2}\ i_{d2}]\ ,$$

or:

$$T_{em}=i_{q1}\lambda_{d1}+i_{q2}\lambda_{d2}-i_{d1}\lambda_{q1}-i_{d2}\lambda_{q2}\ , \tag{2.17}$$

in which:

$$\lambda_{d1}=\sqrt{3/2}M_{1f}\ i_f+\sqrt{3/2}M_{1d}\ i_{kd}+L_{d1}\ i_{d1}+M_{dd}\ i_{d2}, \tag{2.18}$$

$$\lambda_{d2}=\sqrt{3/2}M_{2f}\ i_f+\sqrt{3/2}M_{2d}\ i_{kd}+M_{dd}\ i_{d1}+L_{d2}\ i_{d2}, \tag{2.19}$$

$$\lambda_{q1}=\sqrt{3/2}M_{1q}\ i_{kq}+L_{q1}i_{q1}+M_{dq}\ i_{q2}, \tag{2.20}$$

and,

$$\lambda_{q2}=\sqrt{3/2}M_{2q}\ i_{kq}+M_{dq}\ i_{q1}+L_{q2}\ i_{q2}. \tag{2.21}$$

2.7 – Equivalent Circuits of the Machine

It is a common practice to find an equivalent circuit for a machine. These circuits satisfy the equations of the particular machine being studied, and are often of assistance in obtaining numerical results. Equivalent circuits are of particular value for AC problems, for which the numerical results can be obtained either by digital or with the aid of analog means [8].

Before deriving equivalent circuits, one assumption must be made. The equivalent equations so far derived for machine hold whether or not the quantities are in a per–unit basis. They become easier to handle, however, if per–unit values are used, and , in addition, if it is assumed that the four per–unit mutual inductances on direct axis are all equal (the same assumption holds for the two mutual inductances on quadrature axis). The assumption is very nearly true for a normal synchronous machine, because the leakage fluxes of the field coil and damper bars are distinct and there is a single main flux linking them and the armature windings [8].

Using the equations derived in Section 2.4, and considering the above assumption, following circuits are developed for direct and quadrature axes, separately:

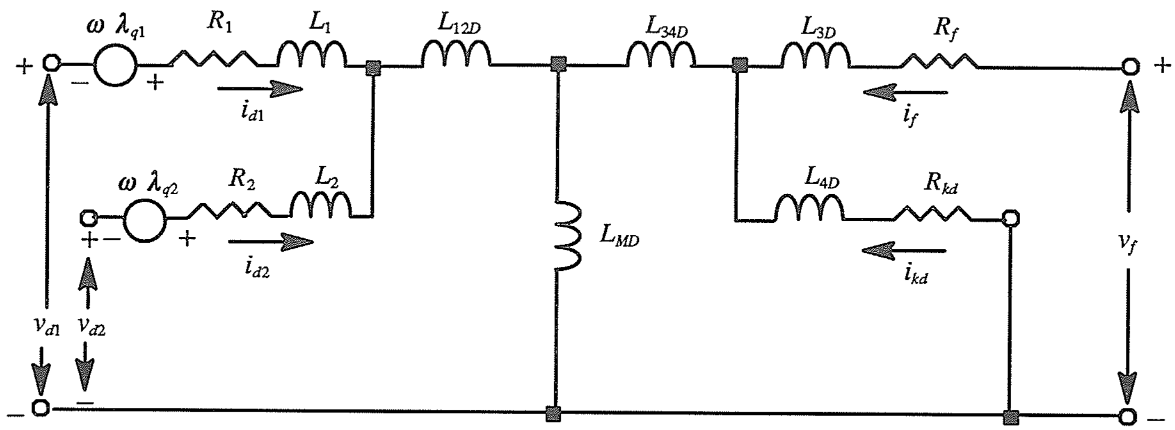


Fig. 2.3 – Equivalent circuit for direct axis

and:

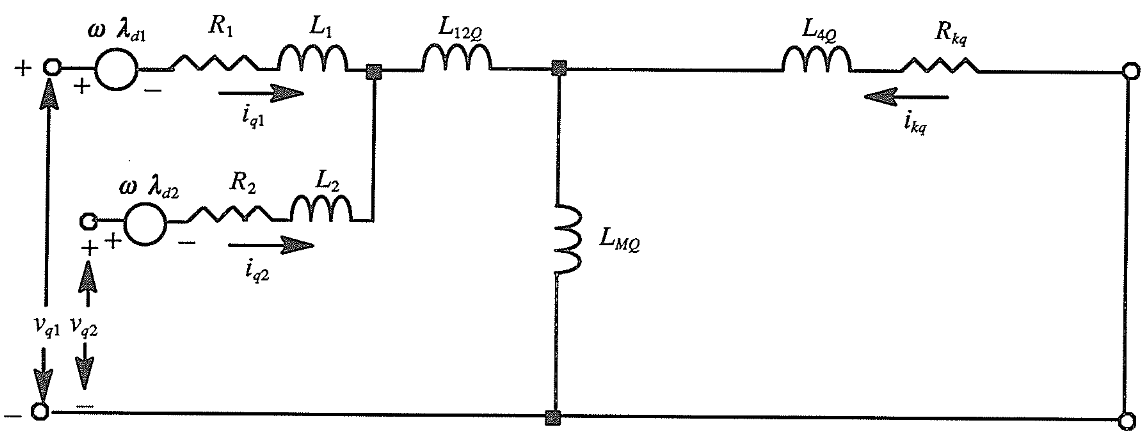


Fig. 2.4 – Equivalent circuit for quadrature axis

In the above equivalent circuits, the separation of circuits for direct and quadrature axes has been made possible by defining speed voltages $\omega\lambda_{d1}$, $\omega\lambda_{d2}$, $\omega\lambda_{q1}$, and $\omega\lambda_{q2}$, which are as follows:

$$\omega\lambda_{d1} = \omega\ [\ L_1 i_{d1} + L_{12D}(i_{d1} + i_{d2}) + L_{MD}(i_{d1} + i_{d2} + i_f + i_{kd})\ ]$$

$$= \omega\ [\ (L_1 + L_{12D} + L_{MD}) i_{d1} + (L_{12D} + L_{MD}) i_{d2} + L_{MD} i_f + L_{MD} i_{kd}\ ], \quad (2.22)$$

$$\omega\lambda_{d2} = \omega\ [\ L_2 i_{d2} + L_{12D}(i_{d1} + i_{d2}) + L_{MD}(i_{d1} + i_{d2} + i_f + i_{kd})\ ]$$

$$= \omega \; [\; (L_2 + L_{12D} + L_{MD})i_{d2} + (L_{12D} + L_{MD})i_{d1} + L_{MD}i_f + L_{MD}i_{kd} \;] \, , \quad (2.23)$$

$$\omega\lambda_{q1} = \omega \; [\; L_1 i_{q1} + L_{12Q}(i_{q1} + i_{q2}) + L_{MQ}(i_{q1} + i_{q2} + i_{kq}) \;]$$

$$= \omega \; [\; (L_1 + L_{12Q} + L_{MQ})i_{q1} + (L_{12Q} + L_{MQ})i_{q2} + L_{MQ}i_{kq} \;] \, , \qquad (2.24)$$

$$\omega\lambda_{q2} = \omega \; [\; L_2 i_{q2} + L_{12Q}(i_{q1} + i_{q2}) + L_{MQ}(i_{q1} + i_{q2} + i_{kq}) \;]$$

$$= \omega \; [\; (L_2 + L_{12Q} + L_{MQ})i_{q2} + (L_{12Q} + L_{MQ})i_{q1} + L_{MQ}i_{kq} \;] \; . \qquad (2.25)$$

If the ohmic voltage drop in each loop is pulled out from right–hand side of the equations to the left–hand aside, the equations will be simplified, and the new equations, governing the behavior of the machine in dq system will be as follows:

$$\begin{bmatrix} v_{d1} + \omega\lambda_{q1} - R_1 i_{d1} \\ v_{d2} + \omega\lambda_{q2} - R_2 i_{d2} \\ v_f - R_f i_f \\ 0 - R_{kd} i_{kd} \end{bmatrix} = \begin{bmatrix} & & \\ & L_D & \\ & & \end{bmatrix} p \begin{bmatrix} i_{d1} \\ i_{d2} \\ i_f \\ i_{kd} \end{bmatrix} , \qquad (2.26)$$

and :

$$\begin{bmatrix} v_{q1} - \omega\lambda_{d1} - R_1 i_{q1} \\ v_{q2} - \omega\lambda_{d2} - R_2 i_{q2} \\ 0 - R_{kq} i_{kq} \end{bmatrix} = \begin{bmatrix} & & \\ & L_Q & \\ & & \end{bmatrix} p \begin{bmatrix} i_{q1} \\ i_{q2} \\ i_{kq} \end{bmatrix} . \qquad (2.27)$$

By equating the L_D and L_Q matrices with previously developed formulas for the machine, parameters in these matrices will be found according to actual parameters in the machine. The process is as follows:

$$\begin{bmatrix} L_{MD} + L_{12D} + L_1 & L_{MD} + L_{12D} & L_{MD} & L_{MD} \\ L_{MD} + L_{12D} & L_{MD} + L_{12D} + L_2 & L_{MD} & L_{MD} \\ L_{MD} & L_{MD} & L_{MD} + L_{34D} + L_{3D} & L_{MD} + L_{34D} \\ L_{MD} & L_{MD} & L_{MD} + L_{34D} & L_{MD} + L_{34D} + L_{4D} \end{bmatrix} = \begin{bmatrix} L_{d1} & M_{dd} & \sqrt{3/2}\,M_{1f} & \sqrt{3/2}\,M_{1d} \\ M_{dd} & L_{d2} & \sqrt{3/2}\,M_{2f} & \sqrt{3/2}\,M_{2d} \\ \sqrt{3/2}\,M_{1f} & \sqrt{3/2}\,M_{2f} & L_f & M_{fd} \\ \sqrt{3/2}\,M_{1d} & \sqrt{3/2}\,M_{2d} & M_{fd} & L_{kd} \end{bmatrix} ,$$

and:

$$\begin{bmatrix} L_{MQ} + L_{12Q} + L_1 & L_{MQ} + L_{12Q} & L_{MQ} \\ L_{MQ} + L_{12Q} & L_{MQ} + L_{12Q} + L_2 & L_{MQ} \\ L_{MQ} & L_{MQ} & L_{MQ} + L_{4Q} \end{bmatrix} = \begin{bmatrix} L_{q1} & M_{dq} & \sqrt{3/2}\,M_{1q} \\ M_{dq} & L_{q2} & \sqrt{3/2}\,M_{2q} \\ \sqrt{3/2}\,M_{1q} & \sqrt{3/2}\,M_{2q} & L_{kq} \end{bmatrix} ,$$

from which:

$$L_{MD}+L_{12D}+L_1=L_{d1}=L_{01}+M_{01}+1/2\ L_{21}+M_{21},$$

$$L_{MD}+L_{12D}+L_2=L_{d2}=L_{02}+M_{02}+1/2\ L_{22}+M_{22},$$

$$L_{MD}+L_{34D}+L_{3D}=L_f,$$

$$L_{MD}+L_{34D}+L_{4D}=L_{kd},$$

$$L_{MD}+L_{12D}=M_{dd}=3/2\ M_0+M_2\cos\gamma,$$

$$L_{MD}=\sqrt{3/2}M_{1f}=\sqrt{3/2}M_{2f}=\sqrt{3/2}M_{1d}=\sqrt{3/2}M_{2d},$$

and:

$$L_{MQ}+L_{12Q}+L_1=L_{q1}=L_{01}+M_{01}-1/2\ L_{21}-M_{21},$$

$$L_{MQ}+L_{12Q}+L_2=L_{q2}=L_{02}+M_{02}-1/2\ L_{22}-M_{22},$$

$$L_{MQ}+L_{4Q}=L_{kq},$$

$$L_{MQ}+L_{12Q}=M_{dq}=3/2\ M_0-M_2\cos\gamma,$$

$$L_{MQ}=\sqrt{3/2}M_{1q}=\sqrt{3/2}M_{2q}.$$

In above equations, parameters in right–hand side are the same parameters which were defined in Section 2.3.

2.8 – Mechanical Dynamics of the Machine

The electromechanical equations for a synchronous machine can be found directly from equating the inertia torque (equal to the moment of inertia, J, times the angular acceleration) to the net mechanical and electromechanical torque acting on the rotor [9]. Thus:

$$J\frac{d^2\theta}{dt^2}=T_{em}-T_{mech.}-D\frac{d\theta}{dt},$$

where:

θ = angular position of the rotor,

T_{em} = electromechanical torque accelerating the rotor,

$T_{mech.}$ = mechanical load torque on the shaft,

and, D = damping coefficient.

The above equation is written for the motor operation and the same equation can be written for the generator operation by changing the signs of T_{em} and $T_{mech.}$.

Therefore, the rate of change of the rotor speed, $\frac{d\omega}{dt} = \frac{d^2\theta}{dt^2}$, will be found as:

$$\frac{d\omega}{dt} = \frac{T_{em} - T_{mech.} - D\omega}{J}. \tag{2.28}$$

The above equation for $\frac{d\omega}{dt}$ will be used later, in modeling the machine, to calculate ω at any time.

2.9 – *Experimental Observations*

Some experimental observations were conducted on a dual wound synchronous machine, with $\gamma = 30^o$. The aim was to observe the steady–state behavior of the machine, as well as the form of some of its important parameters. The parameters being studied were M_{ab}, M_{ax}, and M_{az}. Other parameters of machine are well–discussed and observed in literature and numerous studies. To measure the values of the above parameters, along with their variations with the position of the rotor, θ, the following circuit was used:

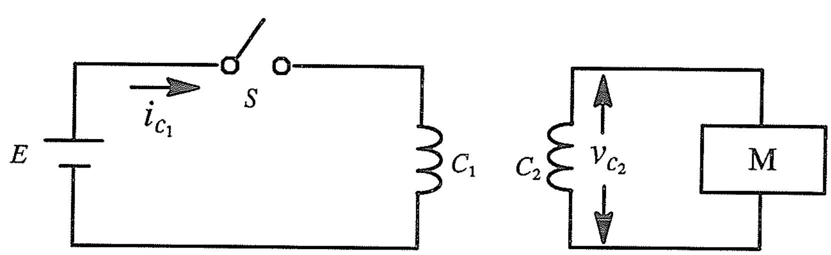


Fig. 2.5 – Circuit for measuring mutual inductances

in which C_1 is coil a in set number 1, and C_2 is the coil whose mutual inductance with a is being studied. At time t_0 S is closed and it remains closed until i_{c_1} reaches to its final value. M is a digital oscilloscope which measures the voltage of the second coil and calculates its integral from t_0 to ∞ . Since :

$$v_{c_2} = M_{c_1c_2} \frac{di_{c_1}}{dt},$$

the mutual inductance $M_{c_1c_2}$ is found from the following equation:

$$M_{c_1c_2} = \frac{\int_{t_0}^{\infty} v_{c_2}\, dt}{I_{c_1}}, \tag{2.29}$$

where I_{c_1} is the change in the value of the current in coil C_1 because of closing the switch S. In other words:

$$I_{c_1} = i_{c_1}(\infty) - i_{c_1}(\ t_0\ ).$$

The values of M_{ab} , M_{ax} , and M_{az} , were found at ten different θ's and are presented in Table 2.1.

Table 2.1 – Measured values for M_{ab} , M_{ax} , M_{az}

θ \ M	M_{ab} (mH)	M_{ax} (mH)	M_{az} (mH)
0	−0.325	0.550	−0.600
20	−0.200	0.450	−0.550
40	−0.140	0.270	−0.475
60	−0.130	0.243	−0.380
80	−0.170	0.243	−0.270
100	−0.240	0.312	−0.210
120	−0.360	0.432	−0.250
140	−0.370	0.502	−0.300
160	−0.380	0.582	−0.470
180	−0.300	0.542	−0.580

The data were analyzed by two methods. First, by Fourier Discrete Transform (FDT) the magnitude and the phase–shift of a sine–wave were found. Then by averaging the data, the vertical shift of the sine–wave, with respect to θ – axis, was found.The results of analysis, along with the formulas for each mutual inductance, proposed in Section 2.3, are presented here. The sine–waves derived for M_{ab}, M_{ax}, and M_{az}, along with the specific points derived from the experiment, are presented in Fig. 2.6, Fig. 2.7, and Fig. 2.8, respectively.

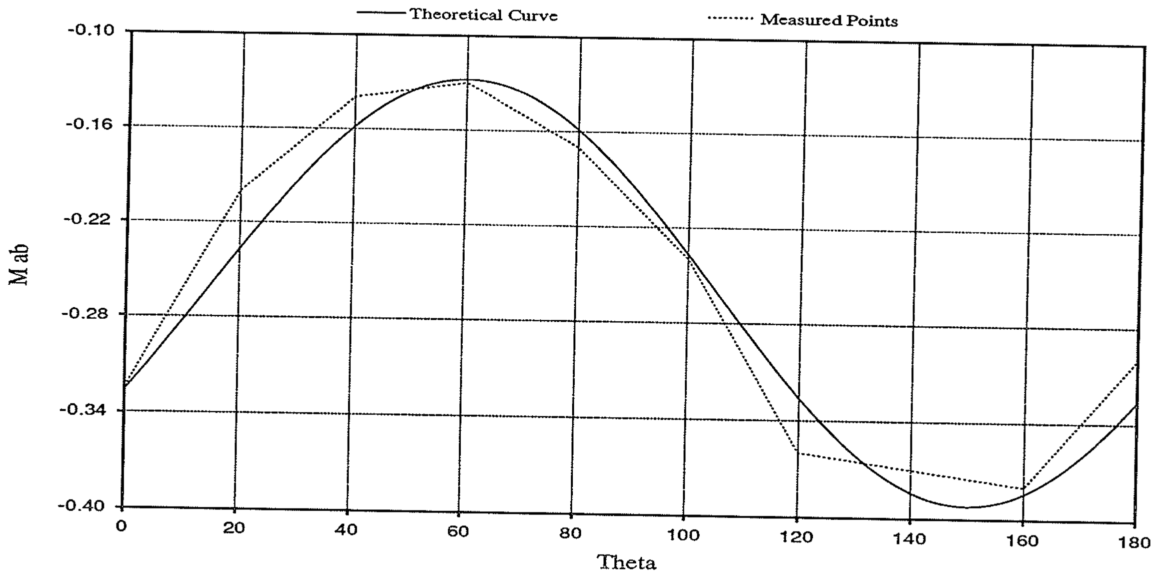
a. M_{ab}

Theoretical formula: $M_{ab} = -M_{01} + M_{21} \cos(2\theta - 120^o)$,

Results of analysis: $M_{01} = 0.26$ mH , $M_{21} = 0.132$ mH , phase shift = 110.5^o.

Derived points are in good vicinity of the derived sine–wave, and the biggest difference is 17% at $\theta = 20^o$.

Fig. 2.6 - Mutual Inductance of a and b



b. M_{ax}

Theoretical formula: $M_{ax} = M_0 \cos\gamma + M_2 \cos\gamma \; . \; \cos(2\theta + \gamma)$,

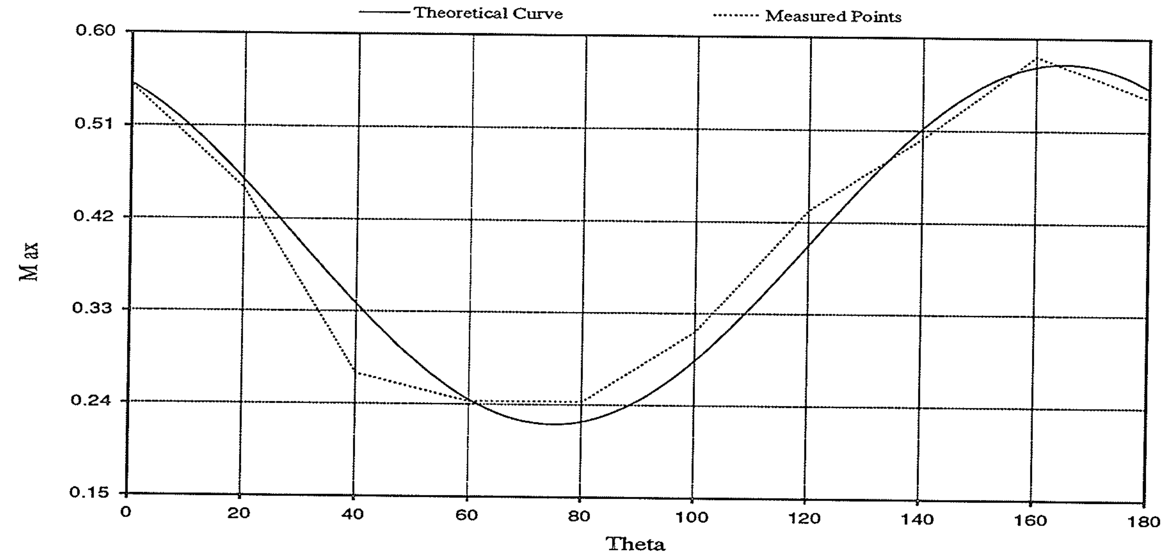
Results of analysis: $M_0 \cos\gamma = 0.398$ mH $\Rightarrow$ $M_0 = 0.459$ mH,

$M_2 \cos\gamma = 0.177$ mH $\Rightarrow$ $M_2 = 0.2044$,

phase–shift = 30^o.

The biggest difference is 20% at $\theta = 40^o$, but other points are very close to the sine–wave.

Fig. 2.7 - Mutual Inductance of a and x

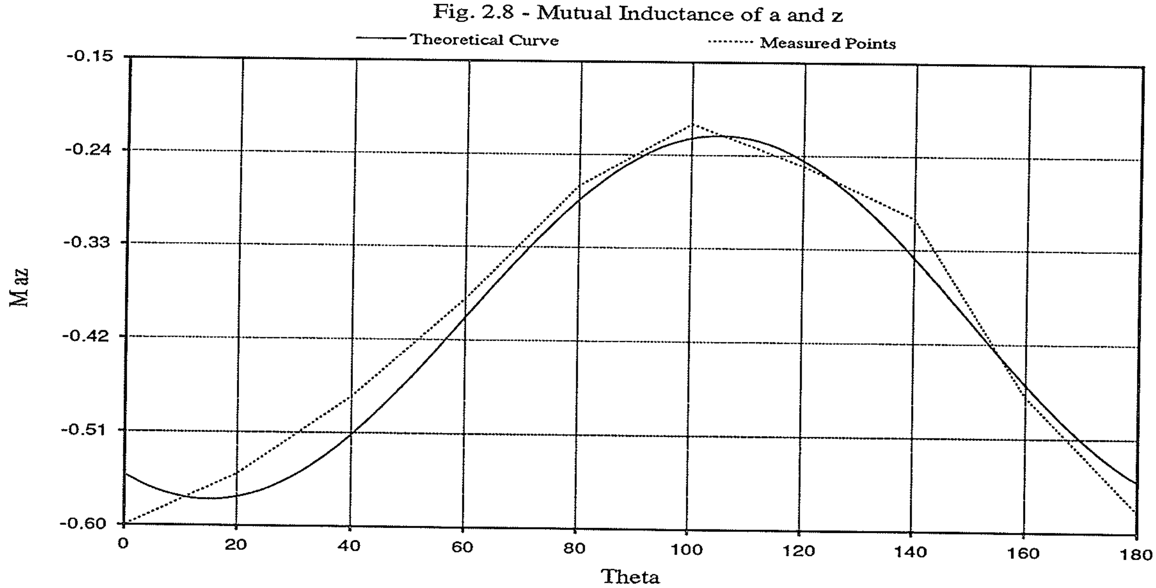


c. M_{az}

Theoretical formula: $M_{az} = -M_0 \cos(\gamma - 60^o) + M_2 \cos(\gamma - 60^o) \ . \ \cos(2\theta + \gamma + 120^o)$.

For this parameter, instead of analyzing the data, the results of analysis for M_{ax} were used. The accordance between derived points and the sine–wave is perfect, and the biggest difference is 9% at $\theta = 0^o$.

Fig. 2.8 - Mutual Inductance of a and z



The above results and discussions ensure the validity and reliability of the formulas introduced to represent various parameters within the machine.

2.10 – Summary of the Chapter

In this chapter, the dual wound synchronous machine was studied from the circuit point of view. Using the techniques of the unified theory of electric machines, the general formulas governing the behavior of the machine, as well as its equivalent circuits, were derived. At the end, some experimental observations were conducted, and as a result, the validity of formulas introduced to represent various parameters within the machine was verified.

Chapter Three

Simulation of the Dual Wound Synchronous Machine

3.1 – Introduction

Digital simulation of power systems is one of the most advanced techniques developed for analyzing the performance of different elements of power systems, individually or in the form of a combination of them, and is made feasible by great improvements in the existing computers. The need for such simulations rise from several facts, amongst which these are the most important ones:

– Analysis and pre–determination of the response of large power system elements, such as generators or transmission lines, to different disturbances or different load conditions is not feasible in real systems.

– Considering the huge growth in the size and in the number of elements in existing power systems, optimal operation of these systems, economically and technically, is a must. This can not be achieved without analyzing different schemes in the design phase, which in turn, is not possible without digital simulation,

and,

– It is not always possible to observe the internal characteristics and conditions of power system elements.

The main idea and background for digital simulation of electromagnetic transients was presented by H. W. Dommel in the April of 1969 issue of IEEE Transactions on PAS. Since then, considerable improvements have been achieved in digital simulation of power systems, by which the design of power systems, as well as the commissioning of these systems, has improved drastically.

In this chapter, the different steps of modeling the dual wound synchronous machine, based on the well–known simulation techniques, will be discussed and at the end, some of the results of such a simulation will be presented.

3.2 – EMTDC Program

Based on the inspirations of H. W. Dommel, the creation and completion of the Electromagnetic Transient DC program, EMTDC, has been going on jointly at Manitoba Hydro, Manitoba HVDC Research Center, and The University of Manitoba since 1976 [10]. During the years, lots of contributions and enhancements have been made to EMTDC to enforce its ability to analyze various power system elements. In the current study, a compatible subroutine, which is developed to analyze the transient performance of the dual wound synchronous machine will be presented.

EMTDC is a software package which simulates the power system in time domain. The algorithm and the location of different subroutines and files inside the program is shown in Fig. 3.1. The program is written in FORTRAN codes [11]. The general architecture of the machine, used to run EMTDC at the Manitoba HVDC Research Center, is shown in Fig. 3.2. Developed subroutines for different power system elements can be regarded as a PE module.

The key to creating models of dynamic systems with EMTDC is through the construction and use of subroutines. A library of subroutines is available for many requirements of AC and DC power systems modeling. If special models, functions, or algorithms are needed, the user can construct them. A user–written subroutine known as DSDYN controls the dynamics of a simulation. Using FORTRAN statements, the user may call any of the available subroutines or functions supplied with EMTDC, or may develop new routines if these are not suitable [10].

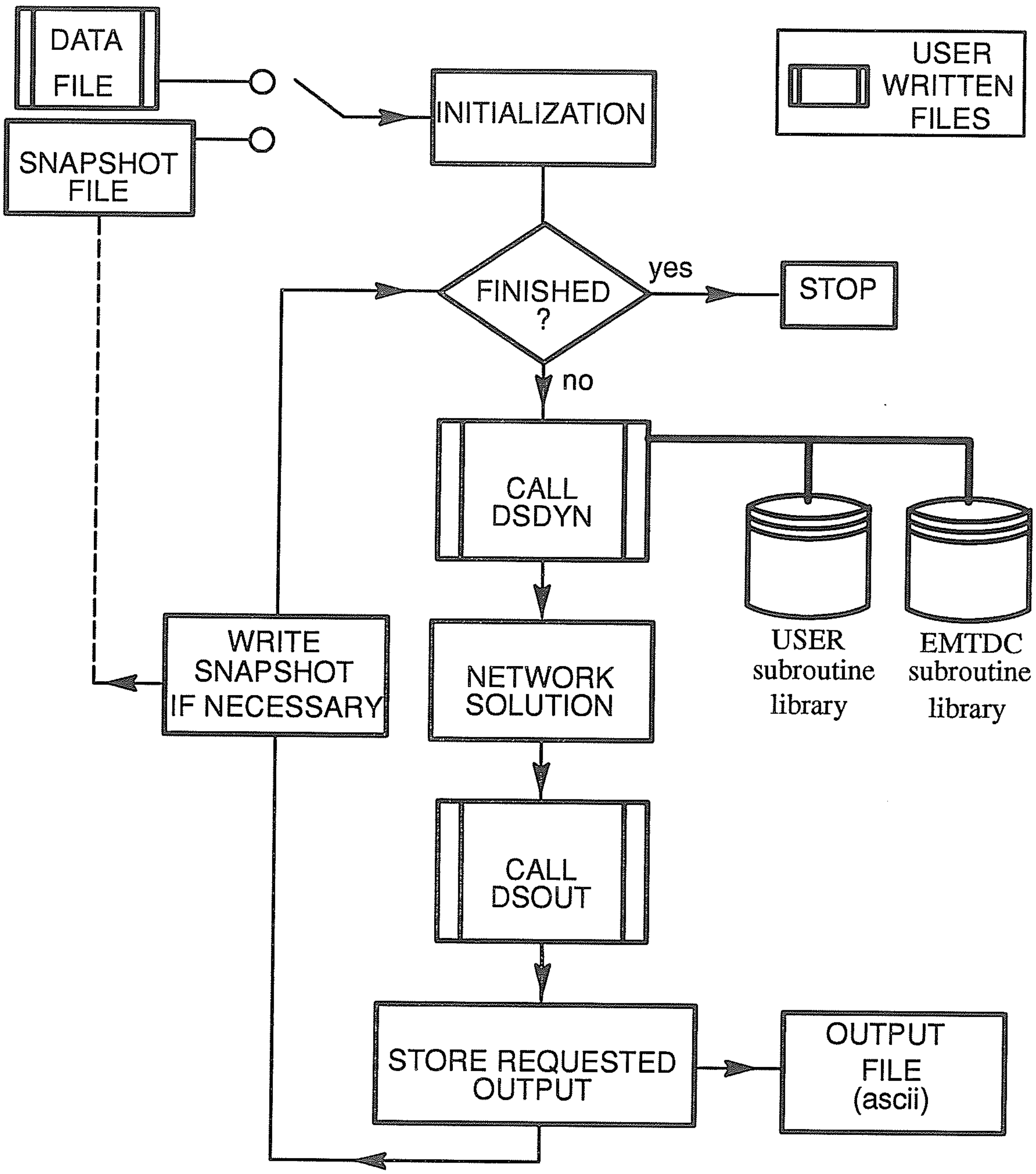


Fig. 3.1 – Simplified EMTDC Algorithm Flow Chart [11]

The data, necessary to run the program, such as time step, duration of analysis, number of sub–systems being studied, existing elements in each sub–system, etc., along with the number of outputs and data about specific power system elements are fed to program through a datafile. The results of simulation, through the defined output channels, will be written in an output or snapshot file. And finally, the number, the nature, and the transmission of output variables is monitored by another user–written subroutine known as DSOUT.

Further details concerning the principles and methods used in EMTDC, along with instructions for using different aspects of this program, can be found in reference [10].

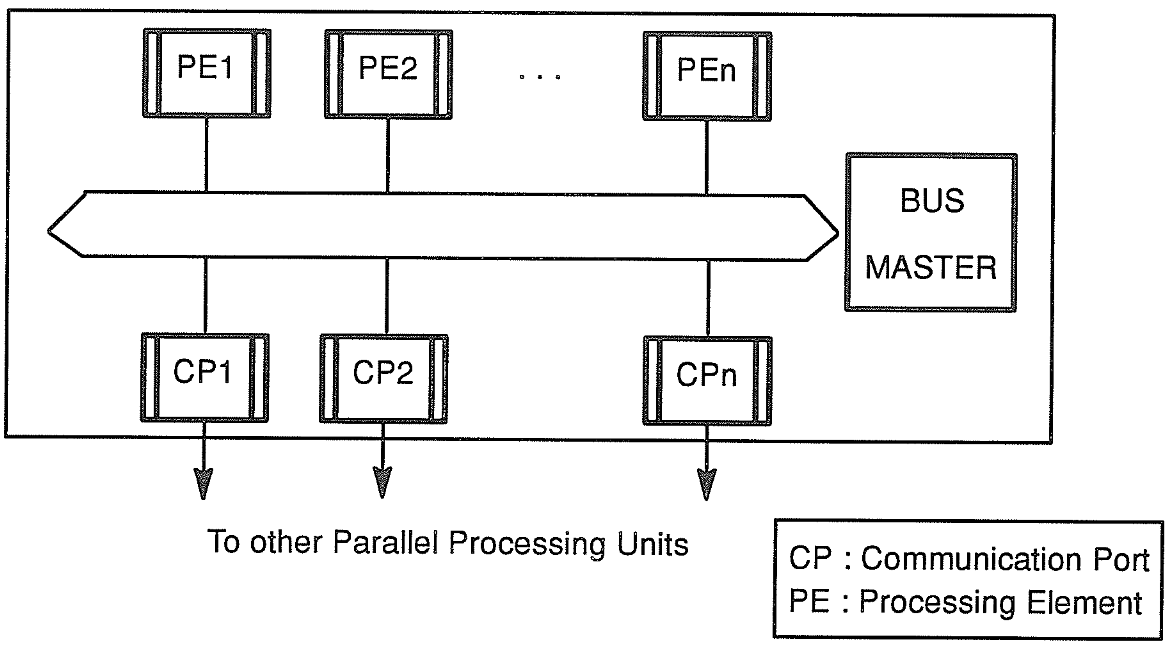


Fig. 3.2 – Digital Simulator , Parallel Processing Unit [11]

3.3 – Machine Equations

Based on the results of analysis of the dual wound synchronous machine in Chapter two, the following equations are used to simulate the machine.

$$\frac{d}{dt}\begin{bmatrix} i_{d1} \\ i_{d2} \\ i_f \\ i_{kd} \end{bmatrix} = \mathbf{L}_D^{-1}\begin{bmatrix} \omega\lambda_{q1} - R_1 i_{d1} \\ \omega\lambda_{q2} - R_2 i_{d2} \\ -R_f i_f \\ -R_{kd} i_{kd} \end{bmatrix} + \mathbf{L}_D^{-1}\begin{bmatrix} v_{d1} \\ v_{d2} \\ v_f \\ 0 \end{bmatrix}, \tag{3.1}$$

and,

$$\frac{d}{dt}\begin{bmatrix} i_{q1} \\ i_{q2} \\ i_{kq} \end{bmatrix} = \mathbb{L}_Q^{-1}\begin{bmatrix} -\omega\lambda_{d1} - R_1 i_{q1} \\ -\omega\lambda_{d2} - R_2 i_{q2} \\ -R_{kq} i_{kq} \end{bmatrix} + \mathbb{L}_Q^{-1}\begin{bmatrix} v_{q1} \\ v_{q2} \\ 0 \end{bmatrix}, \tag{3.2}$$

in which $\mathbb{L}_D^{-1}$ and $\mathbb{L}_Q^{-1}$ are inverse matrices of $\mathbb{L}_D$ and $\mathbb{L}_Q$, respectively, and :

$$\mathbb{L}_D = \begin{bmatrix} L_{MD}+L_{12D}+L_1 & L_{MD}+L_{12D} & L_{MD} & L_{MD} \\ L_{MD}+L_{12D} & L_{MD}+L_{12D}+L_2 & L_{MD} & L_{MD} \\ L_{MD} & L_{MD} & L_{MD}+L_{34D}+L_{3D} & L_{MD}+L_{34D} \\ L_{MD} & L_{MD} & L_{MD}+L_{34D} & L_{MD}+L_{34D}+L_{4D} \end{bmatrix},$$

and,

$$\mathbb{L}_Q = \begin{bmatrix} L_{MQ}+L_{12Q}+L_1 & L_{MQ}+L_{12Q} & L_{MQ} \\ L_{MQ}+L_{12Q} & L_{MQ}+L_{12Q}+L_2 & L_{MQ} \\ L_{MQ} & L_{MQ} & L_{MQ}+L_{4Q} \end{bmatrix}.$$

λ_{d1}, λ_{d2}, λ_{q1}, and λ_{q2} are the same as those defined in equations (2.22), (2.23), (2.24), and (2.25), respectively.

Equations (3.1) and (3.2) are directly derived from equations (2.26) and (2.27), respectively, and have made it possible to express the machine equations in the standard State Variable form of:

$$\dot{\mathbb{X}} = \mathbb{A}\mathbb{X} + \mathbb{B}\mathbb{V} \tag{3.3}$$

in which the state vector $\mathbb{X}$ consists of the currents, and the input vector $\mathbb{V}$ consists of applied voltages.

Also the following equations, derived in Chapter two, are used to find the complete solution for the machine operation:

$$T_{em} = i_{q1}\,\lambda_{d1} + i_{q2}\,\lambda_{d2} - i_{d1}\,\lambda_{q1} - i_{d2}\,\lambda_{q2} \tag{3.4}$$

for electromechanical torque in the machine, and,

$$\frac{d\omega}{dt} = \frac{T_{em} - T_{mech.} - D\omega}{J} \tag{3.5}$$

for mechanical dynamics of the machine. And finally, equations (2.13), (2.14), (2.15), and (2.16) will be used to find P_1, Q_1, P_2, and Q_2, respectively.

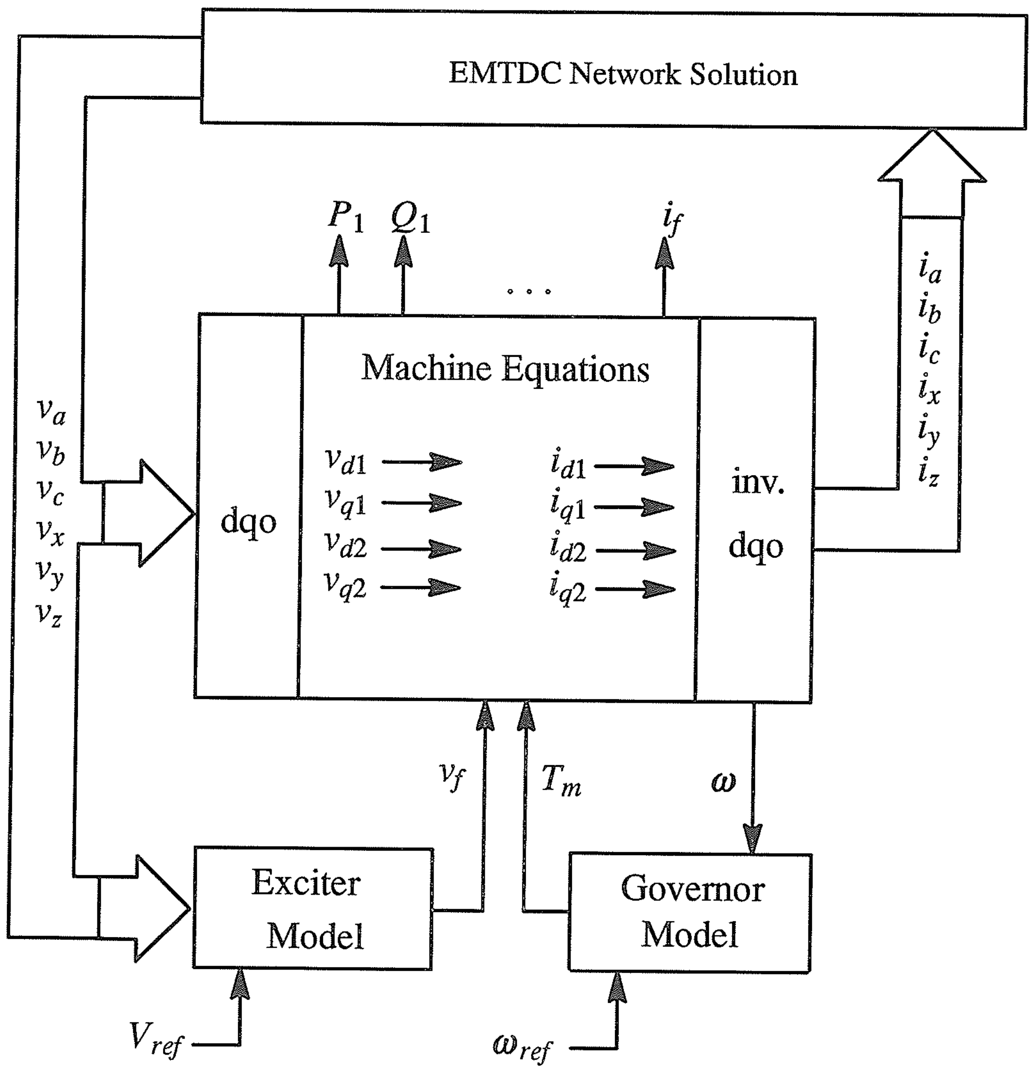


Fig. 3.3 – Model Scheme for Dual wound Synchronous Machine [10]

3.4 – Interfacing the Machine Model to EMTDC

The model derived for the dual wound synchronous machine in the current study is essentially identical to the model of ordinary synchronous machine existing in EMTDC, while the necessary modifications and additions are made to adopt the model to the new conditions and requirements.

In this model, the machine is represented as a current source into the EMTDC network. In this approach, terminal voltages are used to calculate the currents to be injected to the system [10].

Interfacing of the dual wound synchronous machine to the EMTDC program is shown in Fig. 3.3. The machine is terminated to the network through its characteristic impedance. The reason why this type of connection is chosen is discussed in details in reference [10] and will not be repeated here.

3.5 – Interfacing with Mechanical and Control System

Unlike the synchronous machine model in EMTDC, which was essentially written for synchronous generators and using it for simulation of synchronous motors necessitates some minor modifications in the mechanical dynamics part of the program, the model developed for dual wound synchronous machine has the ability to be used for both cases. The three possible cases, as they are introduced at the beginning of the program, are:

a) Motor– Generator case (M– G)

In this case, one set of the stator windings is connected to a three–phase voltage source, and therefore acting in the motor mode. The other set of the stator windings will be in the generator mode and a three–phase voltage system, displaced by γ, with respect to the voltage source, will be generated in it. In this case, there is no need to govern the machine, and mechanical dynamics will be automatically determined within the program. The field voltage will be determined by system studies, i.e., the required level of reactive power generation or consumption.

b) Generator– Generator case (G– G)

In this case, machine shaft will be driven by a prime–mover and the input mechanical torque to the machine will be determined by the governor model, which in turn, uses the speed of the rotor, ω , as feedback. Two sets of three–phase voltages, displaced by γ , will be generated in the stator windings, and the level of the generated voltages, along with the amount of reactive power, will be determined by the exciter model. This mode of operation is of particular value for feeding 12 pulse rectifiers, which must be fed by two separate three–phase voltage sets.

c) Motor – Motor case (M–M)

In this case, machine is fed by the output of a 12 pulse inverter, and the mechanical dynamics will be determined within the program.

Fig. 3.3 depicts the complete connection of the machine with exciter and governor models and with the EMTDC network.

3.6 – Programming

In this section, the programs written to model the machine will be introduced. The FORTRAN codes are presented in Appendix A. The main program, which contains the formulas of the machine, is subroutine DBLSYNC100. There are five support subroutines which help the main program in calculating different necessary parameters. These subroutines are presented in two parts as follows.

3.6.1 – Subroutine DBLSYNC100

Fig. 3.4 shows the flow chart of DBLSYNC100. The location of different parameters of the machine in the array STOR(NEXC+ i), i=1,100, is shown in Table 3.1. These parameters are used and/or updated throughout the main program and the support subroutines. In this

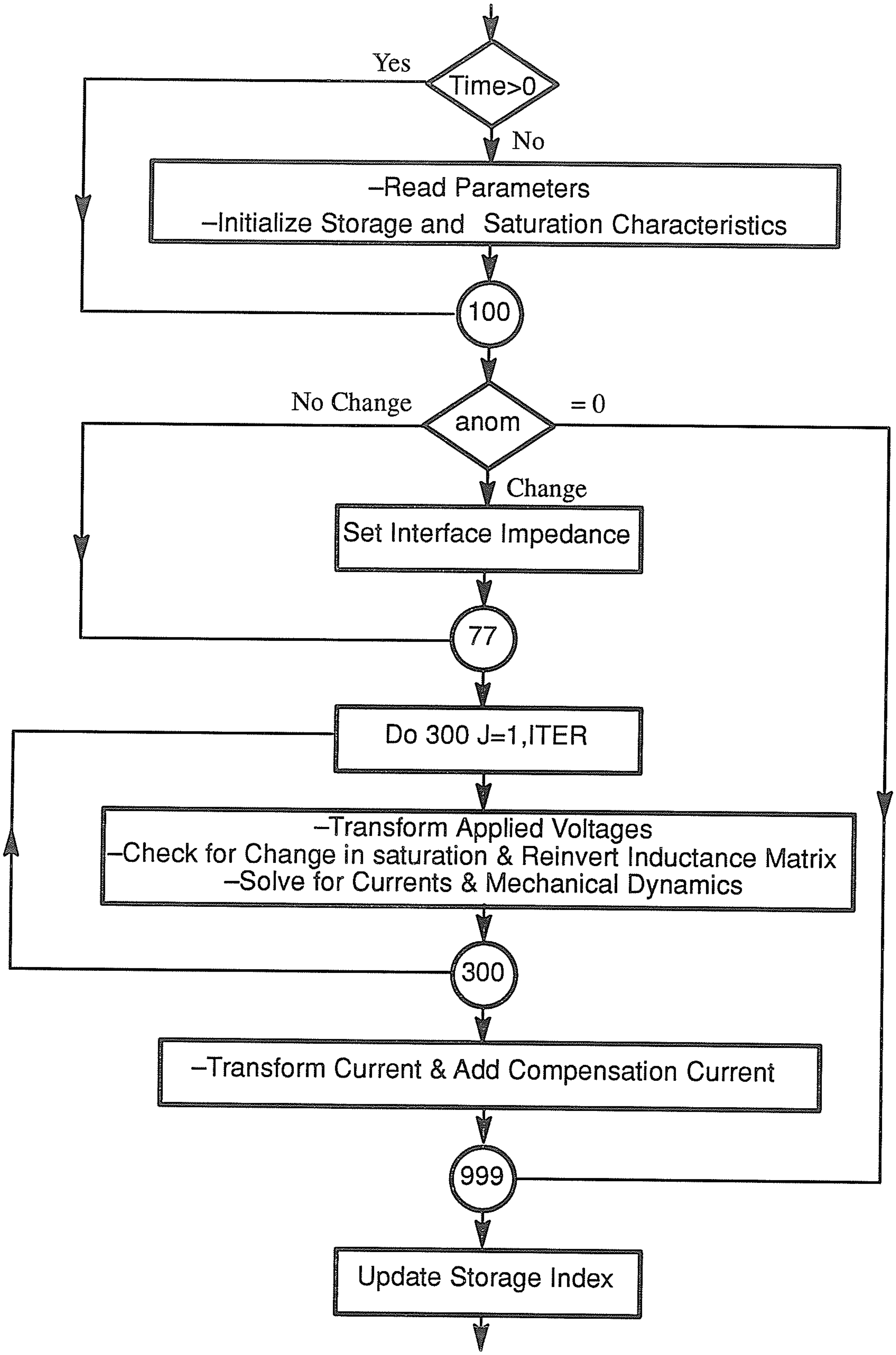


Fig. 3.4 – Flow chart for DBLSYNC100 [10]

Table 3.1 - Locations of different variables of DBLSYNC100

Location		Variable	Description
1.	(31)	-XM	Direct(Quad.)-axis saturated mutual reactance
2.	(32)	-X34	Direct(Quad.)-axis rotor mutual reactance
3.		-X3	field reactance
4.	(34)	-X4	Direct(Quad.)-axis damper reactance
5.		-R3	field resistance
6.	(36)	-R4	Direct(Quad.)-axis damper resistance
7.	(37)	-U1	Direct(Quad.)-axis stator voltage
8.	(38)	-U2	Direct(Quad.)-axis Stator voltage
9.		-UF	field voltage
10.	(40)	-UK	Direct(Quad.)-axis damper applied voltage
11.	(41)	-I1	Direct(Quad.)-axis stator current
12.	(42)	-I2	Direct(Quad.)-axis stator current
13.	(43)	-I3	field (Quad.-axis damper) current
14.		-I4	Direct-axis damper current
15.	(45)	-XIN(1,1)	}
16.	(46)	-XIN(1,2)	}
17.	(47)	-XIN(1,3)	}
18.	(48)	-XIN(1,4)	}
19.	(49)	-XIN(2,2)	} inverted
20.	(50)	-XIN(2,3)	} reactance matrix
21.	(51)	-XIN(2,4)	}
22.	(52)	-XIN(3,3)	}
23.	(53)	-XIN(3,4)	}
24.	(54)	-XIN(4,4)	}
25.	(55)	-PSI1	Direct(Quad.)-axis flux linkage
26.	(56)	-PSI2	Direct(Quad.)-axis flux linkage
27.	(57)	-X12	Direct(Quad.)-axis stator mutual reactance
28.		-IA	phase a stator current
29.		-IX	phase x stator current
30.		-NU	per-unit speed
58.		-J	polar moment of inertia (p.u.)
59.		-D	mechanical damping
60.		-OMO	base radian frequency
61-80.		-(SFM,IM)	mutual saturation curve
81.		-TE	electromechanical torque
82.		-H	inertia constant
83.		-R1	stator resistance
84.		-R2	stator resistance
85.		-GG1N	compensating conductance
86.		-GG2N	compensating conductance
87.		-ANOM	subroutine's activating signal
88.		-X1	stator reactance
89.		-X2	stator reactance
90.		-XMDO	unsaturated value of XM
91.		-VBASE1	base stator voltage
92.		-VBASE2	base stator voltage
93.		-ABASE1	base stator current
94.		-ABASE2	base stator current
95.		-FB	base field current
96.		-THETA	machine angle
97.		-SFM	mutual reactance saturation factor
98.		-GAMA	phase shift between two sets (rad.)
99-100.		-spare	

table storage locations for variables 1 to 27 are for direct axis parameters and the corresponding variables for quadrature axis are displaced by 30 locations. Internal machine quantities can be easily observed via their storage locations.

The subroutine is defined as follows:

```
 SUBROUTINE  DBLSYNC100(MS,NA,NB,NC,NX,NY,NZ,ANOM,EFD,TMECH,
+            TE,FLD,ITER,PREAL1,PREACT1,PREAL2,PREACT2,OMEGA,
+            CONSPD,THETA,DELTA)
```

The subroutine parameters are:

–MS,NA,NB,NC,NX,NY,NZ	– Subsystem and nodes for phases a, b, c, x, y, and z,
–ANOM	– put ANOM = 1.0 to activate the subroutine, the subroutine is skipped if ANOM = 0.0,
–EFD	– applied field voltage (EFD=1.0 for rated open circuit voltage on the air–gap line,
–TMECH	– mechanical torque in per unit,
–TE	– electromechanical torque in per unit,
–FLD	– field current (FLD=1.0 when EFD=1.0 in steady state),
–ITER	– number of subiteration steps (usually 1),
–PREAL1,PREAL2	– real power in per unit,
–PREACT1,PREACT2	– reactive power in per unit,
–OMEGA	– machine angular speed calculated within program in RAD/ second,
–CONSPD	– for M–G and M–M cases, CONSPD must be 0.0 or a positive number. Mechanical dynamics will be determined inside the model with initial speed OMEGA=CONSPD,
	– for G–G case, CONSPD must be negative and

always: OMEGA= –CONSPD.

–THETA –Rotor position at the end of each time–step, in Electrical Radians. Always: 0 < THETA < 6.28.

–DELTA –The load angle between the field and the direct axis, in Radians.

Circuit parameters of the machine are fed into the program via the datafile. The number of cards (or lines) needed for transferring the data is seven, and these cards are entered directly after the VAR list in the datafile, unless, of course, some other subroutines requiring data cards are called in DSDYN before DBLSYNC100. The data, entered on each card are as follows:

–CARD 1 –X1,X2,XMDO,X12D,X34D,X4D,X3D, where:

X1,X2 = stator leakage reactances (p.u.),

XMDO = d–axis unsaturated magnetizing reactance (p.u.),

X12D = stator d–axis mutual reactance (p.u.),

X34D = rotor mutual reactance)p.u.),

X4D = d–axis damper leakage reactance (p.u.),

X3d = field leakage reactance (p.u.).

–CARD 2 – XMQ,X12Q,X4Q, where:

XMQ = q–axis magnetizing reactance (p.u.),

X12Q = stator q–axis mutual reactance (p.u.),

X4Q = q–axis damper leakage reactance (p.u.).

–CARD 3 – R1,R2,R3D,R4D,R4Q, where:

R1,R2 = stator resistances (p.u.),

R3D = field resistance (p.u.),

R4D = d–axis damper resistance (p.u.),

R4Q = q–axis damper resistance (p.u.).

–CARD 4 – H,OMO,D,GAMA, where:

H = inertia constant (MW–sec. / MVA),

OMO = base angular frequency (Rad/sec.),

D = mechanical damping (acting on p.u. speed),

GAMA = phase shift between stator windings (degrees).

–CARD 5 – X1,Y1,X2,Y2, ... , X10,Y10, where : (Xi,Yi) are points on the saturation curve.

–CARD 6 – VBASE1,ABASE1,VBASE2,ABASE2, where:

VBASE = rated RMS phase voltage (KV),

ABASE = rated RMS phase current (KA).

–CARD 7 – Initial values for: THETA,ID1,ID2,IQ1,IQ2,ID3.

The circuit parameters, entered via the first three cards, are in per unit system.The per unit system used in this model is described in reference [10]. In this system the base values are as follows [12]:

$$V_{base1} = V_{ao} \quad (\text{ rms }),$$

$$V_{base2} = V_{xo} \quad (\text{ rms }),$$

$$I_{base1} = I_{ao} \quad (\text{ rms }),$$

$$I_{base2} = I_{xo} \quad (\text{ rms }).$$

The same voltage bases are used in the dq system, but the base currents are $\frac{3}{2} I_{ao}$ and $\frac{3}{2} I_{xo}$.

In both systems:

$$P_{base1} = 3 V_{ao} \, I_{ao} ,$$

and,

$$P_{base2} = 3 V_{xo} \, I_{xo} .$$

The associated bases are:

ω_{base} = rated radian frequency (usually 376.99 rad/s for 60 Hz),

$$\Phi_{base1} = \frac{V_{ao}}{\omega_{base}} \quad \text{(base flux linkage),}$$

$$\Phi_{base2} = \frac{V_{xo}}{\omega_{base}} \quad \text{(base flux linkage),}$$

$$\nu_{base} = \frac{\omega_{base}}{Pole\ Pairs} \quad \text{(base mechanical speed),}$$

$$\theta_m = \frac{\theta}{Pole\ Pairs} \quad \text{(mechanical angle),}$$

$$T_{base} = \frac{P_{base}}{\nu_{base}} \quad \text{(electromechanical torque),}$$

$$J_{base} = \frac{P_{base}}{\omega_{base}\ (\nu_{base})^2} \quad \text{(angular moment of inertia).}$$

It must be noted that the problem of saturation in the machine electromagnetic circuit is taken in account in the model, by considering the fact that the saturation in X_{MD} is the only saturation with considerable effect on machine operation [10]. For this purpose, the saturation curve of the machine is fed into the program via the datafile, and the saturation factor for X_{MD} is determined in support subroutine SATRN, based on the magnitude of the magnetizing current :

$$i_{MD} = i_{d1} + i_{d2} + i_f + i_{kd} \ . \tag{3.6}$$

The matrix $\mathbf{L}_D^{-1}$ is re–calculated each time there is a significant change in the saturation factor.

And finally, in order to solve the equation (3.3), the Trapezoidal Integration is used. In this method if:

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BV}$$

then:

$$\mathbf{X}(t) = \mathbf{X}(t-\Delta\ t) + \frac{\mathbf{AX}(t) + \mathbf{AX}(t-\Delta\ t)}{2} \cdot \Delta\ t + \frac{\mathbf{BV}(t) + \mathbf{BV}(t-\Delta\ t)}{2} \cdot \Delta\ t$$

in which $\mathbf{X}$ is the current vector [13].

3.6.2 – Support Subroutines

The following subroutines support the DBLSYNC100 subroutine. These subroutines do not require storage locations, but may use or update the storage variables:

SUBROUTINE DINVERT(IX,N)

This subroutine is called by DBLSYNC100 and inverts the direct axis reactance matrix (IX=0) and the quadrature axis reactance matrix (IX=30). The rank of matrix (N*N) may be either 3 or 4 and must be specified.

SUBROUTINE DAXIS(D,DD,Q,DQ,IXD,IXQ)

This subroutine gives the $\mathbf{AX} + \mathbf{BV}$ terms in the equation (3.3). The inverted matrices $\mathbf{L}_D^{-1}$ and $\mathbf{L}_Q^{-1}$ are specified by IXD=0 for $\mathbf{L}_D^{-1}$ and IXQ=30 for $\mathbf{L}_Q^{-1}$.

SUBROUTINE DTRDQO(A,B,C,X,Y,Z,D1,Q1,O1,D2,Q2,O2,THETA,GAMA,IDIR)

This subroutine performs the three–phase to dqo transformation(IDIR=1) and the inverse dqo to three–phase transformation (IDIR=–1), according to equations (2.10) and (2.11).

SUBROUTINE DSAT(IS)

This subroutine stores the saturation characteristic for mutual magnetizing (IS=63). This subroutine is called by DBLSYNC100. Ten pairs of of points (I,SF) are stored, where SF is the saturation factor and I is the per unit current. When entering data (via card 5 in datafile) the first point must be (0.0,1.0) and the second (I1,1.0), where I1 is the per unit current at which the onset of saturation occures. If less than ten points are available, the last pair should be (–1.0,–1.0). When the saturation factors are entered, the subroutine checks for monotonically decreasing factors with monotonically increasing currents, and returns.

Alternately, a current–voltage characteristics may be entered with the first pair of points (0.0,0.0) and the second (I1,V1), where I1 is the current in any units at which saturation commences. The voltage must be input in per unit. Again, if less than ten points are available the last pair entered must be (–1.0,–1.0). The program in this case replaces the voltage with the saturation factor and re–scales the current to a per unit value, based on the unsaturated value of reactance previously input [10].

SUBROUTINE SATRN(C,SFI,SFT,IS)

This subroutine determines saturation factors based on the magnetizing current. The instantaneous saturation factor is determined by linear interpolation between points on the curve and by an exponential decay beyond the last point (this ensures that for every high current, the reactance remains positive). The tangential saturation factor is not interpolated and is obtained directly from the entered data.

3.7 – The Results of Machine Analysis by DBLSYNC100

In this Section, the results of analyzing a dual wound synchronous machine by EMTDC, using the DBLSYNC100 subroutine will be presented. The data used for the model are borrowed from the reference [14], and are measured by standard techniques on a synchronous machine with two sets of stator windings, displaced by 30°. The above measurements have been made with the two sets of stator windings being connected in series, i.e., a and x, b and y, and c and z have been connected in series to form three single split coils. Therefore, necessary modifications were made on all parameters to extract the corresponding data for the dual wound case. Except for angular inertia, J, which has been assumed to be equal to 500 p.u., the other parameters, derived from the above modifications, are presented in Table 3.2.

The machine is connected to a power system by one stator set, and is brought to steady state at rated speed. At TIME=3.0 Sec., an electric load is applied to the other set of windings, as is shown in Fig. 3.5.

Table 3.2 – Parameters of the Test Machine

Parameters	p.u.
x_a	0.0279
x_x	0.0279
x_{MD}	0.3268
x_{34D}	0.0
x_{12D}	0.0
x_{kd}	0.0756
x_f	0.0394
x_{MQ}	0.1395
x_{12Q}	0.0
x_{kq}	0.1395
R_1	0.042
R_2	0.042
R_{kd}	0.181
R_{kq}	0.1109
R_f	$2.25E-3$

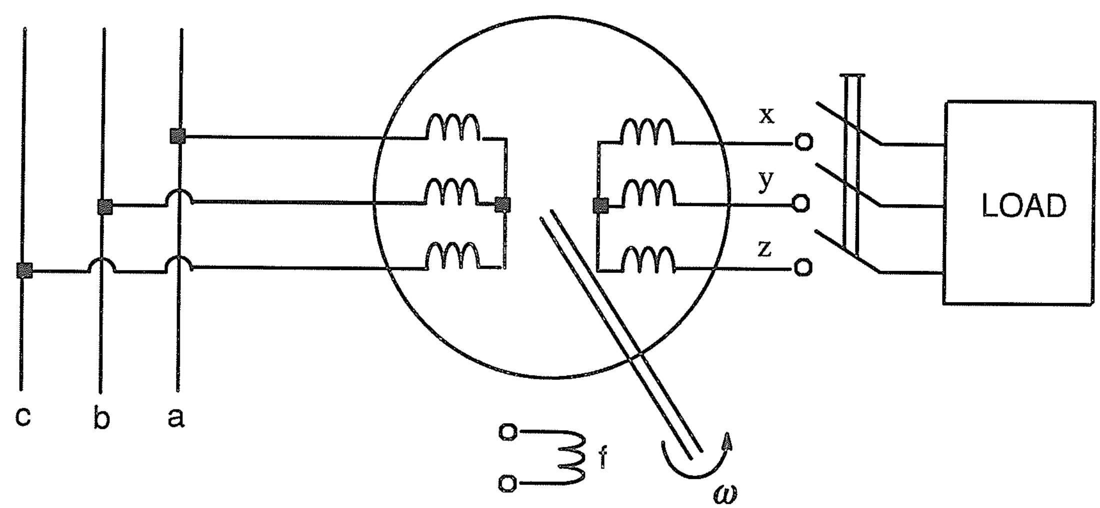


Fig. 3.5 – The dual wound synchronous machine

The characteristics of the system and the load are as follows:

System	*Load*
$V_{L\text{-}L} = 104 \quad V$	$S = 6200 \quad VA \ (0.83 \ P.U.)$
$f = 60 \quad Hz$	$\cos\phi = 0.8$

The applied voltage, v_a, along with the generated voltage, v_x, are shown in Fig. 3.6. Because of the absence of any significant current before the connection of the load, these voltages are almost equal, and are displaced by $\gamma = 30^o$. After the load is connected to the machine (at TIME=3.0 Sec.), because of the voltage drop in stator leakage reactances and resistances, the magnitude of v_x is slightly smaller than that of v_a.

In Fig. 3.7, the current drawn from the source, i_a, and the load current, i_x, are shown. Before the connection of the load, i_x is zero. After the load is connected to the machine, because of the fluctuations in the speed, and thus the consequent fluctuations in the direction of reactive power transferred between the network and the machine, i_a has some fluctuations, and after about 1.0 second it reaches to its steady state, as it can be seen in Fig. 3.10 to Fig. 3.14.

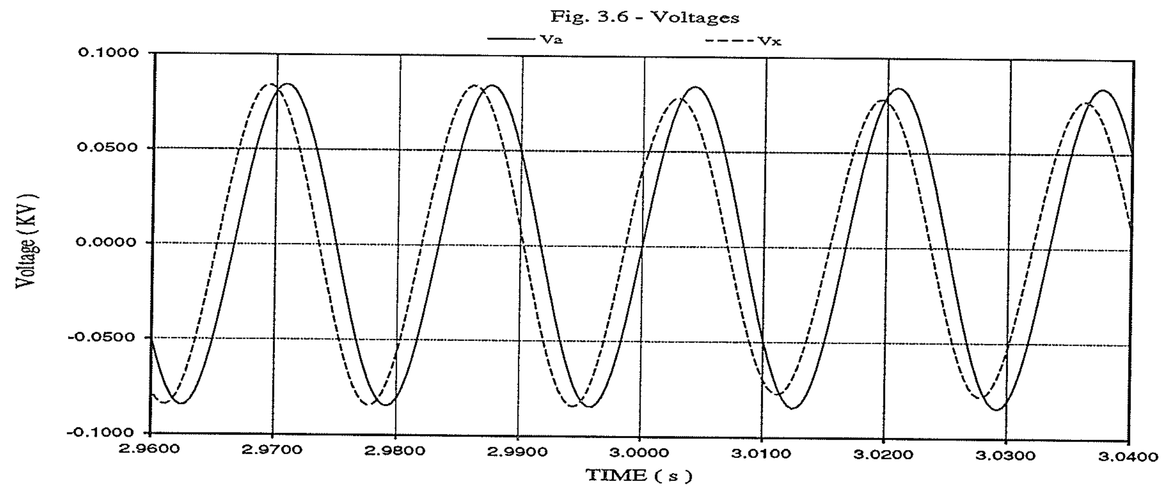
In Fig. 3.8 and Fig. 3.9, voltages and currents of the source and the load are shown respectively.

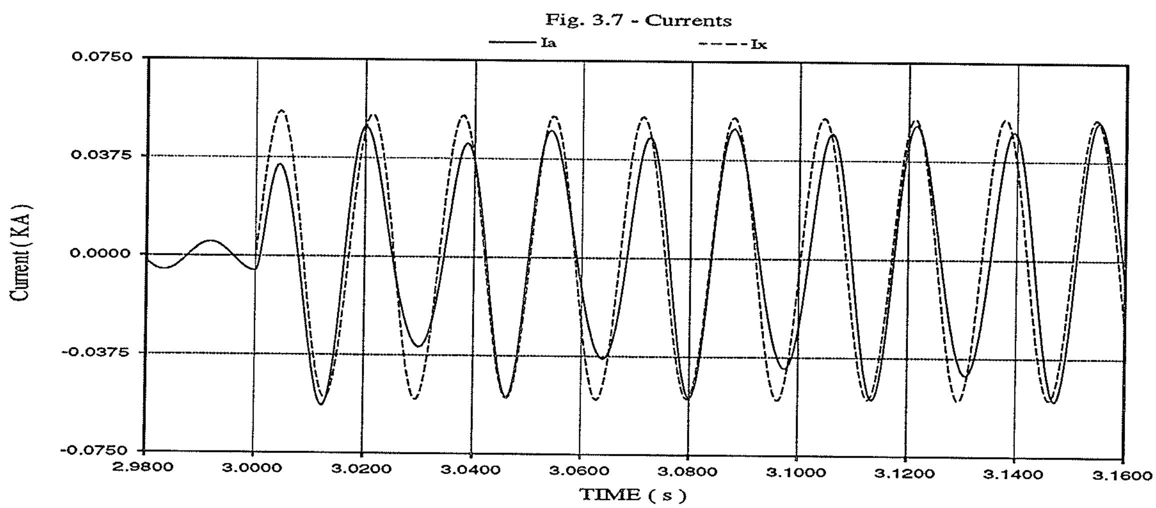
In Fig. 3.10, the per unit speed of the machine, ω, and the electromechanical torque, T_e, are shown, before and after the connection of the load.

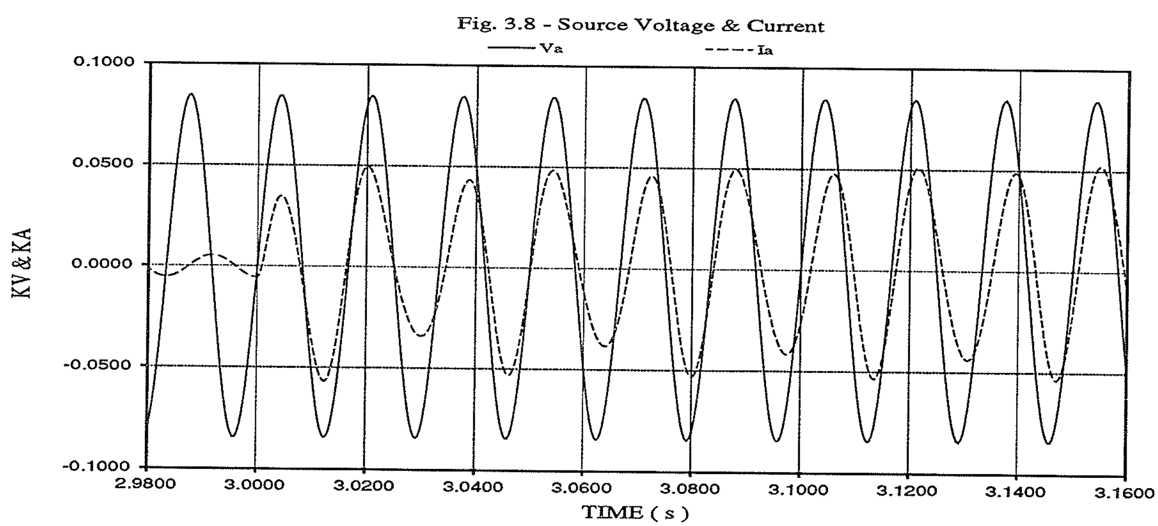
Fig. 3.11 shows the field voltage and current, v_f and i_f, both in per unit. Fluctuations in field current, because of the induced currents in it, after the load is connected, are evident.

Fig. 3.12 and Fig. 3.13 show the real and reactive powers, respectively, for both sets of machine windings.

And in Fig. 3.14, the currents in the rotor damper bars, i_{kd} and i_{kq}, are shown. The dependence of these currents on the speed of the rotor, and the fact that these currents are zero in the steady state, is evident from the derived curves.







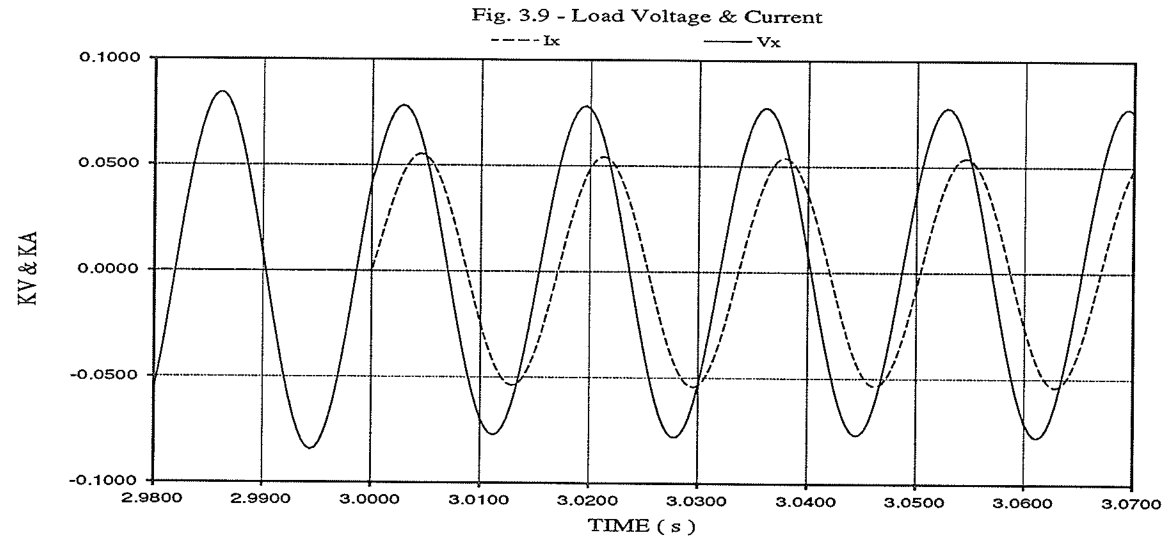


Fig. 3.9 - Load Voltage & Current
Ix
Vx
KV & KA
0.1000
0.0500
0.0000
-0.0500
-0.1000
2.9800
2.9900
3.0000
3.0100
3.0200
3.0300
3.0400
3.0500
3.0600
3.0700
TIME (s)

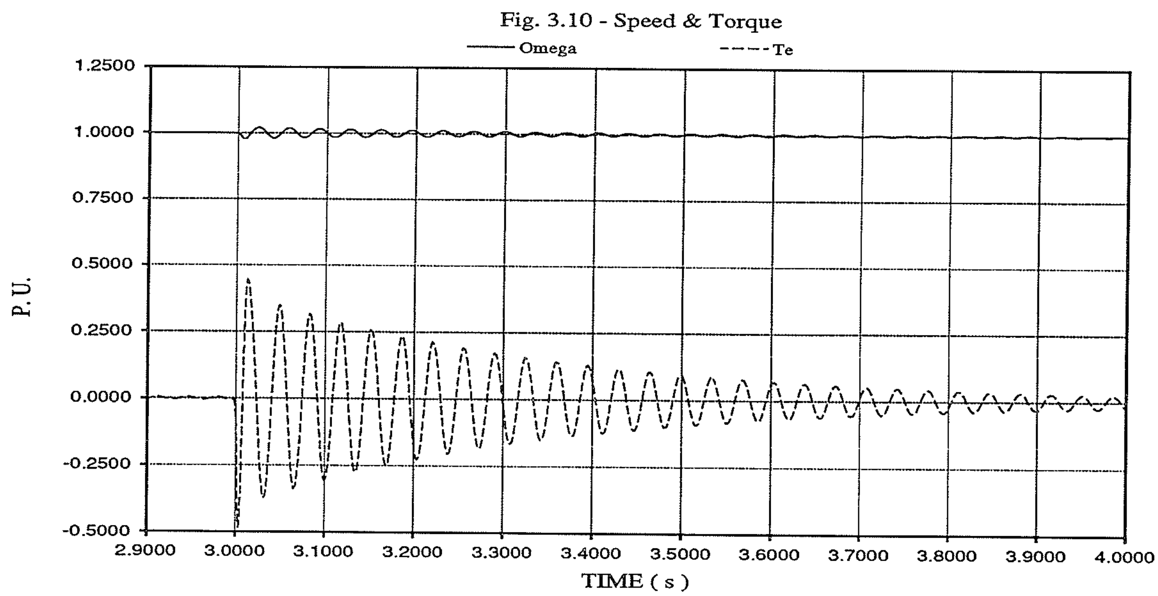


Fig. 3.10 - Speed & Torque
Omega
Te
P. U.
1.2500
1.0000
0.7500
0.5000
0.2500
0.0000
-0.2500
-0.5000
2.9000
3.0000
3.1000
3.2000
3.3000
3.4000
3.5000
3.6000
3.7000
3.8000
3.9000
4.0000
TIME (s)

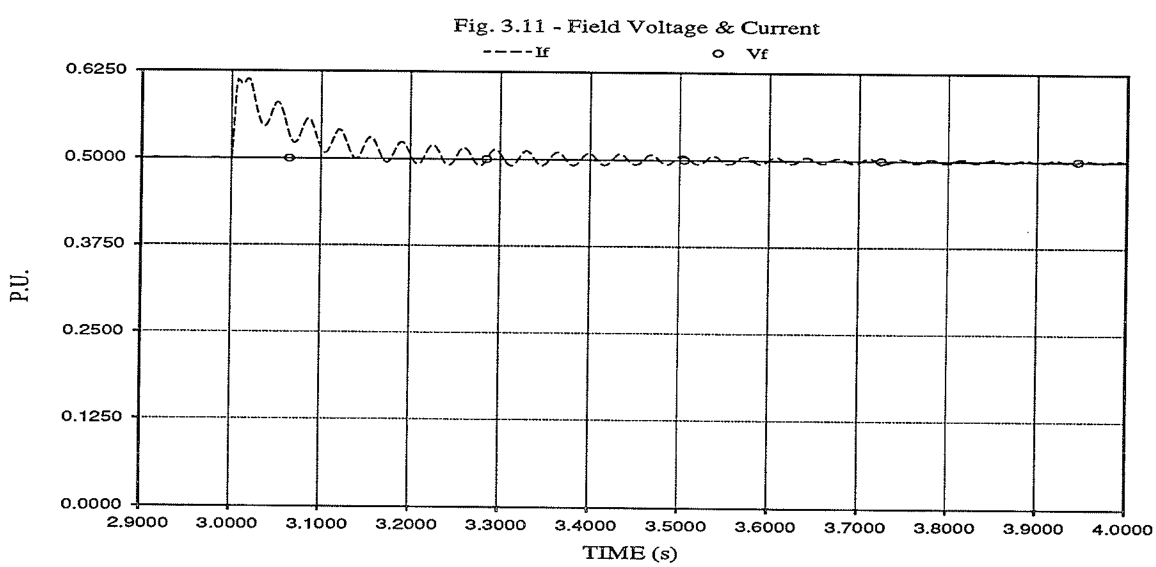


Fig. 3.11 - Field Voltage & Current
If
Vf
P.U.
0.6250
0.5000
0.3750
0.2500
0.1250
0.0000
2.9000
3.0000
3.1000
3.2000
3.3000
3.4000
3.5000
3.6000
3.7000
3.8000
3.9000
4.0000
TIME (s)

Fig. 3.12 - Real Powers

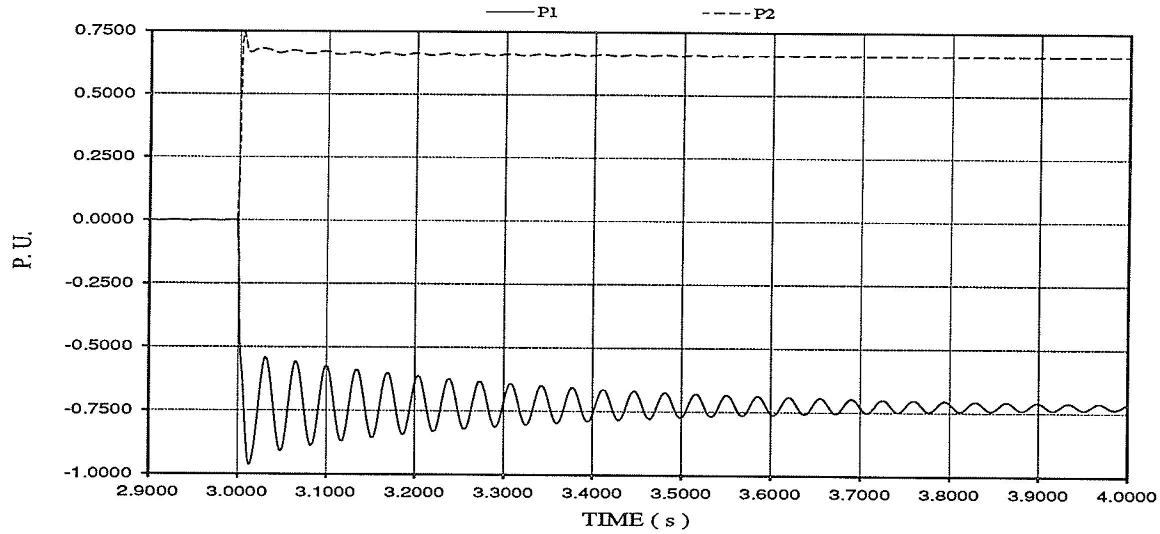


Fig. 3.13 - Reactive Powers

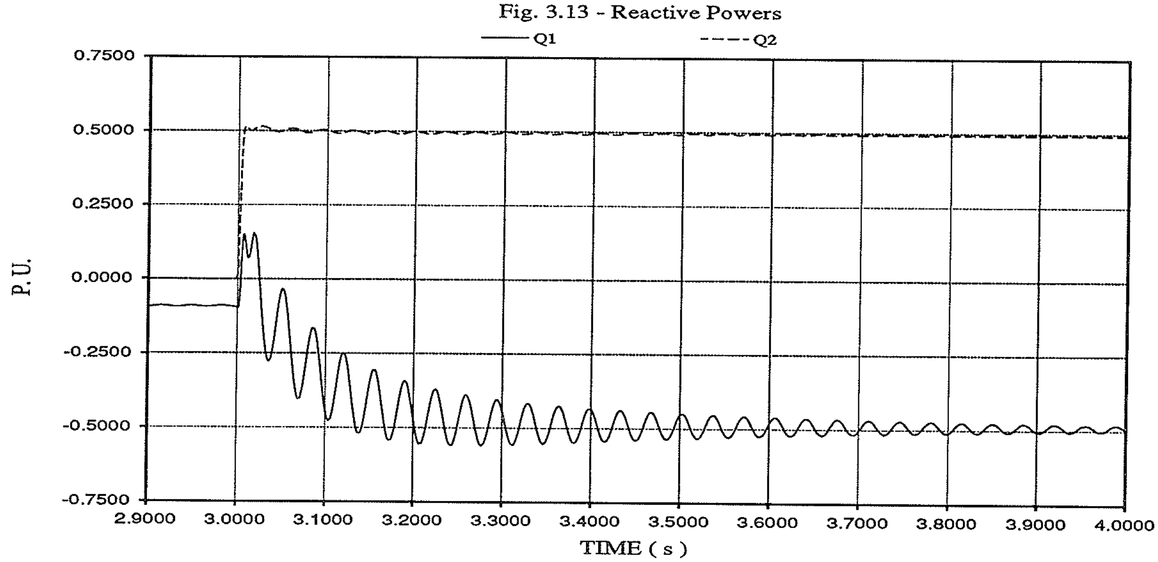
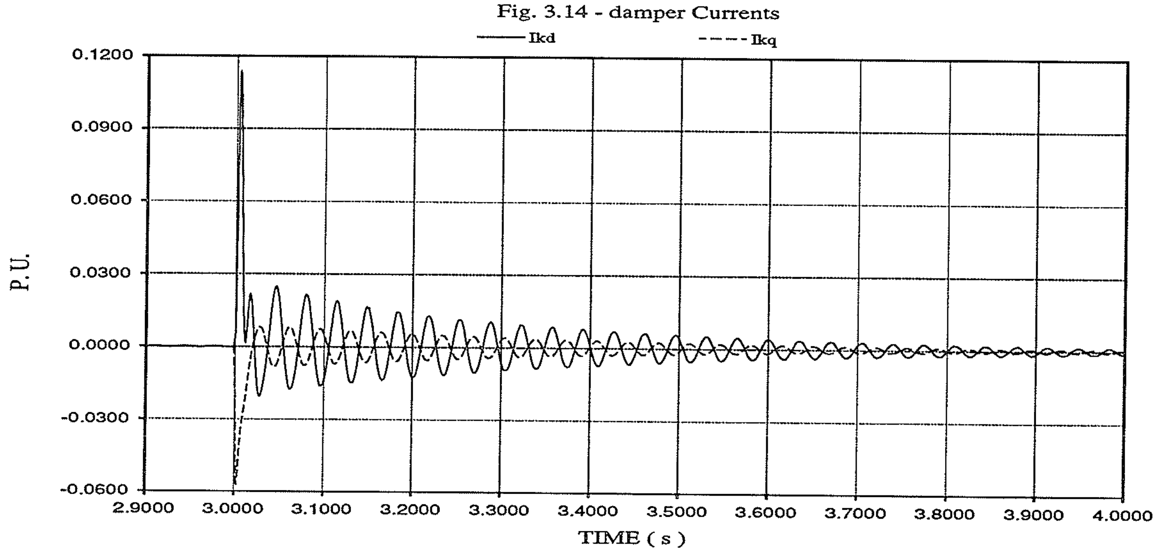


Fig. 3.14 - damper Currents



It is evident that because of the low magnitude of the the field voltage, i.e. $v_f = 0.5\ P.U.$, the machine is underexcited. Simulation of the machine in overexcitation mode, with $v_f = 1.25\ P.U.$, shows that the starting and the steady–state behavior of the machine is almost the same, except for the direction of the reactive power associated with the source–side winding, and the angle between source voltage, v_a, and source current, i_a.

The simulation was repeated for the overexcited machine, and some important results are presented here (load is applied at TIME=4.0 sec.).

Fig. 3.15 shows v_a and i_a, and the fact that i_a is leading the v_a can easily be seen.

In Fig. 3.16, field voltage and current, v_f and i_f respectively, along with the variations in the magnitude of the field current after the load is applied, are shown.

And finally, in Fig. 3.17, the reactive powers of the source and the load are shown. It is evident that before the application of the load on the machine, the source–side winding is injecting a 0.6 P.U. reactive power into the system. After the connection of the load, the injected reactive power decreases to meet the demand for reactive power on the load side, but the machine still injects some 0.18 P.U. of reactive power into the system. This feature of the dual wound synchronous machine is the reason why it is an ideal tool to be used along with the "Load commutated inverter", as it will be discussed in the next Chapter.

The last important fact, derived from the results of the simulations, is that the variations in the voltage and power magnitude, raised from the variation of the load, are mostly concentrated in the source side, and the load voltage and power are almost constant. This ensures the flow of the power to the load to be smooth and reliable, without having unwanted voltage fluctuations on the load. This advantage of the dual wound synchronous machine can be attributed to the stored kinetic energy in the machine rotor, and the transformer action between the two sets of windings, which is not largely affected by the small variations in the rotor speed.

Fig. 3.15 - Source Voltage & Current

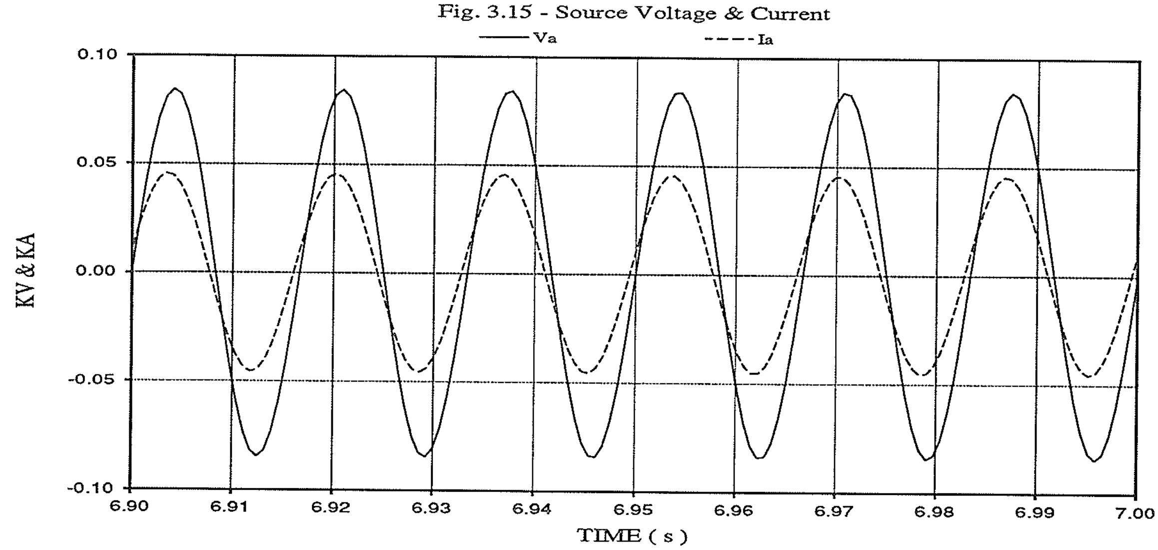


Fig. 3.16 - Field Voltage & Current

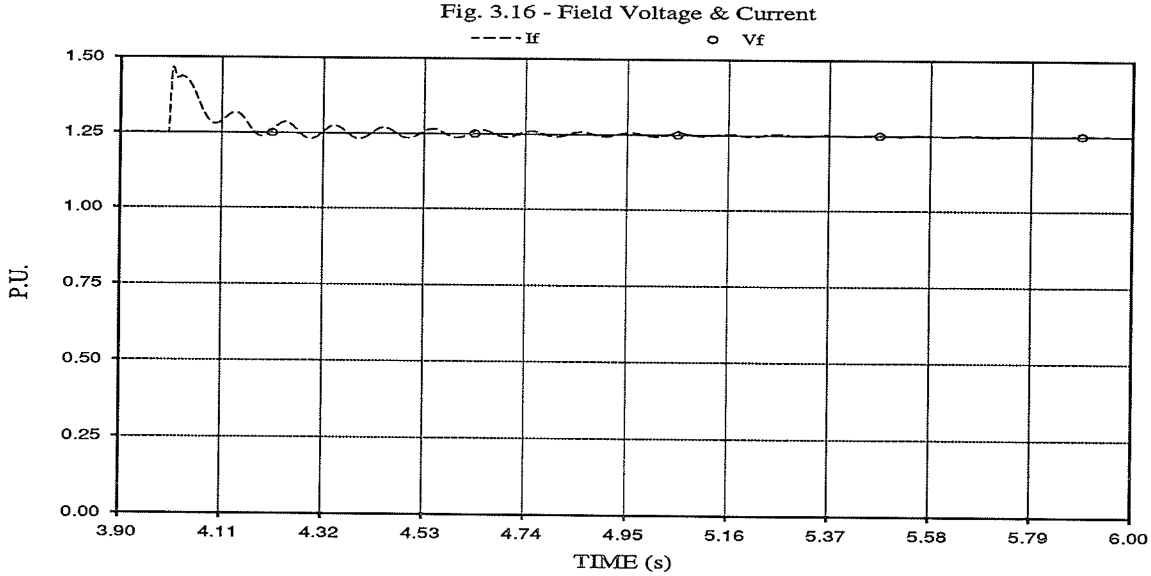
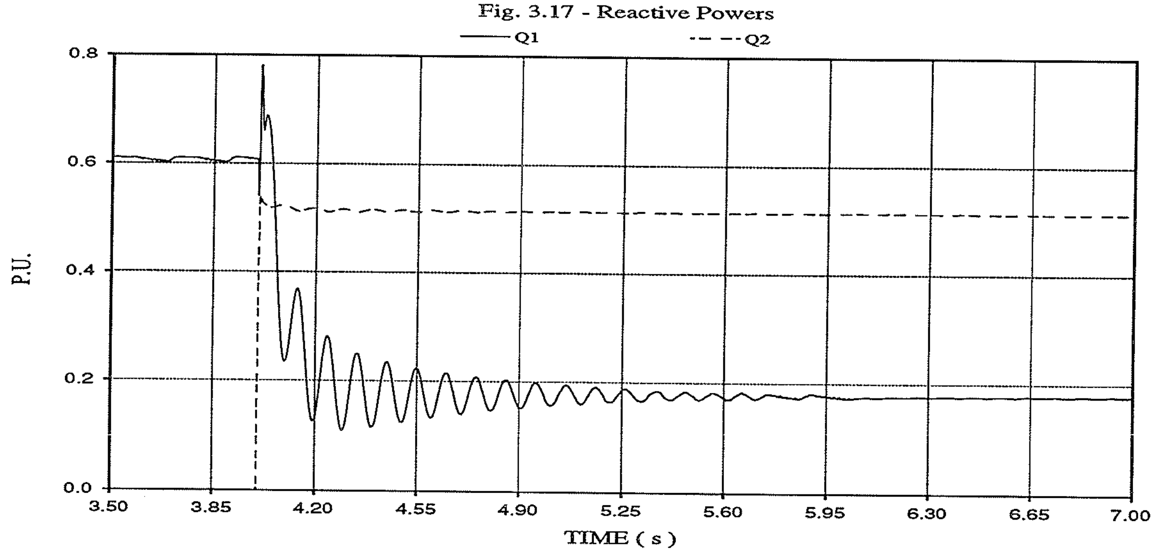


Fig. 3.17 - Reactive Powers



During the simulation of the machine, it was noticed that the starting current is very high, and the machine can not synchronize with the 60 Hz system with an inertia, J, larger than about 50 p.u. A double check was made on the machine to make sure that the measured parameters and the proposed equivalent circuits are in reasonable margins with the actual machine.

First, it was observed that the starting current, with applied voltage of about 0.2 p.u., is higher than 15 p.u., and this is because of the fact that the machine is designed as an AC alternator, and therefore its damper bars are not designed to help start the machine from standstill by induction machine action.

Then, at standstill, with $\theta = 0^o$, a 0.07 p.u. voltage was applied to the machine, and currents in phases a, b, and c were measured. The same voltage was applied to the equivalent circuits, after transforming it to the dqo system, and the currents were found from circuit analysis. The results of analysis were in very good accordance with the measured quantities, and thus re–ensuring that both the equivalent circuits and the modified parameters of the machine are realistic and reliable.

3.8 – Summary of the Chapter

In this chapter, the digital model developed to analyze the dual wound synchronous machine, subroutine DBLSYNC100, and its support subroutines, as well as the possible ways to use this model in conjunction with EMTDC program, were introduced.

At the end, the results of the simulation of the machine, by the above mentioned model, were presented.

Chapter Four

System Studies

4.1 – Introduction

In this chapter the dual wound synchronous machine model, developed and discussed in previous chapters, will be used in conjunction with other EMTDC program models, such as rectifier, distributed transmission line, thyristor, etc., to digitally assemble the proposed scheme, and to examine some operating aspects of the system. Starting the synchronous machine from standstill and bringing the speed to rated value, using the Static Variable Frequency Systems (SVFS) technique, will be simulated, and proper control regimes to govern the operation of the whole system will be introduced in a general manner.

Detailed study of the steady state operation, including harmonic analysis and the response of the system to load variations, as well as its response to various faults, requires the complete study and design of the control regimes, which due to its complexity is considered to be beyond the scope of this project, and is suggested to be the subject of an independent project.

4.2 – SVFS Techniques for Starting Synchronous Machines

Large synchronous machines, in general, need the help of an electrical or mechanical drive to start from standstill, or even from low speeds. The general task of such starting devices is to accelerate a rotating machine up to a speed at which it can begin to run on its own, or can be synchronized to a main supply system. This speed is highly dependent on the specific application for which the synchronous machine is used, as well as the characteristics of the machine itself. Common types of these starters include: starting with DC/AC starter motors, diesel prime–movers, asynchronous starting, frequency starting with exciting machine group, Unger connection, etc. All these starting schemes have their own advantages and limitations. A summary of technical features of these methods can be found in references [15,16].

A novel method for starting synchronous machines, which has been in use for more than two decades now, is the Static Variable Frequency Starting (SVFS). This method, which employs the solid state technology helps the machine start from standstill by applying a phase synchronized, variable frequency voltage, generated by semiconductor devices.

Compared to other methods of starting, the SVFS method has so many advantages which makes it unique in the class of starters. Some of these advantages include: the possibility of remote installation from the machine, the possibility of using one start up system for several machines, the capability of controlled braking, the capability of variable speed, minimal voltage drop in the supply network during the start up, etc. Some other advantages can be achieved by proper design of the system. For example, the harmonic disturbances can be reduced by choosing proper pulse–numbers for converters, and the relative cost can be minimized by increasing the number of machines which use the same start up system [15,16].

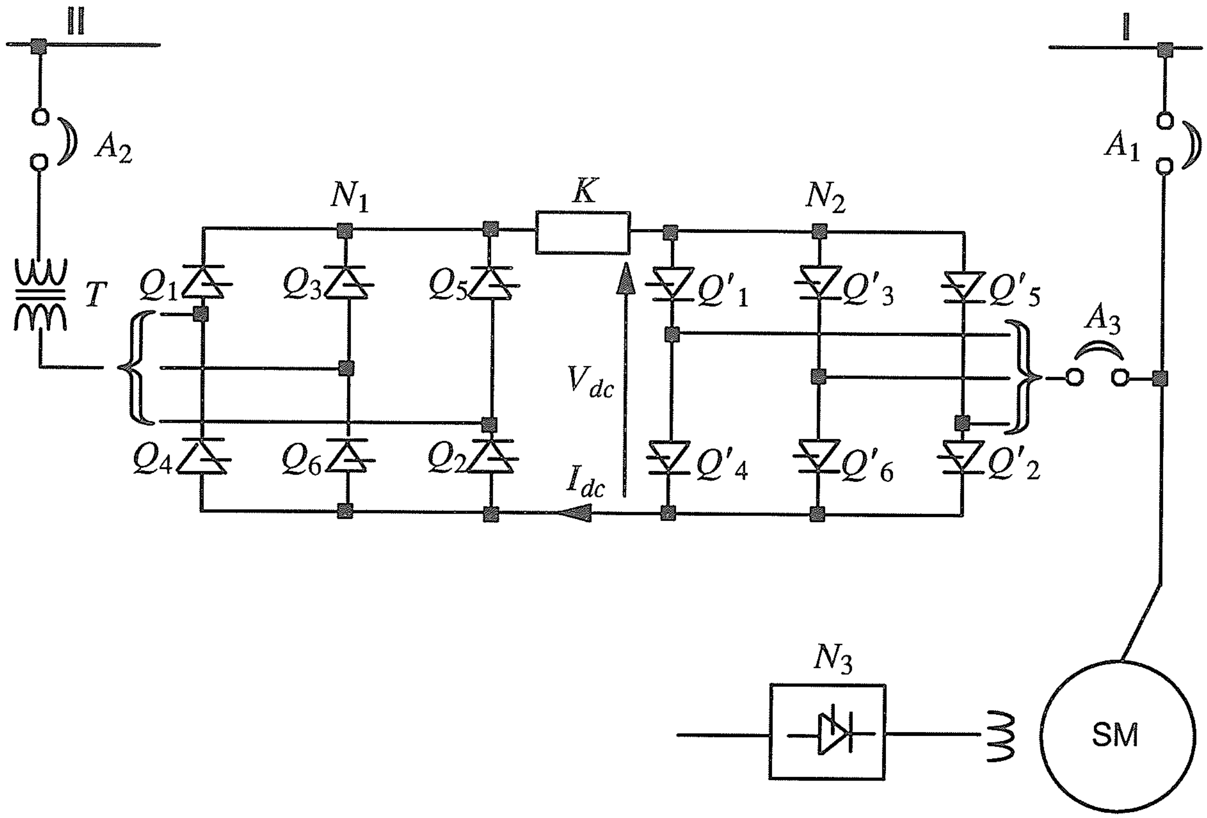
4.2.1 – Technical Features

The SVFS system receives power from a supply system at constant voltage and frequency, and converts it into power with variable voltage and frequency, in order to start and accelerate a synchronous machine. Fig. 4.1 shows the principle diagram of such a system.

The conversion is achieved through the two thyristor groups with three phase bridge connections and a DC buffer circuit. This buffer circuit, normally a reactor, performs the task of decoupling the different three phase bridge frequencies and smoothing the DC current, I_{dc}.

The power required to start the machine is dependent on the following parameters: a) Magnitude and curve–shape of opposing torque on machine shaft, b) Moment of inertia of the machine, and c) Run up time and speed [15].

At low speeds, where machine voltage is not large enough, the commutation in the inverter is achieved by pulsing the rectifier, i.e., by bringing the current in the inverter to zero by



I	= Main supply system	N_1	= Rectifier
II	= Auxiliary supply system	N_2	= Inverter
A_1, A_2, A_3	= Circuit breakers	N_3	= Converter for excitation
T	= Transformer	K	= Reactor

Fig. 4.1 – Static Variable Frequency Starter [15]

forced retarding in the rectifier. When the speed and consequently the generated voltage in the machine is large enough, the commutation in the inverter is done by these voltages, and through a proper control regime, the speed can be brought to rated value.

In Fig. 4.2 the block diagram of the control system, used for starting the machine is shown.

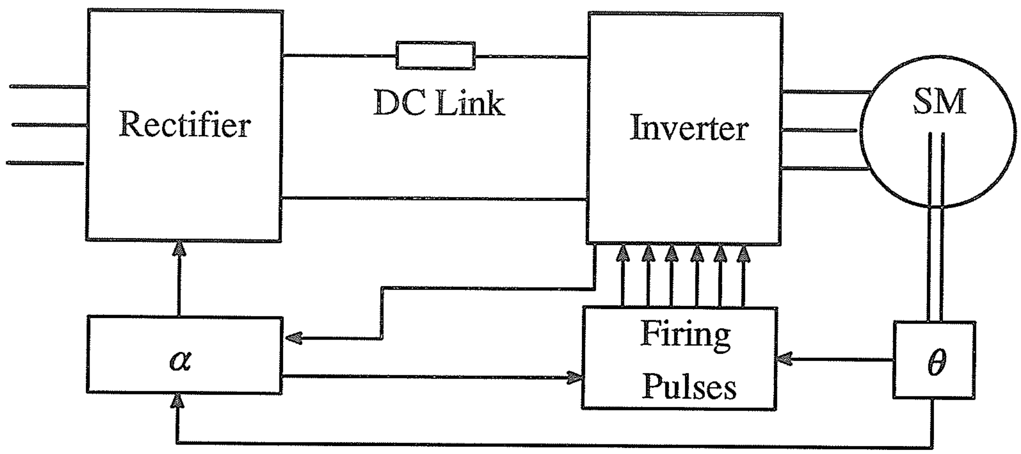


Fig. 4.2 – Block diagram of the starting system

At the beginning of the starting process, based on the position of the rotor, i.e., the value of θ, the two thyristors in the inverter which can produce the maximum electromechanical torque on the shaft are chosen and fired.

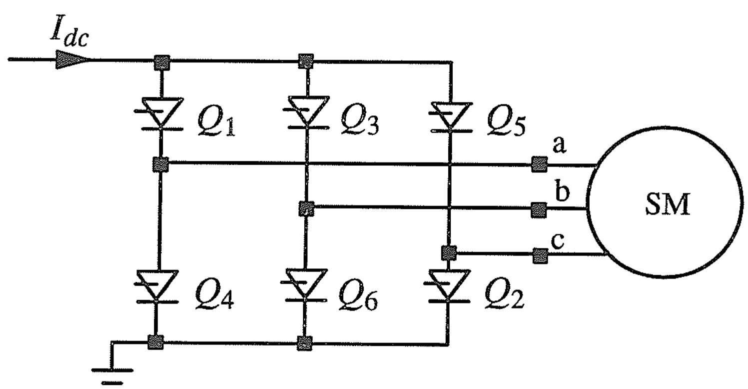
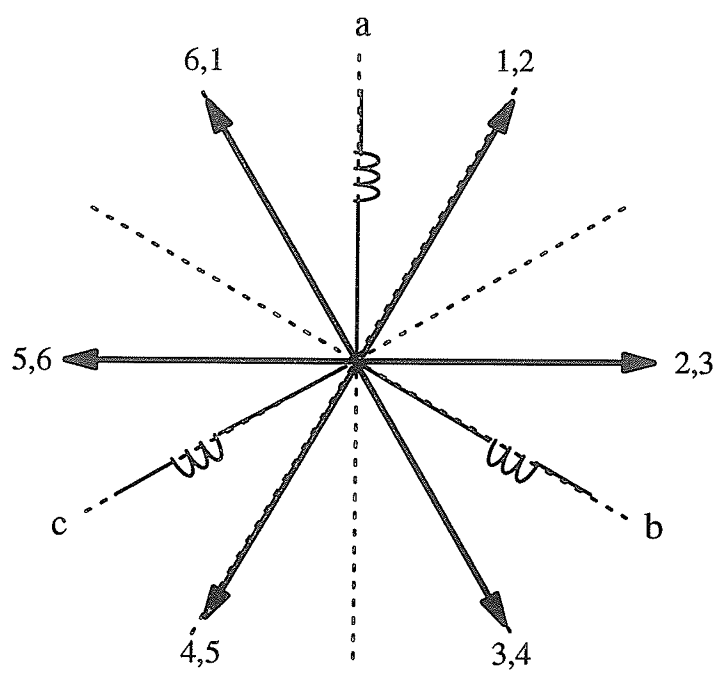


Fig. 4.3 – Thysistors connected to each machine phase

Examining the inverter in Fig. 4.3 shows that the electromagnetic field produced in the air-gap of the machine is maximum in directions dictated by the chosen combinations of conducting thyristors. It was stated in Chapter One that at each instant two thyristors, one in the upper group and one in the lower group, must be conducting. Also, it was conventionally accepted in Chapter Two that $\theta = 0$ when the field axis is aligned with the axis of phase a. Considering above points, the six possible directions of the electromechanical field, produced by the stator windings in machine air–gap are shown in Fig. 4.4.



Q1,Q2 : Into phase a, out of phase c

Q2,Q3 : Into phase b, out of phase c

Q3,Q4 : Into phase b, out of phase a

Q4,Q5 : Into phase c, out of phase a

Q5,Q6 : Into phase c, out of phase b

Q6,Q1 : Into phase a, out of phase b

Fig. 4.4 – Direction of stator electromagnetic field

Since the electromechanical torque produced by the interaction between the electromagnetic fields of rotor and stator is proportional to the sine of the angle separating them, the maximum torque will be produced if the angle between these two fields is 90° or as close as possible to 90°. Based on this simple principle, the correct combinations of conducting thyristors in the inverter, for each definite interval of θ, are shown in Table 4.1.

Table 4.1 – Correct combination of conducting thyristors

θ	Upper group	Lower group
$0-60$	3	2
$60-120$	3	4
$120-180$	5	4
$180-240$	5	6
$240-300$	1	6
$300-360$	1	2

Having the rectifier producing necessary DC voltage and current, and when the appropriate combination of thyristors is chosen and fired by the control system, the produced torque will force the rotor to rotate in such direction leading to a decrease in the displacement angle between the two fields.

If the rotor passes the axis of the stator field, the direction of the torque will be reversed, and thus, the gained speed will be suppressed. So, before this happens, the flow of power to the machine must be stopped. This is performed by a sudden increase in the value of firing angle in the rectifier, i.e., α will be pushed to a value greater than 90°. This causes the DC voltage to drop to a negative value, and the negative voltage not only stops the flow of current into the inverter, but also helps the conducting thyristors to regain their blocking ability. When the thyristors are fully turned off the rectifier will be reactivated, and the control system fires the next combination of thyristors based on the new position of the rotor. The new torque helps the rotor, which has already gained some momentum, to accelerate. This process of on–off pulsing continues until the machine has gained enough speed. At this point, the generated voltages in the machine start to perform line commutation on the inverter thyristors. A proper control regime, which governs the flow of real power into the machine based on the speed, then can bring the speed to its rated value and keep it inside an allowed interval of variations. Such a control regime must use rated speed and rated DC current in transmission line as settings, and real speed and real DC current as feedbacks to determine the value of α in the rectifier. The firing signals for the inverter are produced based on the phase of voltages generated in the machine. This can be achieved by a Phase Locked Loop, or by deriving the phases directly from θ, by knowing the rotor load angle, δ. The block diagram of such control system is shown in Fig. 4.5.

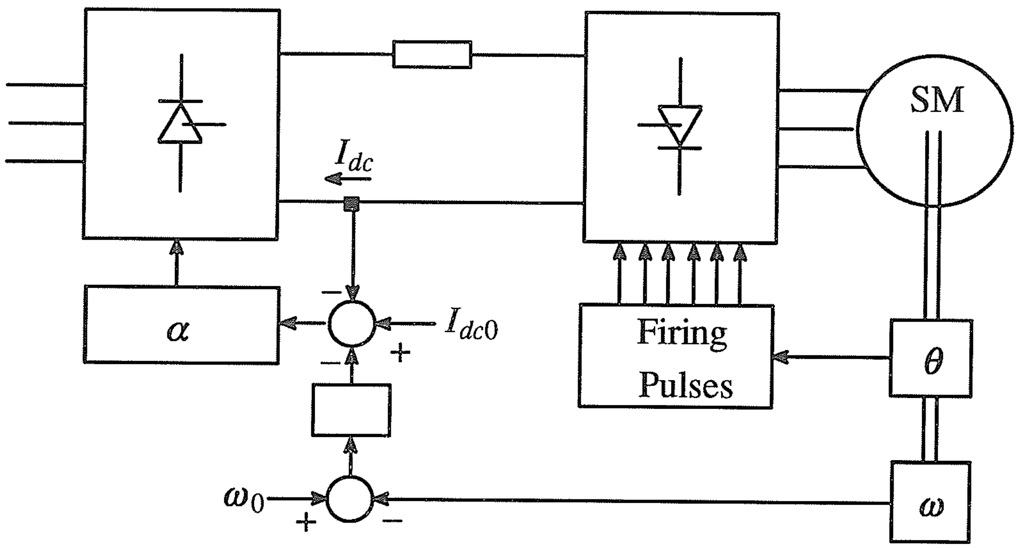


Fig. 4.5 – Block diagram of the accelerating system

4.2.2 – SVFS with a Long Transmission Line

The techniques introduced in the previous section for starting synchronous machines have been successfully designed and implemented in industries. Moreover, the SVFS system is not only capable of starting a synchronous machine, but also of driving it at variable speed [15,16]. An example of such a system, used in conjunction with a dual wound synchronous machine for supplying railway coaches, is presented in reference [17].

Using the above mentioned system for supplying remote loads, i.e., with a long transmission line between the rectifier and the inverter, however, presents new problems which must be carefully considered. The first problem arises in the starting process, where the current in transmission line must be reduced to zero, each time an off signal is released. This can be particularly hard to achieve, if the line has a significantly large inductance. Other problems arise during the steady state operation and during faults on the line or converters, but will not be discussed in the current study.

In order to examine the operation of the system in the presence of a long transmission line, the control systems introduced in previous section, along with a transmission line between the two converters were digitally simulated. The model chosen for transmission line, in particular, showed a great amount of influence on the outcome of the simulations.

The diagram of the system is shown in Fig. 4.6.

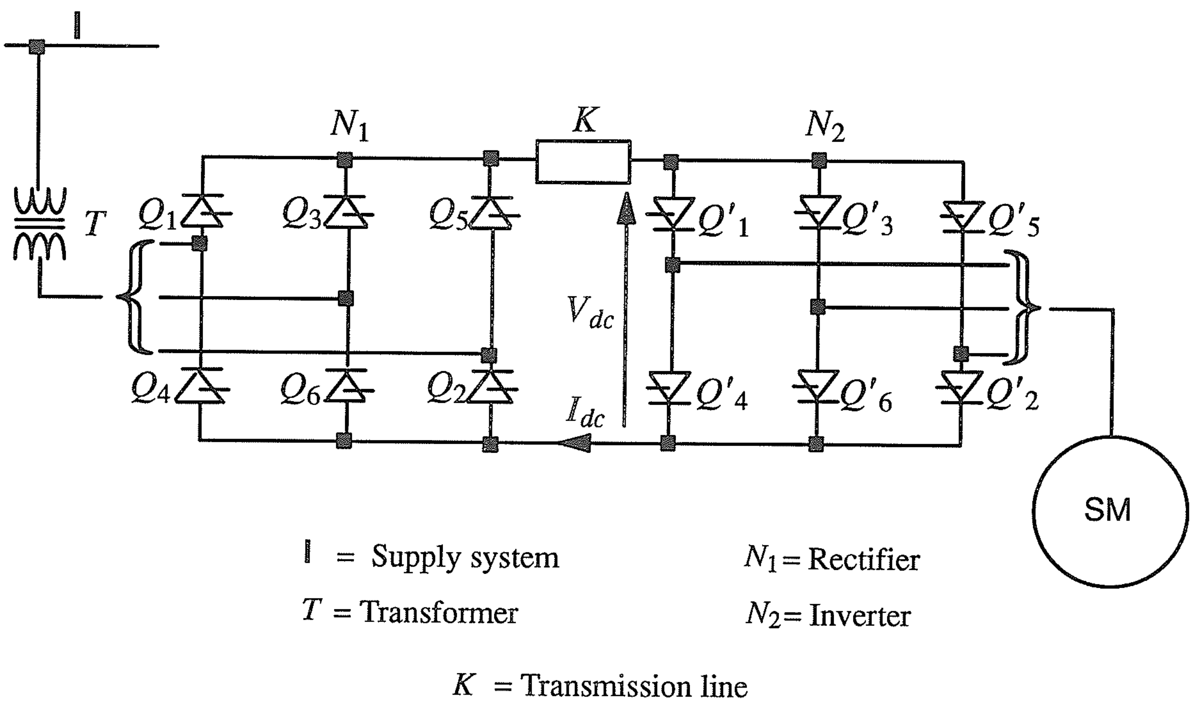


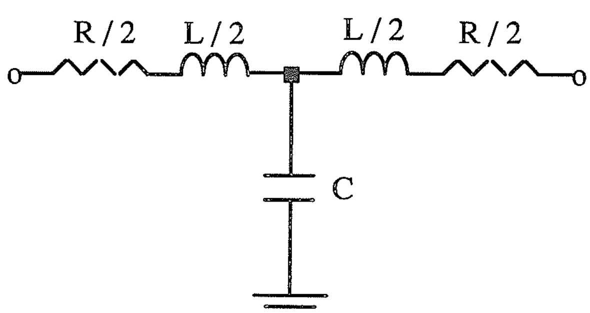
Fig. 4.6 – Studied system

Two different transmission lines were selected. Line number one was chosen from reference [18] and was modelled with lumped parameters. Table 4.2 shows the specifications of this transmission line.

Table 4.2 – Line number one specifications

Code word	Dove
Length km	150
DC, 20°C R_a $\Omega / 1{,}000\,ft$	0.0307
Inductance L_a $mH / mile$	1.114
Capacitance C_a $\mu F / mile$	0.0275

The above mentioned line was simulated in two ways. First it was represented by a single T–model [18] as shown in Fig. 4.7.



$$R = 15.1\ \Omega$$

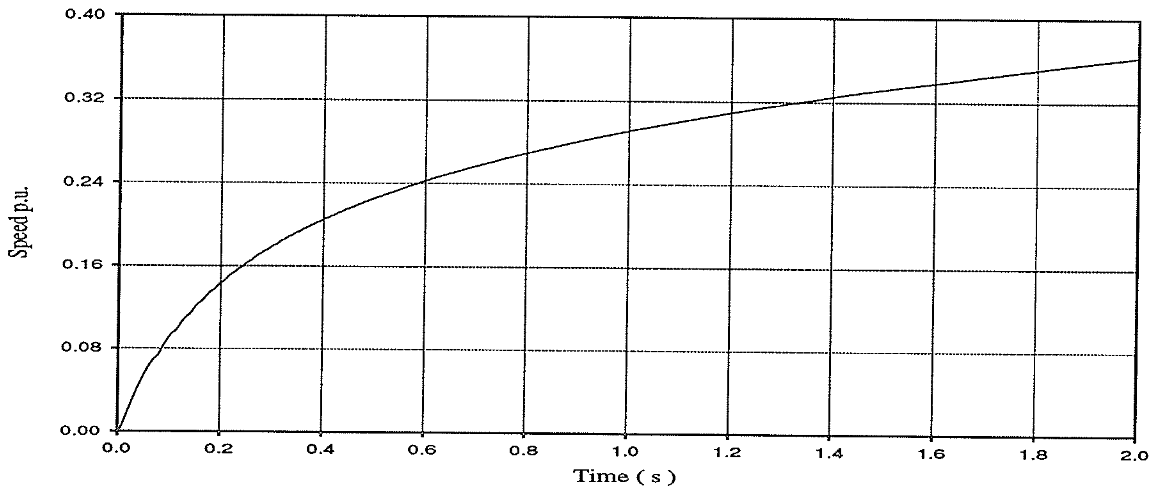
$$L = 103.8\ mH$$

$$C = 2.56\ \mu F$$

Fig. 4.7 – T–model line

The machine speed for this starting simulation is shown in Fig. 4.8. The firing angle in the rectifier for this simulation and also for other simulations is kept at such values which do not result in high currents in the line.

Fig. 4.8 - Speed with T-Model T. Line



Next, the line was represented by a multiple pi–model [18], consisting of 10 resistors equal to R/10, 10 inductors equal to L/10, and 9 capacitors equal to C/9, as is shown in Fig. 4.9.The machine speed is shown in Fig. 4.10.

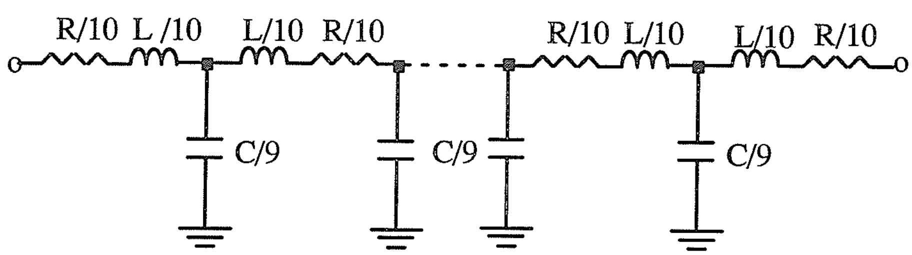
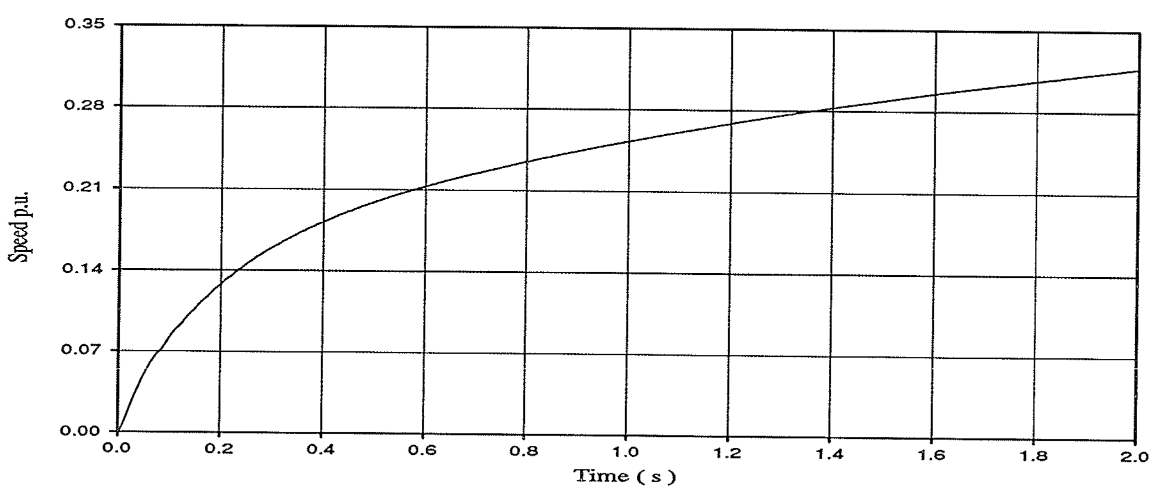


Fig. 4.9 – Multiple pi–model line

Fig. 4.10 - Speed with Multiple pi-Model T. Line



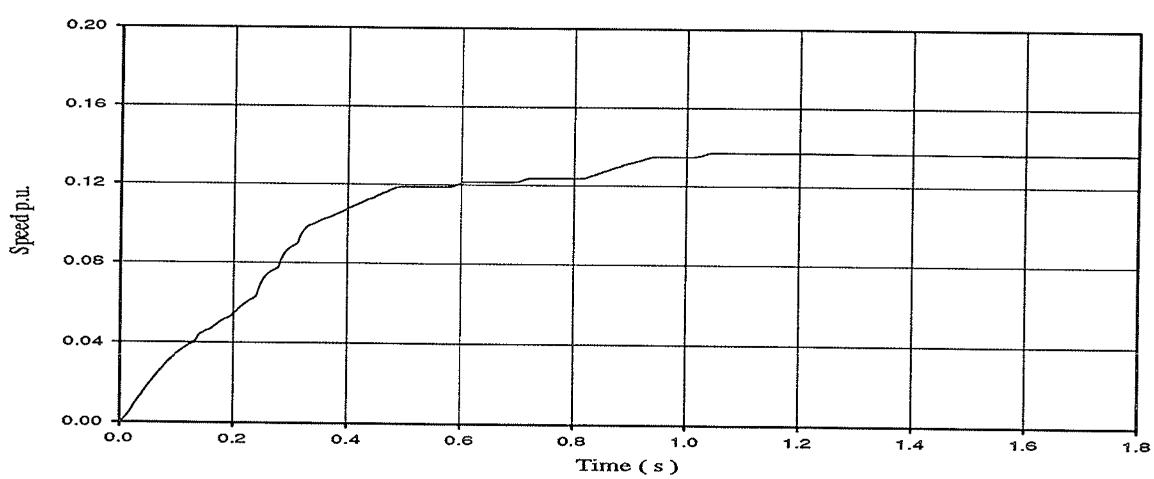
Transmission line number two was selected from reference [19] and modeled with distributed parameters [18]. The specifications of the line, as well as necessary inputs to the distributed parameter model for transmission lines in EMTDC program are presented in Table 4.3.

Table 4.3 – Distributed parameter model for transmission line

Conductor # (1 – 1) ——>	1	Line Lenght(km):	100
Conductor Name:	Partridge	Gnd Res.(ohm–m):	100
Conductor Type (AC/DC)	DC	Low Freq.(Hz):	1.6
V(kV)(AC:L–L,rms,DC:L–G,pk):	22.5	High Freq(Hz)	100
V Phase(Deg.):	0.0	Non–Transposed Conductors	
Line I (kA)(AC:rms/DC:pk):	0.045	Transform Freq.(Hz):	1.6
Line I Phase(Deg.):	0.0		
# of Sub–Conductors:	1		
Sub–Cond Radius(cm):	1.613		
Sub–Cond Spacing(cm):	1.0		
Horiz. Dist. X(m):	0.0		
Height at Tower Y(m):	18.0		
Sag at Midspan(m):	4.5		
DC Resistance(ohms/km):	0.219		

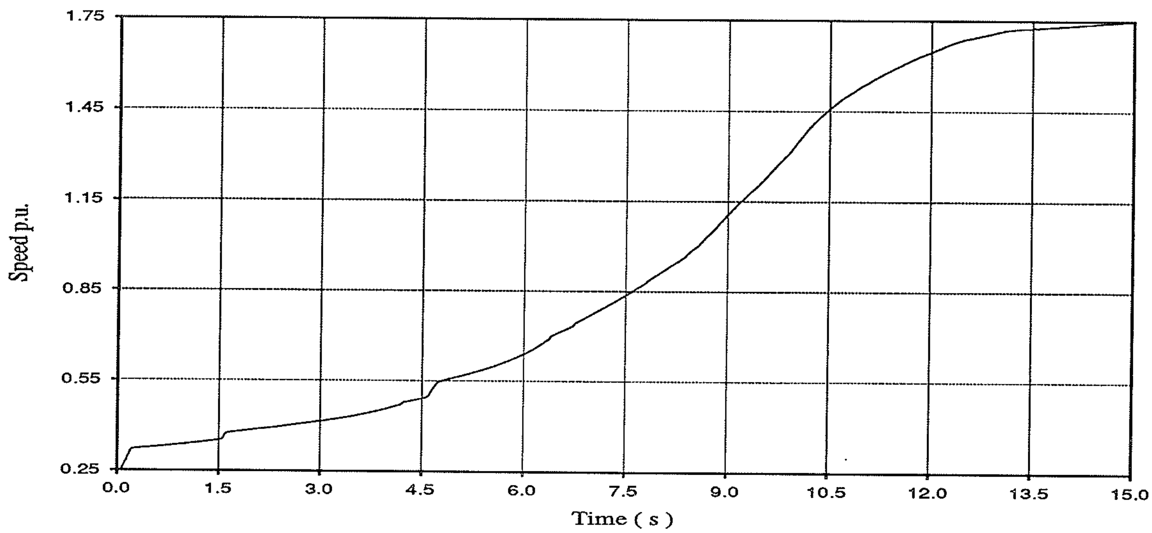
The machine speed is shown in Fig.4.11.

Fig. 4.11 - Speed with Distributed T. Line Model



Next, the process of accelerating the machine, using the generated voltage in the machine for commutating in the inverter was simulated. Transmission line was modelled by distributed parameters, and it was assumed that the machine has been successfully brought to 0.25 p.u. speed. The result of first simulation, using the control regime shown in Fig. 4.5 and setting the $I_{dc0} = 1\ p.u.$ is shown in Fig. 4.12.

Fig. 4.12 - Speed with Idc0=1.0



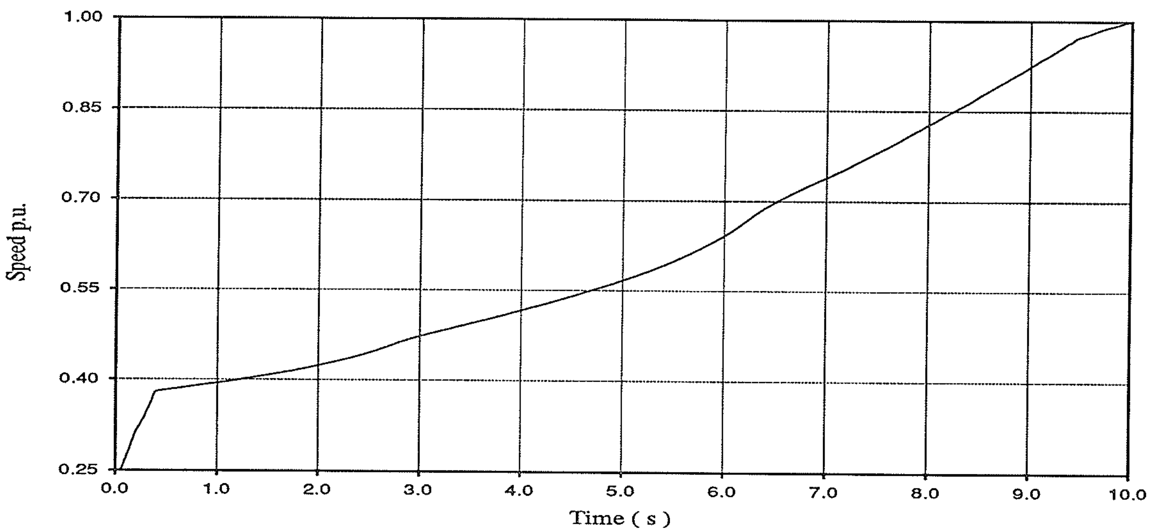
It is obvious that the system is able to drive the machine well above the rated speed, if the setting of the control system, I_{dc0}, is not dynamically adjusted.

To make the process of acceleration confined to the range of rated speed, the DC current setting for control system was dynamically changed according to the following equation:

$$\begin{cases} I_{dc0} = \dfrac{0.95 * (30.0 - TIME)}{30.0} + 0.05\ p.u. & , \mathrm{TIME} < 30.0 \\ I_{dc0} = 0.05\ p.u. & , \mathrm{TIME} > 30.0 \end{cases} \tag{4.1}$$

The result is shown in Fig. 4.13.

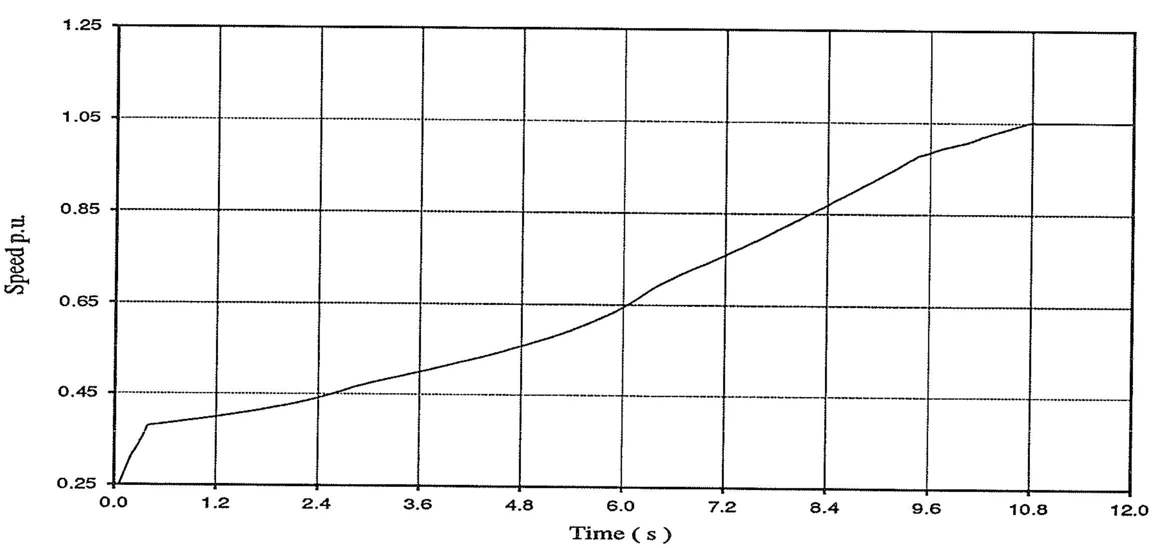
Fig. 4.13 - Speed with Variable IdcO



Since the DC current setting does not approach zero, when the rated speed is achieved, the machine speed still tends to increase beyond the rated value.

Finally, the control system is adjusted to use the speed as a feedback and stop supplying power to the machine when the machine is working at rated speed. In other words, the machine is acting like a DC machine, in which the electromechanical torque is adjusted by the current flowing into the machine. The result of this simulation is shown in Fig. 4.14.

Fig. 4.14 - Speed



All the above simulations indicate the existence of a very strong possibility of starting and accelerating the synchronous machine in the presence of a fairly long transmission line. The importance of transmission line parameters is shown clearly.

Compared to the majority of conventional cases, in which the synchronous machines need to be started while having mechanical loads on their shafts, e.g. in gas turbines, pumps, etc. [15], the proposed scheme does not impose any mechanical load on machine shaft, and the application of the electrical load has to be delayed until the rated speed and the steady state have been achieved. This fact positively contributes to feasibility of the system anticipated operation, and can be regarded as the reason behind the relatively short starting times in the above simulations.

The FORTRAN codes of dynamic subroutines modeling the above systems, as well as the data files used in conjunction with EMTDC program are presented in Appendix B.

At this point, it is worthwhile to elaborate on the reason why the current source inverter (CSI) has been selected for the proposed scheme, whereas in the project proposal a voltage source inverter (VSI) was suggested.

In VSI inverters, because of the stiff DC voltage applied on the inverter thyristors, there exist six diodes, each reversely connected in parallel with one thyristor. During the commutation, the current is diverted from the conducting thyristor and is forced to close its path through the reverse diodes. The forward voltage drop across the diode is large enough to help the outgoing thyristor regain its blocking ability. During the starting simulations, these reverse diodes imposed a negative impact on the starting process, thus preventing the machine from accelerating. In other words, through the path provided by these diodes, the current in the machine windings was able to continue to flow, even when the current in the line had been reduced to zero. The continuous flow of current in the machine produces an alternating torque, which tends to dampen the machine speed, and therefore neutralizes the starting process. The use of CSI, which does not have reverse diodes, eliminated this problem easily.

Moreover, the VSI is highly dependent on the machine generated reactive power for its commutation. The machine must generate enough reactive power to supply the load and to make the inverter output current lead its voltage, if the commutation is to be achieved successfully. This can not be guaranteed when the variations in the load are large and unpredictable. In other words, an abrupt increase in the reactive power demand in the load, can lead to commutation failure in the inverter. The CSI, because of its dependence on the voltages generated in the machine, and because of its ability to adjust its frequency to the machine speed, does not face such a risk.

Use of the CSI instead of the VSI, however, creates a new disadvantage. When using the VSI, the rectifier is responsible for supplying a stiff DC voltage to the system. This can be achieved by setting a constant value of firing angle in the rectifier, without the need to send any feedback from the machine to the rectifier. Other controls are done at the inverter location. But, with a CSI inverter, in order to control the machine, the current injected to the inverter has to be adjusted, based on the feedbacks coming from the machine. In the case of remote loads, where the rectifier and the machine are separated by long distances, the feedback signals must be sent to the rectifier through a reliable communication system, and the failure of the communication system will lead to the failure of the whole system.

It can be concluded from the above facts that the proposed scheme probably can not be regarded as the best choice for supplying the remote loads.

4.3 – Control Regimes

The last closed–loop control system used in previous section, and depicted in Fig. 4.5, has the ability of governing the system under different load conditions. It detects the variations in the speed, resulted from the variations in the load, and by means of decreasing or increasing the frequency inside the inverter, i.e., increasing or decreasing the speed of sending firing signals to thyristors respectively, keeps the machine and the inverter in synchronism. Then, by changing the power flow into the inverter, the control system brings the speed back to its rated value. A machine working under such control system is called a " Self–Controlled Synchronous Machine" (SCSM).

Various SCSM control schemes are introduced in literature, including, for example, reference [20].

4.4 – Summary of the Chapter

In this chapter, the proposed scheme was digitally simulated. It was observed that regardless of the model chosen to represent the transmission line, the machine can be started by the SVFS techniques, and that the machine speed can be brought to the rated speed by implementing a proper control system. The importance of a communication system between the rectifier and the machine was also underlined.

Chapter Five

Conclusions and Recommendations

5.1 – Conclusions

During the course of the current study, the dual wound synchronous machine was analyzed from the circuit point of view. The impedance matrix of the machine was derived from analysis and confirmed by experimental tests. Separate dqo transformations were applied to the two stator windings to develop the two–axis model of the machine. This model provided the equivalent circuit from which steady–state operation could be determined as well as the state form of the machine equations for transient analysis.

Using the results of the above analysis, a digital simulation program for transient and steady state operation of the machine was developed. The program is a compatible subroutine for the EMTDC program. Simulation of the machine by the above mentioned subroutine, named DBLSYNC100, showed good agreement with laboratory observations.

Using the DBLSYNC100 subroutine, the results of the machine simulation showed that the machine can be conveniently controlled in terms of voltage and reactive power generation, as well as speed regulations. Also, it was observed that while working under motor–generator conditions, the machine does not transfer transients in the motor side to the generator side, thus preventing large variations of voltage on the electric loads, when the machine is experiencing transients on the motor side.

Finally the proposed system consisting of a three phase rectifier, a 150 km long transmission line, an inverter and a dual wound synchronous machine was simulated. The synchronous machine is responsible for supplying the electric energy, as well as performing the load commutation on the inverter. The main objective of these simulations was to examine the feasibility of starting the synchronous machine by static variable frequency systems, and to observe the interaction between the machine and the inverter in the accelerating mode, both in the presence of a monopolar DC transmission line.

It was shown that the system can be successfully started, using various models for the transmission line.

Since the inverter is dependent on the synchronous machine for commutation, the inverter must be a current source inverter. The control system must regulate the firing delay angle in the rectifier to regulate the accelerating or decelerating torque in the machine.

The major disadvantage of the proposed scheme is that the speed of the machine, as well as the flow of the power to the load must be controlled by the rectifier, which is located at a long distance from the machine and the load. This necessitates the existence of a reliable communication system between the load location and the rectifier site. Consequently, the failure of the communication system will result in the complete failure of the system. Also, the variations in the machine speed, and consequently in the load frequency, must be compensated by the rectifier, through supplying proper amount of the DC current to create enough accelerating or decelerating torque in the machine. This can create oscillations in the system, depending on the speed at which the current can be changed in the transmission line.

5.2 – Recommendations

Although the feasibility of the proposed system for supplying remote loads was shown by simulations, it is recommended that the control systems be designed and simulated in conjunction with other elements of the system, and the steady state and the fault response of the system be observed for the specific conditions of the remote load to be supplied.

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Appendix A

FORTRAN Codes of Subroutine

DBLSYNC100

and the Support

Subroutines

```
      SUBROUTINE DBLSYNC100(MS,NA,NB,NC,NX,NY,NZ,ANOM,EFD,TMECH,
     +TE,FLD,ITER,PREAL1,PREACT1,PREAL2,PREACT2,OMEGA,CONSPD,
     +THETA,DELTA)
C
C This is the salient-pole double wound synchronous machine simulation
C subroutine. This subroutine calls the following support
C subroutines:
C
C              DINVERT(IX,N)
C              DAXIS(DI,DDI,QI,DQI,IXD,IXQ)
C              DTRDQO(A,B,C,X,Y,Z,D1,Q1,O1,D2,Q2,O2,THETA,GAMA,IDIR)
C              DSAT(IX)
C              SATRN(C,SFI,SFT,IX)
C
C The machine can be run in three ways:
C
C  1. The Motor-Generator case (M-G case). One side is connected to the
C     power source, and the other to the electrical load. There may
C     or may not be some mechanical load on machine's shaft.
C
C  2. The Generator-Generator case (G-G case). The machine is run by a
C     prime-mover and two sets of three-phase voltages, displaced
C     by GAMA, are produced by the machine.
C
C  3. The Motor-Motor case (M-M case). The stator's windings are connected
C     to two separate three-phase voltage sets, or are fed by the
C     output of a 12 pulse inverter.
C
C The argument parameters are:
C
C   - MS,NA,NB,NC,       - Subsystem and nodes for phase a,b,c,
C     NX,NY,NZ             x,y, and z.
C
C   - ANOM               - Put ANOM = 1.0 to activate the subroutine ;
C                          subroutine is skipped if ANOM = 0.0 .
C
C   - EFD                - Applied field voltage (EFD=1.0 for rated
C                          open circuit voltage on the air gap line;
C                          (SEE SECTION 10.1.3 of Manual).
C
C   - TMECH              - Mechanical torque in per unit.
C                          MUST BE A GLOBAL VARIABLE.
C                          Input  variable for M-G and M-M cases.
C                          Output variable for G-G case.
C
C   - TE                 - Electromechanical torque in per unit.
C
C   - FLD                - Field current (FLD = 1.0 when EFD = 1.0
C                          in steady state; SEE SECTION 10.1.3 of Manual)
C
C   - ITER               - number of subiteration steps (usually 1).
C
C   - PREAL1,PREAL2      - Real power in per unit (positive for
C                          generator operation)for sets 1 and 2.
C
C   - PREACT1,PREACT2    - Reactive power in per unit supplied by the
```

```
C                            machine (positive for over excitation)
C                            for sets 1 and 2.
C
C    - OMEGA               - machine angular speed calculated within
C                            program in RAD/S.
C
C    - CONSPD              - For M-G and M-M cases, CONSPD must be 0.0 or a
C                            positive number. Mechanical dynamics determine
C                            the speed with initial speed OMEGA=CONSPD.
C
C                          - For G-G case, CONSPD must be negative and
C                            OMEGA=-CONSPD.
C
C    - THETA               - Rotor's position at the end of each time-step,
C                            in Electric Radians . Always: 0 < THETA < 6.28.
C
C    - DELTA               - The load angle between the field and the direct
C                            axis, in Radians.
C
C
C The input parameters to be read only at the beginning of the run
C (T=0) from the data file in free format are:
C
C - CARD 1- Direct-Axis Rectances: Stator Leakages, X1 and X2;
C           Unsaturated Magnetizing ,XMDO; Stator Mutual Leakage,
C           X12D; Rotor Mutual Leakage, X34D; Damper Leakage, X4D;
C           Field Leakage, X3D.
C
C - CARD 2- Quad.-Axis Reactances: Magnetizing, XMQ; Stator Mutual
C           Leakage, X12Q; Damper Leakage, X3Q.
C
C - CARD 3- Resistances: Stator,R1 and R2; Field, R3D; Direct-Axis
C            damper, R4D; Quad-Axis Damper, R3Q.
C
C - CARD 4- Ineria Constant, H; Base Angular Freq, OMO;
C           Mechanical Damping, D; Phase Shift Between Two Sets
C           Of Stator Windings, GAMA (in degrees).
C           PLEASE NOTE THAT D IS USED TO ALLOW FOR WINDAGE AND
C           ROTATIONAL FRICTION AND THUS OPERATES ON THE P.U. SPEED
C           OF THE MOTOR.  IF D>0.05, D IS LIMITED TO .05 !
C
C - CARD 5- The saturation curve is stored as pairs of points
C           (I,SF), beginning at (0.0,1.0) and (I1,1.0) where
C           SF is the saturation factor and I1 is the per unit
C           current at which the onset of saturation occurs.
C           A maximum of 10 pairs of points can be stored.
C           If less than 10 pairs are used the last pair must
C           be (-1.0,-1.0). The saturation curve in per unit
C           may be input directly or the voltage-current
C           characteristic may be entered again
C           starting with (0.0,0.0) and (I1,V1) to (I9,V9) or
C           (-1.0,-1.0). See subroutine SAT(IX) for further details.
C
C - CARD 6- VBASE1, ABASE1, VBASE2, ABASE2
C           Rated RMS Phase Voltages in KV, and Rated RMS Phase
C           currents in KA, For Both Sets.
```

```
C
C - CARD 7- Initial values for: THETA, ID1, ID2, IQ1, IQ2, ID3
C
C   Where:
C          - THETA is the angle that the D axis of the rotor
C            leads the A phase winding axis towards the
C            B phase winding axis ( The physical rotor angle ! )
C
C            THETA = Load Angle + PI + Phase A Terminal Voltage
C                    Sine Wave Angle.
C
C          - ID1 is the stator's 1st set current transformed
C            to the D axis.
C          - ID2 is the stator's 2nd set current transformed
C            to the D axis.
C          - IQ1 is the stator's 1st set current transformed
C            to the Q axis.
C          - IQ2 is the stator's 2nd set current transformed
C            to the Q axis.
C          - ID3 is the field current
C
C        All currents are referenced on the internal current
C        p.u. bases.
C
C  Note: The Q axis leads the D axis in this model and the
C        curents ID1, ID2, IQ1, and IQ2 are defined as positive
C        into the machine.
C
C  ************************
C  P IS POS. OUT OF THE MACHINE
C  Q IS POS. OUT OF THE MACHINE
C  ************************
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
C  VARIABLE DECLARATIONS
C
      REAL ABASE1,ABASE2,ANOM,ATER,A1
      REAL CINA,CINB,CINC,CINX,CINY,CINZ,CLA,CLB,CLC,CLX,
     +     CLY,CLZ,CON,CONSPD
      REAL D,DDI,DDT,DED,DELT,DELTA,DEQ,DHT,DI,DQI,DT,DTHET,DTHET1
      CHARACTER*72 DUMLIN
      REAL EDI,EFD,EQI
      REAL FINTIM,FLD
      REAL GAMA
      REAL H
      REAL IA,IB,IC,IX,IY,IZ,IM
      INTEGER I,ICH,IIN1,ITER,IXD,IXQ
      INTEGER J
      INTEGER MS
      INTEGER N1TEST,N2TEST,N3TEST,N4TEST,N5TEST,N6TEST,N7TEST,
     +        NA,NB,NC,NEXC,NX,NY,NZ
      REAL NU
      REAL O1,O2,OMEGA,OMO
      REAL PGB,PREACT1,PREACT2,PREAL1,PREAL2,PRINT,PSID1,PSIQ1,
```

```
     +     PSID2,PSIQ2
      REAL QI
      REAL RAMPV1,RAMPV2
      REAL SA1,SA2,SFMT,SFMI,STOR
      REAL TE,THETA,TIME,TMECH,TS
      REAL UD1,UD2,UF,UO1,UO2,UQ1,UQ2
      REAL VA,VAR,VB,VBASE1,VBASE2,VC,VX,VY,VZ
      REAL X1,X2,X12D,X12Q,X34D,XD11,XD22,XF,XI1,XI2,XI3,XI4,
     +     XI5,XI6,XKD,XM,XMDO,XMQ,XT1
C
      COMMON /S1/ TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/ STOR(ND10),NEXC
      COMMON /S4/ VAR(ND11),CON(ND12),PGB(ND13)
      COMMON /S9/ N1TEST,N2TEST,N3TEST,N4TEST,N5TEST,N6TEST,
     +            N7TEST
      DIMENSION DI(4),QI(4),DDI(4),DQI(4),EDI(4),EQI(4),DED(4),
     +          DEQ(4)
C
      IF (TIME.GT.0.0) GO TO 100
C
     IF((N1TEST.NE.ND1).OR.(N2TEST.NE.ND2).OR.(N3TEST.NE.ND3).OR.
     +   (N4TEST.NE.ND4).OR.(N5TEST.NE.ND5).OR.(N6TEST.NE.ND6).OR.
     +   (N7TEST.NE.ND7))THEN
         DUMLIN(1:10) = 'DBLSYNC100'
         A1 = 0.0
         CALL OUTMSG(403,ICH,ICH,ICH, A1, A1, DUMLIN )
      ENDIF
C
C
C       CARD 1: X1,X2,XMDO,X12D,X34D,XKD,XF
C       CARD 2: XMQ,X12Q,XKQ
C       CARD 3: R1,R2,RF,RKD,RKQ
       IIN1=50
C
C  READ FIRST CARD OF MACHINE DATA
C
       CALL RDCMNT
       READ(IIN1,*) X1,X2,XMDO,X12D,X34D,XKD,XF
C
       STOR(NEXC+88)=X1
       STOR(NEXC+89)=X2
       STOR(NEXC+90)=XMDO
       STOR(NEXC+27)=X12D
       STOR(NEXC+2)=X34D
       STOR(NEXC+4)=XKD
       STOR(NEXC+3)=XF
       CALL RDCMNT
       READ (IIN1,*) STOR(NEXC+31),STOR(NEXC+57),STOR(NEXC+34)
       CALL RDCMNT
       READ (IIN1,*) STOR(NEXC+83),STOR(NEXC+84),STOR(NEXC+5),
     +               STOR(NEXC+6),STOR(NEXC+36)
       CALL RDCMNT
       READ (IIN1,*) H,OMO,D,GAMA
       CALL RDCMNT
       READ (IIN1,*) (STOR(NEXC+I),I=61,80)
       CALL RDCMNT
```

```
      READ (IIN1,*) VBASE1,ABASE1,VBASE2,ABASE2
      CALL RDCMNT
      READ (IIN1,*) XI1,XI2,XI3,XI4,XI5,XI6
      STOR(NEXC+96)=XI1
      STOR(NEXC+11)=XI2
      STOR(NEXC+12)=XI3
      STOR(NEXC+41)=XI4
      STOR(NEXC+42)=XI5
      STOR(NEXC+13)=XI6
C
C  STOR(NEXC+99) IS THE LOAD ANGLE + PHASE A TERMINAL VOLTAGE
C  SINE WVAE ANGLE.
C
      STOR(NEXC+99)=STOR(NEXC+96)-3.14159
C
C SET AND STORE BASE VALUES
C
      STOR(NEXC+91)=VBASE1
      STOR(NEXC+93)=ABASE1
      STOR(NEXC+92)=VBASE2
      STOR(NEXC+94)=ABASE2
      GAMA=GAMA*3.1415927/180.0
      STOR(NEXC+98)=GAMA
C
C ESTABLISH SATURATION CHARACTERISTICS AND SET PARAMETERS
C TO INITIAL VALUES.
C
      CALL DSAT(63)
C
      STOR(NEXC+58)=2.0*OMO*H
      STOR(NEXC+59)=D
      STOR(NEXC+60)=OMO
      STOR(NEXC+82)=H
      STOR(NEXC+10)=0.0
      STOR(NEXC+14)=0.0
      STOR(NEXC+32)=0.0
      STOR(NEXC+33)=0.0
      STOR(NEXC+35)=0.0
      STOR(NEXC+40)=0.0
      STOR(NEXC+43)=0.0
      STOR(NEXC+44)=0.0
      STOR(NEXC+87)=0.0
      STOR(NEXC+97)=0.0
      STOR(NEXC+100)=0.0
C
C SET THE FIELD BASE VALUE
C
      STOR(NEXC+95)=STOR(NEXC+5)/STOR(NEXC+90)
C
C SET THE INITIAL SPEED
C
      IF(CONSPD.LT.0.0) THEN
         STOR(NEXC+30) = -CONSPD/OMO
      ELSE
         STOR(NEXC+30) =  CONSPD/OMO
      ENDIF
```

```
C
C INVERT THE QUAD-AXIS INDUCTANCE MATRIX.
C
      CALL DINVERT(30,3)
100   CONTINUE
      IF(ANOM.LE.0.0) GO TO 999
      DT=DELT*STOR(NEXC+60)
C
C  CHECK TO SEE IF DAMPING COEFFICIENT HAS BEEN USED
C  CORRECTLY. (NORMAL=0.0)
C  SINCE THE DAMPING TORQUE OPERATES ON THE PER UNIT SPEED, THE
C  DAMPING COEFFICIENT WILL BE DIVIDED BY OMO IF OUT OF RANGE.
C
      IF(STOR(NEXC+59).GT.0.05)STOR(NEXC+59)=STOR(NEXC+59)
     +                                        /STOR(NEXC+60)
C
C  SETTING INTERFACE IMPEDANCE TO XD11 and XD22
C
      IF (ABS(STOR(NEXC+87)-ANOM).LE.1.0E-05) GO TO 77
      STOR(NEXC+87)=ANOM
      XT1=STOR(NEXC+2)+STOR(NEXC+3)*STOR(NEXC+4)/(STOR(NEXC+3)
     +   +STOR(NEXC+4))
      XD11=STOR(NEXC+88)+STOR(NEXC+90)*XT1/(STOR(NEXC+90)+XT1)
      XD22=STOR(NEXC+89)+STOR(NEXC+90)*XT1/(STOR(NEXC+90)+XT1)
      XD11=STOR(NEXC+91)/STOR(NEXC+93)*XD11
      XD22=STOR(NEXC+92)/STOR(NEXC+94)*XD22
      STOR(NEXC+85)=ANOM*DT*0.5/XD11
      STOR(NEXC+86)=ANOM*DT*0.5/XD22
77    CONTINUE
C
      GGIN(NA,MS)=GGIN(NA,MS)+STOR(NEXC+85)
      GGIN(NB,MS)=GGIN(NB,MS)+STOR(NEXC+85)
      GGIN(NC,MS)=GGIN(NC,MS)+STOR(NEXC+85)
      GGIN(NX,MS)=GGIN(NX,MS)+STOR(NEXC+86)
      GGIN(NY,MS)=GGIN(NY,MS)+STOR(NEXC+86)
      GGIN(NZ,MS)=GGIN(NZ,MS)+STOR(NEXC+86)
C
C  SYSTEM MEASURED VOLTAGES
C
      RAMPV1 = 1.0 / STOR(NEXC+91)
      RAMPV2 = 1.0 / STOR(NEXC+92)
      VA=VDC(NA,MS) * RAMPV1
      VB=VDC(NB,MS) * RAMPV1
      VC=VDC(NC,MS) * RAMPV1
      VX=VDC(NX,MS) * RAMPV2
      VY=VDC(NY,MS) * RAMPV2
      VZ=VDC(NZ,MS) * RAMPV2
C
      DTHET=0.0
C
      DO 300 J=1,ITER
      THETA=STOR(NEXC+96)
      GAMA=STOR(NEXC+98)
C
      CALL DTRDQO(VA,VB,VC,VX,VY,VZ,UD1,UQ1,UO1,UD2,UQ2,UO2,
     +            THETA,GAMA,1)
```

```
      STOR(NEXC+7)=UD1
      STOR(NEXC+37)=UQ1
      STOR(NEXC+8)=UD2
      STOR(NEXC+38)=UQ2
C
C  CALCULATE THE LOAD ANGLE, DELTA.
C
      VD=UD1
      VQ=UQ1
      IF(ABS(VQ).LT.1.0E-6) VQ=1.0E-6
      DELTA=ATAN(VD/VQ)
C
      UF=EFD*STOR(NEXC+95)*1.414214
      STOR(NEXC+9)=UF
C
      DO 1 I=1,4
         DI(I)=STOR(NEXC+I+10)
         QI(I)=STOR(NEXC+I+40)
1     CONTINUE
C
C GET SATURATION FACTOR
C
      IM=DI(1)+DI(2)+DI(3)+DI(4)
      CALL SATRN(IM,SFMI,SFMT,63)
C
C CHECK FOR CHANGE IN SATURATION FACTOR AND INVERT D-AXIS
C INDUCTANCE MATRIX
C
      IF ( ABS(SFMT-STOR(NEXC+97)) .GT. 1.0E-6 ) THEN
C
C SATURATION REQUIRES TANGENTIAL REACTANCE
C
         STOR(NEXC+1)=STOR(NEXC+90)*SFMT
         CALL DINVERT(0,4)
         STOR(NEXC+97)=SFMT
      ENDIF
C
C FLUX CALCULATIONS REQUIRE INSTANTANEOUS REACTANCE
C
      XM=STOR(NEXC+90)*SFMI
      STOR(NEXC+1)=XM
      ATER=ITER
      DDT=DT/ATER
C
C PREDICT THE CURRENTS
C
      IXD=0
      IXQ=30
      CALL DAXIS(DI,DDI,QI,DQI,IXD,IXQ)
C
      DO 4 I=1,4
         EDI(I)=DI(I)+DDT*DDI(I)
         EQI(I)=QI(I)+DDT*DQI(I)
4     CONTINUE
C
C CORRECT THE CURRENTS
```

```
C
       IXD=0
       IXQ=30
       CALL DAXIS(EDI,DED,EQI,DEQ,IXD,IXQ)
       DHT=0.5*DDT
C
       DO 5 I=1,4
          DI(I)=DI(I)+DHT*(DDI(I)+DED(I))
          QI(I)=QI(I)+DHT*(DQI(I)+DEQ(I))
          STOR(NEXC+I+10)=DI(I)
          STOR(NEXC+I+40)=QI(I)
5      CONTINUE
C
       PREAL1 = (-UD1*DI(1)-UQ1*QI(1))*0.5
       PREACT1= (+UD1*QI(1)-UQ1*DI(1))*0.5
       PREAL2 = (-UD2*DI(2)-UQ2*QI(2))*0.5
       PREACT2= (+UD2*QI(2)-UQ2*DI(2))*0.5
C
C
       FLD=DI(3)*STOR(NEXC+90)*0.707107
       X1=STOR(NEXC+88)
       X2=STOR(NEXC+89)
       X12D=STOR(NEXC+27)
       PSID1=XM*(DI(1)+DI(2)+DI(3)+DI(4))+X12D*(DI(1)+DI(2))+X1*DI(1)
       PSID2=XM*(DI(1)+DI(2)+DI(3)+DI(4))+X12D*(DI(1)+DI(2))+X2*DI(2)
       XMQ=STOR(NEXC+31)
       X12Q=STOR(NEXC+57)
       PSIQ1=XMQ*(QI(1)+QI(2)+QI(3))+X12Q*(QI(1)+QI(2))+X1*QI(1)
       PSIQ2=XMQ*(QI(1)+QI(2)+QI(3))+X12Q*(QI(1)+QI(2))+X2*QI(2)
       STOR(NEXC+25)=PSID1
       STOR(NEXC+26)=PSID2
       STOR(NEXC+55)=PSIQ1
       STOR(NEXC+56)=PSIQ2
C
C CALCULATE ELECTROMECHANICAL TORQUE
C
       TE=(PSID1*QI(1)+PSID2*QI(2)-PSIQ1*DI(1)-PSIQ2*DI(2))*0.5
       STOR(NEXC+81)=TE
C
C CALCULATE SHAFT TORQUE OR SHAFT SPEED
C
       OMO=STOR(NEXC+60)
       IF (CONSPD.GE.0.0) THEN
          NU=STOR(NEXC+30)
          TS=TMECH+STOR(NEXC+59)*NU
          NU=NU+DDT*(TE-TS)/STOR(NEXC+58)
          STOR(NEXC+30)=NU
          OMEGA=NU*OMO
       ELSE
          NU=-CONSPD/OMO
          OMEGA=-CONSPD
          STOR(NEXC+30)=NU
          TMECH=TE+STOR(NEXC+59)*NU
       ENDIF
C
C CALCULATE ROTOR'S NEW POSITION
```

```
C
      DTHET1=NU*DDT
      THETA=THETA+DTHET1
      DTHET=DTHET+DTHET1
C
C  STOR(NEXC+99) IS THE LOAD ANGLE + PHASE A TERMINAL VOLTAGE
C  SINE WAVE ANGLE.
C
      STOR(NEXC+99)=STOR(NEXC+99)+(NU-1.0)*DDT
      IF(THETA.GT.6.28318532)THETA=THETA-6.28318532
      STOR(NEXC+96)=THETA
C
300   CONTINUE
C
C END OF INTEGRATION
C
C CONVERT TO A B C SYSTEM CURRENTS
C
      O1=0.0
      O2=0.0
C
      CALL DTRDQO(IA,IB,IC,IX,IY,IZ,DI(1),QI(1),O1,DI(2),QI(2),O2,
     +              THETA,GAMA,-1)
C
      STOR(NEXC+28)=IA
      STOR(NEXC+29)=IX
C
C  OUTPUT CURRENT
C
      SA1=STOR(NEXC+93)*ANOM
      SA2=STOR(NEXC+94)*ANOM
C
      CINA=-IA*SA1
      CINB=-IB*SA1
      CINC=-IC*SA1
      CINX=-IX*SA2
      CINY=-IY*SA2
      CINZ=-IZ*SA2
C
C COMPENSATING CURRENT
C
      CLA=VDC(NA,MS)*STOR(NEXC+85)
      CLB=VDC(NB,MS)*STOR(NEXC+85)
      CLC=VDC(NC,MS)*STOR(NEXC+85)
      CLX=VDC(NX,MS)*STOR(NEXC+86)
      CLY=VDC(NY,MS)*STOR(NEXC+86)
      CLZ=VDC(NZ,MS)*STOR(NEXC+86)
C
C SUM CURRENTS INJECTED INTO NODE
C
      CCIN(NA,MS)=CINA+CLA+CCIN(NA,MS)
      CCIN(NB,MS)=CINB+CLB+CCIN(NB,MS)
      CCIN(NC,MS)=CINC+CLC+CCIN(NC,MS)
      CCIN(NX,MS)=CINX+CLX+CCIN(NX,MS)
      CCIN(NY,MS)=CINY+CLY+CCIN(NY,MS)
      CCIN(NZ,MS)=CINZ+CLZ+CCIN(NZ,MS)
```

```
C
999     NEXC=NEXC+100
        RETURN
        END
C
C ############################################################
C
      SUBROUTINE DINVERT(IX,N)
C
C  This subroutine is called by DBLSYNC100 and inverts the direct
C  axis reactance matrix (IX=0) and the quadrature axis reactance
C  matrix (IX=30). The rank of matrix (NxN) may be either 3 or 4
C  and must be specified.
C
      INCLUDE 'emt.d'
C
C     VARIABLE DECLARATION
C
      INTEGER I,IJ,IX,J,K,L,N,NEXC
      REAL    DET,STOR,T,U
      REAL    XA,XB,XC,XIN,X1,X2,X3,X4,X5,X6,X7,X8,X9
C
      COMMON /S2/ STOR(ND10),NEXC
      DIMENSION IJ(10), XIN(4,4)
C
      XA=STOR(NEXC+IX+1)
      XB=XA+STOR(NEXC+IX+27)
      XC=XA+STOR(NEXC+IX+2)
C
      IF (N.EQ.4) THEN
         XIN(1,1)=XB+STOR(NEXC+88)
         XIN(1,2)=XB
         XIN(1,3)=XA
         XIN(1,4)=XA
         XIN(2,2)=XB+STOR(NEXC+89)
         XIN(2,3)=XA
         XIN(2,4)=XA
         XIN(3,3)=XC+STOR(NEXC+3)
         XIN(3,4)=XC
         XIN(4,4)=XC+STOR(NEXC+4)
         DO 1 I=1,4
         DO 1 J=1,I
         IF(J.EQ.I)GO TO 1
         XIN(I,J)=XIN(J,I)
  1      CONTINUE
         DO 2 I=1,N
         IJ(I)=0
  2      CONTINUE
         L=0
 12      L=L+1
         IF (L.GT.N) GO TO 100
         T=0.0
         DO 11 J=1,N
         IF (IJ(J).GT.0) GO TO 11
         U=ABS(XIN(J,J))
         IF (U.LT.T) GO TO 11
```

```
      T=U
      K=J
 11   CONTINUE
      IJ(K)=1
      XIN(K,K)=1.0/XIN(K,K)
      DO 3 I=1,N
      DO 3 J=1,N
      IF (I-K) 4,3,4
  4   CONTINUE
      IF (J-K) 5,3,5
  5   CONTINUE
      XIN(I,J) = XIN(I,J) - ((XIN(I,K) * XIN(K,K)) * XIN(K,J))
  3   CONTINUE
      DO 6 I=1,N
      IF (I - K) 7,6,7
  7   CONTINUE
      XIN(I,K) = XIN(I,K) * XIN(K,K)
      XIN(K,I) = - (XIN(K,I) * XIN(K,K))
  6   CONTINUE
      GO TO 12
100   CONTINUE
      STOR(NEXC+15)=XIN(1,1)
      STOR(NEXC+16)=XIN(1,2)
      STOR(NEXC+17)=XIN(1,3)
      STOR(NEXC+18)=XIN(1,4)
      STOR(NEXC+19)=XIN(2,2)
      STOR(NEXC+20)=XIN(2,3)
      STOR(NEXC+21)=XIN(2,4)
      STOR(NEXC+22)=XIN(3,3)
      STOR(NEXC+23)=XIN(3,4)
      STOR(NEXC+24)=XIN(4,4)
    ELSE
      X1=XB+STOR(NEXC+88)
      X2=XB
      X3=XA
      X5=XB+STOR(NEXC+89)
      X6=XA
      X9=XA+STOR(NEXC+34)
      X4=X2
      X7=X3
      X8=X6
      DET=X1*(X5*X9-X6*X8)+X2*(X6*X7-X4*X9)+X3*(X4*X8-X5*X7)
      STOR(NEXC+45)=(X5*X9-X8*X6)/DET
      STOR(NEXC+46)=(X8*X3-X2*X9)/DET
      STOR(NEXC+47)=(X2*X6-X5*X3)/DET
      STOR(NEXC+48)=0.0
      STOR(NEXC+49)=(X1*X9-X7*X3)/DET
      STOR(NEXC+50)=(X4*X3-X1*X6)/DET
      STOR(NEXC+51)=0.0
      STOR(NEXC+52)=(X1*X5-X4*X2)/DET
      STOR(NEXC+53)=0.0
      STOR(NEXC+54)=0.0
    ENDIF
    RETURN
    END
C
```

```
C ##############################################################
C
      SUBROUTINE DAXIS(D,DD,Q,DQ,IXD,IXQ)
C
C This subroutine is called by DBLSYNC100.
C The inverted matrices inv(Ld) or inv(Lq) are specified
C by index IXD and IXQ; 0 for inv(Ld) and 30 for inv(Lq).
C
C  THIS SUBROUTINE GIVES THE A.X+B.U TERMS IN THE EQUATION
C  DX/DT=A.X+B.U WHERE X IS THE CURRENTS.
C
C  IXD=0  FOR DIRECT AXIS
C  IXQ=30 FOR QUAD-AXIS
C
      INCLUDE 'emt.d'
C
C  VARIABLE DECLARATIONS
C
      REAL D,DD,DQ
      INTEGER I,IXD,IXQ
      INTEGER J
      INTEGER K
      INTEGER NEXC
      REAL NU
      REAL PSID1,PSID2,PSIQ1,PSIQ2
      REAL Q
      REAL R1,R2,RF,RKD,RKQ
      REAL SD,SQ,STOR
      REAL UD1,UD2,UQ1,UQ2,UF
      REAL X1,X2,X12D,X12Q,XD,XMD,XMQ,XQ
C
      COMMON /S2/STOR(ND10),NEXC
C
      DIMENSION XD(4,4),XQ(4,4),D(4),Q(4),SD(4),SQ(4),DD(4),DQ(4)
C
      IXD=IXD+15
      IXQ=IXQ+15
C
C  FILLING IN INVERSE INDUCTION MATRIX FROM STORAGE
C
      K=0
C
      DO 2 I=1,4
        DO 1 J=I,4
          XD(I,J)=STOR(NEXC+IXD+K)
          XQ(I,J)=STOR(NEXC+IXQ+K)
          K=K+1
  1     CONTINUE
        DD(I)=0.0
        DQ(I)=0.0
  2   CONTINUE
C
      XD(2,1)=XD(1,2)
      XD(3,1)=XD(1,3)
      XD(3,2)=XD(2,3)
      XD(4,1)=XD(1,4)
```

```
      XD(4,2)=XD(2,4)
      XD(4,3)=XD(3,4)
      XQ(2,1)=XQ(1,2)
      XQ(3,1)=XQ(1,3)
      XQ(3,2)=XQ(2,3)
      XQ(4,1)=XQ(1,4)
      XQ(4,2)=XQ(2,4)
      XQ(4,3)=XQ(3,4)
      XMD=STOR(NEXC+1)
      XMQ=STOR(NEXC+31)
      X1=STOR(NEXC+88)
      X2=STOR(NEXC+89)
      UD1=STOR(NEXC+7)
      UD2=STOR(NEXC+8)
      UQ1=STOR(NEXC+37)
      UQ2=STOR(NEXC+38)
      UF=STOR(NEXC+9)
      RF=STOR(NEXC+5)
      RKD=STOR(NEXC+6)
      RKQ=STOR(NEXC+36)
      X12D=STOR(NEXC+27)
      X12Q=STOR(NEXC+57)
      R1=STOR(NEXC+83)
      R2=STOR(NEXC+84)
      NU=STOR(NEXC+30)
      PSID1=XMD*(D(1)+D(2)+D(3)+D(4))+X12D*(D(1)+D(2))+X1*D(1)
      PSID2=XMD*(D(1)+D(2)+D(3)+D(4))+X12D*(D(1)+D(2))+X2*D(2)
      PSIQ1=XMQ*(Q(1)+Q(2)+Q(3))+X12Q*(Q(1)+Q(2))+X1*Q(1)
      PSIQ2=XMQ*(Q(1)+Q(2)+Q(3))+X12Q*(Q(1)+Q(2))+X2*Q(2)
      SD(1)=UD1-R1*D(1)+NU*PSIQ1
      SD(2)=UD2-R2*D(2)+NU*PSIQ2
      SD(3)=UF-RF*D(3)
      SD(4)=-RKD*D(4)
      SQ(1)=UQ1-R1*Q(1)-NU*PSID1
      SQ(2)=UQ2-R2*Q(2)-NU*PSID2
      SQ(3)=-RKQ*Q(3)
      SQ(4)=0.0
C
      DO 3 I=1,4
         DO 4 J=1,4
            DD(I)=DD(I)+XD(I,J)*SD(J)
            DQ(I)=DQ(I)+XQ(I,J)*SQ(J)
4        CONTINUE
3     CONTINUE
C
      RETURN
      END
C
C ##########################################################
C
      SUBROUTINE DTRDQO(A,B,C,X,Y,Z,D1,Q1,O1,D2,Q2,O2,THETA,
     +             GAMA,IDIR)
C
C This subroutine performs the three phase to D,Q,O transformation
C (IDIR=1) and the inverse transformation (IDIR=-1).
C
```

```
C  VARIABLE DECLARATIONS
C
      REAL A
      REAL B
      REAL C,C11,C12,C13,C21,C22,C23
      REAL D1,D2,DEG120
      REAL GAMA
      INTEGER IDIR
      REAL O1,O2
      REAL Q1,Q2
      REAL S11,S12,S13,S21,S22,S23
      REAL THETA
      REAL X
      REAL Y
      REAL Z
C
      DEG120=2.094395103
      C11=COS(THETA)
      C12=COS(THETA-DEG120)
      C13=0.0-C11-C12
      C21=COS(THETA+GAMA)
      C22=COS(THETA+GAMA-DEG120)
      C23=0.0-C21-C22
      S11=SIN(THETA)
      S12=SIN(THETA-DEG120)
      S13=0.0-S11-S12
      S21=SIN(THETA+GAMA)
      S22=SIN(THETA+GAMA-DEG120)
      S23=0.0-S21-S22
C
      IF(IDIR.LT.0) GO TO 66
C
C ABC AND XYZ TO DQO1 AND DQO2 CONVERSION
C
      D1=(C11*A+C12*B+C13*C)*0.66666667
      Q1=(-S11*A-S12*B-S13*C)*0.66666667
      O1=(A+B+C)*0.33333333
      D2=(C21*X+C22*Y+C23*Z)*0.66666667
      Q2=(-S21*X-S22*Y-S23*Z)*0.66666667
      O2=(X+Y+Z)*0.33333333
      RETURN
C
C DQO1 and DQO2 TO ABC and XYZ CONVERSION
C
66    A=(C11*D1-S11*Q1)+O1
      B=(C12*D1-S12*Q1)+O1
      C=(C13*D1-S13*Q1)+O1
      X=(C21*D2-S21*Q2)+O2
      Y=(C22*D2-S22*Q2)+O2
      Z=(C23*D2-S23*Q2)+O2
C
      RETURN
      END
C
C ##########################################################
C
```

```
      SUBROUTINE DSAT(IS)
C
C This subroutine stores the saturation characteristic for
C mutual magnetizing reactance (IS = 63).
C This subroutine is called by DBLSYNC100 and requires no storage.
C Ten pair of points (I,SF) are stored where SF is the saturation factor
C and I is the per unit current. When entering data via card 5, the first
C point must be (0.0,1.0) and the second (I1.0,1.0) where I1 is the per
C unit current at which the onset of saturation occurs. If less than ten
C points are available , the last pair should be (-1.0,-1.0). When the
C saturation factors are entered the subroutine checks for monotonically
C decreasing factors with monotonically increasing currents and returns.
C
C Alternately a voltage-current characteristic may be entered with the
C first pair of points (0.0,0.0) and the second (I1,V1) where I1 is the
C current in any units at which saturation commences. The voltage must
C be input in per unit. Again if less than 10 points are available the
C last pair entered must be (-1.0,-1.0) The program in this case
C replaces the voltage with the saturation factor and rescales the
C current to a per unit value based on the unsaturated value of
C inductance previously input.
C
      INCLUDE 'emt.d'
C
C  VARIABLE DECLARATIONS
C
      REAL AB
      CHARACTER*72 DUMLIN
      INTEGER IS,ISF
      INTEGER J
      INTEGER NEXC
      REAL STOR
      REAL XO
C
      COMMON /S2/ STOR(ND10),NEXC
      ISF = IS + 16
      IF ( (STOR(NEXC+IS-1).GT.0.999).AND.
     +     (STOR(NEXC+IS-1).LE.1.001) ) GOTO 8
      XO = STOR(NEXC+IS+1)/STOR(NEXC+IS)
      STOR(NEXC+IS-1) = 1.0
C
C CALCULATE SATURATION FACTOR FROM VOLTAGE-CURRENT CURVE.
C
      AB = 1.0
      AB = XO/STOR(NEXC+90)*SQRT(2.0)
      DO 1 J= IS,ISF,2
         IF (STOR(NEXC+J).LT.0.0) GOTO 8
         STOR(NEXC+J+1) = STOR(NEXC+J+1)/(STOR(NEXC+J)*XO)
         STOR(NEXC+J) = AB*STOR(NEXC+J)
1     CONTINUE
8     DO 2 J=IS,ISF,2
         IF (STOR(NEXC+J).LT.0.0) RETURN
         IF (STOR(NEXC+J).LT.STOR(NEXC+J-2)) GOTO 3
         IF (STOR(NEXC+J+1).GT.STOR(NEXC+J-1)) GOTO 3
2     CONTINUE
      RETURN
```

```
3     CALL OUTMSG(403,NEXC,NEXC,NEXC, AB, AB, DUMLIN )
      RETURN
      END
C
C ########################################################
C
      SUBROUTINE SATRN(C,SFI,SFT,IS)
C
C This subroutine is called by DBLSYNC100 and determines
C saturation factors based on the current for the mutual
C reactance (IS=63).
C
C The instantaneous saturation factor is determined
C by linear interpolation between points on the curve and by an
C exponential decay beyond the last points (this ensures that for very
C high currents the reactance remains positive).
C
C The tangential saturation factor is not interpolated and is
C obtained directly from the entered data.
C
      INCLUDE 'emt.d'
C
C  VARIABLE DECLARATIONS
C
      REAL ALPHA
      REAL C,CO
      REAL DI,DS
      INTEGER IS,ISF,IX
      INTEGER J
      INTEGER NEXC
      REAL SFI,SFT,SFO,STOR
C
      COMMON /S2/ STOR(ND10),NEXC
      ISF=IS+16
C
      DO 1 J=IS,ISF,2
         IX=J-1
         IF(STOR(NEXC+J).LT.0.0) GO TO 3
         IF(STOR(NEXC+J).GT.C) GO TO 2
1     CONTINUE
      IX = IX+2
      GO TO 3
C
C Current is Within Tables
C
2     DI=1.0/(STOR(NEXC+IX+1)-STOR(NEXC+IX-1))
      DS=STOR(NEXC+IX+2)-STOR(NEXC+IX)
C
C Interpolated Instantaneous Saturation Factor
C
      SFI=STOR(NEXC+IX)+DS*(C-STOR(NEXC+IX-1)) * DI
C
C Non-Interpolated Tangential Saturation Factor
C
      SFT=( (STOR(NEXC+IX+2)*STOR(NEXC+IX+1))-
     +      (STOR(NEXC+IX  )*STOR(NEXC+IX-1))  ) * DI
```

```
      RETURN
C
C Exponential Decay
C
3     SFO = STOR(NEXC+IX-2)
      CO  = STOR(NEXC+IX-3)
      ALPHA=ALOG(STOR(NEXC+IX)/SFO)/(CO-STOR(NEXC+IX-1))
      SFI  = SFO*EXP(ALPHA*(CO-C))
      DI=1.0/(STOR(NEXC+IX-1)-STOR(NEXC+IX-3))
C
C Non-Interpolated Tangential Saturation Factor of the Last Section
C
      SFT=((STOR(NEXC+IX)*STOR(NEXC+IX-1))-
     +       (STOR(NEXC+IX-2)*STOR(NEXC+IX-3)))*DI
      RETURN
      END
```

Appendix B

FORTRAN Codes of Subroutines

DSDYN & DSOUT

and the Datafiles

for Starting and Accelerating

Simulations

```
      SUBROUTINE DSDYN
C
C This subroutine simulates the system with transmission line being
C modelled with both lumped and distributed parameters, and starts
C the synchronous machine from standstill by pulsing action.
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/ TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/ STOR(ND10),NEXC
      COMMON /S4/ VAR(ND11),CON(ND12),PGB(ND13)
      COMMON /S10/ PULS(6),CT(6)
C
C Variable declarations.
C
      REAL A0,ALPHA,AORD
      REAL CDD,CT,DTHET
      REAL EBO,EFD,EFVD,E0,E1,F,FLD,GAMMA,IMAX,P1,P2,PI,PI_2,Q1,Q2
      REAL RDT,ROFF,RON,SP,SPEED,THETA,V0
      REAL TIME,DELT,PRINT,FINTIM,CON,VAR,VMAX,PGB,STOR
      INTEGER NEXC,PULS
C
C Set the initial values.
C
      IF(TIME.LT.DELT) THEN
C
      PI   = 3.141592654
      PI_2= 6.283185308
C
      RON  = 0.005
      ROFF = 1.0E+6
      EBO  = 1.0E+5
      EFVD = 0.001
      RDT  = 5.0E+5
      CDD  = 0.05
C
C  E0    - Initial value of EFD
C  E1    - Final value of EFD
C  TF    - Time to ramp EFD
C  V0    - Voltage during the switching process (per unit)
C  A0    - AORD during the first phase of switching
C  F     - System frequency
C  SPEED - Machine speed at TIME=0.0 (per unit)
C
      E0    = VAR(1)
      E1    = VAR(2)
      TF    = VAR(3)
      V0    = VAR(4)
      A0    = ACOS(V0)+PI/6.0
      F     = VAR(5)
      SPEED = VAR(6)
C
      THETA=0.0
      DTHET=0.0
      OMEGA=SPEED*376.99
```

```
      DO 1 I=1,6
       CT(I)=0.0
  1   CONTINUE
C
      ENDIF
C
C  Source Voltages
C
      T1=F*PI_2*TIME
      T2=PI_2/3.0
      VMAX=1.41*8.87
      ES(18,1)=VMAX*SIN(T1)
      ES(19,1)=VMAX*SIN(T1-T2)
      ES(20,1)=VMAX*SIN(T1+T2)
C
C Control system's model
C
      CALL DCONT(A0,AORD,THETA,IT1,IT2,DTHET,IPULS)
C
C Rectifier's model
C
      CALL G6P200(1,18,19,20,
     &            14,15,17, 0,14,16,
     &            15, 0,14,17,16, 0,
     &            AORD,10.0,100.0,F,1,1,0,
     &            ALPHA,GAMMA,RDT,CDD,RON,ROFF,EFVD,EBO)
C
C Inverter's model
C
      CALL THYR25(1,10, 7,RON,ROFF,PULS(1),EBO,EFVD,RDT,CDD,CT(1))
C
      CALL THYR25(1, 9, 0,RON,ROFF,PULS(2),EBO,EFVD,RDT,CDD,CT(2))
C
      CALL THYR25(1,10, 8,RON,ROFF,PULS(3),EBO,EFVD,RDT,CDD,CT(3))
C
      CALL THYR25(1, 7, 0,RON,ROFF,PULS(4),EBO,EFVD,RDT,CDD,CT(4))
C
      CALL THYR25(1,10, 9,RON,ROFF,PULS(5),EBO,EFVD,RDT,CDD,CT(5))
C
      CALL THYR25(1, 8, 0,RON,ROFF,PULS(6),EBO,EFVD,RDT,CDD,CT(6))
C
C Field voltage
C
      IF(TIME.LT.TF)THEN
       EFD = E0 + (E1-E0)*TIME/TF
      ELSE
       EFD = E1
      ENDIF
C
      TMECH =0.0
      CONSPD=VAR(9)*376.99
C
C Machine's model
C
      CALL DBLSYNC100(1,7,8,9,4,5,6,1.0,EFD,TMECH,TE,FLD,1,
     +               P1,Q1,P2,Q2,OMEGA,CONSPD,THETA,DELTA,
```

```
     +                    DTHET)
C
      SPEED=OMEGA/376.99
C
      IMAX=1.0/30.0
C
      PGB( 1)=CDC(10,11,1)/IMAX
      PGB( 2)=(CDC(7,10,1) - CDC(7,7,1))/IMAX
      PGB( 3)=(CDC(8,10,1) - CDC(8,8,1))/IMAX
      PGB( 4)=(CDC(9,10,1) - CDC(9,9,1))/IMAX
      PGB( 5)=CDC(18,18,1)/IMAX
      PGB( 7)=VDC(18,1)/VMAX
      PGB( 8)=VDC(15,1)/VMAX
      PGB( 9)=VDC(14,1)/VMAX
      PGB(10)=VDC(10,1)/VMAX
      PGB(11)=AORD
      PGB(12)=VDC(7,1)/VMAX
      PGB(13)=VDC(8,1)/VMAX
      PGB(14)=VDC(9,1)/VMAX
      PGB(15)=TE
      PGB(16)=SPEED
      PGB(17)=THETA
      PGB(18)=IPULS
      PGB(19)=EFD
      PGB(20)=FLD
      PGB(21)=CT(1)/IMAX
      PGB(22)=CT(2)/IMAX
      PGB(23)=CT(3)/IMAX
      PGB(24)=CT(4)/IMAX
      PGB(25)=CT(5)/IMAX
      PGB(26)=CT(6)/IMAX
      PGB(27)=IT1
      PGB(28)=IT2
      PGB(29)=CT(IT1)/IMAX
      PGB(30)=CT(IT2)/IMAX
C
      RETURN
      END
C
C ######################################################################
C
      SUBROUTINE DSOUT
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/ TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/ STOR(ND10),NEXC
      COMMON /S4/ VAR(ND11),CON(ND12),PGB(ND13)
C
      REAL TIME,DELT,PRINT,FINTIM,CON,VAR,VMAX,PGB,STOR
C
      RETURN
      END
C
C ######################################################################
```

```
C
      SUBROUTINE DCONT(A0,AORD,THETA,IT1,IT2,DTHET,IPULS)
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/  TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/  STOR(ND10),NEXC
      COMMON /S4/  VAR(ND11),CON(ND12),PGB(ND13)
      COMMON /S10/ PULS(6),CT(6)
C
      REAL ANGLE,AORD,A0,CT,DTHET,PI,PI_2
      REAL ROTATE,ROT1,ROT2,THETA,TIMER1,TOFF
      REAL TIME,DELT,PRINT,FINTIM,CON,VAR,VMAX,PGB,STOR
      INTEGER INDEX,IPULS,IT1,IT2,K,PULS
C
      PI   = 3.141592654
      PI_2 = 6.283185308
C
      IF(TIME.LT.DELT)THEN
       TOFF   = DELT
       TIMER1= TOFF
       IPULS = 1
       INDEX = 1
       ROTATE= 0.0
      ENDIF
C
      ROTATE=ROTATE+DTHET
      ROT1   = THETA*180.0/PI
      ROT2   = ROTATE*180.0/PI
c
      IF(IPULS.EQ.1) GO TO 20
      IF(INDEX.EQ.1) GO TO 20
C
      IF(CT(IT1).LE.0.0.AND.CT(IT2).LE.0.0.AND.ROT2.GE.60.01)THEN
       TIMER1=0.0
      ENDIF
C
20    CONTINUE
C
      IF(TIMER1.LT.TOFF) THEN
       INDEX = 1
       AORD=3.7
       GO TO 16
      ELSE
       INDEX = 0
       IF(TIMER1.EQ.TOFF) THEN
        K=0
        IF(ROT1.GE.  0.0.AND.ROT1.LT. 60.0) K=0
        IF(ROT1.GE. 60.0.AND.ROT1.LT.120.0) K=1
        IF(ROT1.GE.120.0.AND.ROT1.LT.180.0) K=2
        IF(ROT1.GE.180.0.AND.ROT1.LT.240.0) K=3
        IF(ROT1.GE.240.0.AND.ROT1.LT.300.0) K=4
        IF(ROT1.GE.300.0.AND.ROT1.LT.360.0) K=5
        IF(ROT1.GT.360.0) ROT1 = ROT1 - 360.0
        ROTATE=(ROT1-K*60.0)*PI/180.0
```

```
        ENDIF
       ENDIF
C
       ROT2  = ROTATE*180.0/PI
       ANGLE = 58.0
       IF(ROT2.LT.ANGLE)THEN
        IPULS = 1
       ELSE
        IPULS = 0
       ENDIF
C
       DO 8 I=1,6
       PULS(I) = 0
8      CONTINUE
C
       IF(IPULS.EQ.1) THEN
        AORD=A0
        IF(K.EQ.0) GO TO 9
        IF(K.EQ.1) GO TO 10
        IF(K.EQ.2) GO TO 11
        IF(K.EQ.3) GO TO 12
        IF(K.EQ.4) GO TO 13
        IF(K.EQ.5) GO TO 14
C
9       PULS(3)=1
        PULS(2)=1
        IT1=3
        IT2=2
        GO TO 15
10      PULS(4)=1
        PULS(3)=1
        IT1=3
        IT2=4
        GO TO 15
11      PULS(5)=1
        PULS(4)=1
        IT1=5
        IT2=4
        GO TO 15
12      PULS(6)=1
        PULS(5)=1
        IT1=5
        IT2=6
        GO TO 15
13      PULS(6)=1
        PULS(1)=1
        IT1=1
        IT2=6
        GO TO 15
14      PULS(2)=1
        PULS(1)=1
        IT1=1
        IT2=2
C
15      CONTINUE
       ELSE
```

```
        AORD=3.7
       ENDIF
C
16     CONTINUE
       TIMER1=TIMER1+DELT
C
       RETURN
       END
```

```
      SUBROUTINE DSDYN
C
C This subroutine simulates the acceleration of the machine.
C Transmission line is modeled with distributed parameters.
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/ TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/ STOR(ND10),NEXC
      COMMON /S4/ VAR(ND11),CON(ND12),PGB(ND13)
      COMMON /S10/ PULS(6),CT(6)
C
C Variable declarations.
C
      REAL ALPHA1,AORD
      REAL CDD,CT,CONSPD,DELTA
      REAL EBO,EFD,EFVD,EF0,F,FLD,GAMMA
      REAL ID,IMAX1,IMAX2
      INTEGER IPULS,IT1,IT2
      REAL OMEGA,P1,P2,PI,PI_2,Q1,Q2,RDT,ROFF,RON,SPD,SPEED
      REAL TE,TFR,THETA,TMECH,T1,T2,VMAX1,VMAX2
      REAL TIME,DELT,PRINT,FINTIM,CON,VAR,PGB,STOR
      INTEGER NEXC,PULS
C
C Set the initial values.
C
      IF(TIME.LT.DELT) THEN
C
      PI   = 3.141592654
      PI_2 = 6.283185308
C
      TIMER= 0.0
      RON  = 0.005
      ROFF = 1.0E+6
      EBO  = 1.0E+5
      EFVD = 0.001
      RDT  = 5.0E+5
      CDD  = 0.05
C
C  F     - System frequency.
C  SPD   - Machine speed at TIME=0.0 (per unit).
C  SPEED - Machine speed.
C  EF0   - Machine field voltage at TIME=0.0.
C  TFR   - Time to let the machine spin freely.
C  THETA - Rotor's mechanical position.
C  DELTA - Rotor's load angle.
C
      F     = VAR(1)
      SPD   = VAR(2)
      SPEED = SPD
      EF0   = VAR(3)
      THETA = VAR(4)
      TFR   = VAR(5)
      DELTA = 0.0
C
```

```
      ENDIF
C
C  Source Voltages
C
      VMAX1=1.41*9.617
      VMAX2=22.5
      IMAX1=0.0347
      IMAX2=0.0444
      T1=F*PI_2*TIME
      T2=PI_2/3.0
C
      ES(18,1)=VMAX1*SIN(T1)
      ES(19,1)=VMAX1*SIN(T1-T2)
      ES(20,1)=VMAX1*SIN(T1+T2)
C
C ID   - DC current in the T. Line, in per unit.
C AORD - Delay angle for the rectifier.
C
      ID=(CDC(10,11,1))/IMAX2
      CALL DCONT1(ID,AORD,SPEED)
C
      ALPHA1=0.0
      CALL DCONT2(THETA,ALPHA1,DELTA,IPULS,IT1,IT2)
C
C  Let the machine spin freely for TFR second.
C
      IF(TIMER.LT.TFR) THEN
       AORD=3.7
       DO 1 I=1,6
        PULS(I)=0
  1    CONTINUE
      ENDIF
C
C Rectifier's model.
C
      CALL G6P200(1,18,19,20,
     &             14,15,17, 0,14,16,
     &             15, 0,14,17,16, 0,
     &             AORD,10.0,100.0,F,1,1,0,
     &             ALPHA,GAMMA,RDT,CDD,RON,ROFF,EFVD,EBO)
C
C Inveter's model.
C
      CALL THYR25(1,10, 7,RON,ROFF,PULS(1),EBO,EFVD,RDT,CDD,CT(1))
C
      CALL THYR25(1, 9, 0,RON,ROFF,PULS(2),EBO,EFVD,RDT,CDD,CT(2))
C
      CALL THYR25(1,10, 8,RON,ROFF,PULS(3),EBO,EFVD,RDT,CDD,CT(3))
C
      CALL THYR25(1, 7, 0,RON,ROFF,PULS(4),EBO,EFVD,RDT,CDD,CT(4))
C
      CALL THYR25(1,10, 9,RON,ROFF,PULS(5),EBO,EFVD,RDT,CDD,CT(5))
C
      CALL THYR25(1, 8, 0,RON,ROFF,PULS(6),EBO,EFVD,RDT,CDD,CT(6))
C
      EFD    = EF0
```

```
      TMECH  = 0.0
      CONSPD = SPD*376.99
C
C Machine's model.
C
      CALL DBLSYNC100(1,7,8,9,4,5,6,1.0,EFD,TMECH,TE,FLD,1,
     +                P1,Q1,P2,Q2,OMEGA,CONSPD,THETA,DELTA)
C
      SPEED=OMEGA/376.99
C
C Phase a's real angle.
C
      THETA1=THETA+PI
      IF(THETA1.GE.PI_2)THETA1=THETA1-PI_2
C
C Output quantities.
C
      PGB( 1)=CDC(10,11,1)/IMAX2
      PGB( 2)=(CDC(7,10,1) - CDC(7,7,1))/IMAX1
      PGB( 3)=(CDC(8,10,1) - CDC(8,8,1))/IMAX1
      PGB( 4)=(CDC(9,10,1) - CDC(9,9,1))/IMAX1
      PGB( 5)=CDC(18,18,1)/IMAX1
      PGB( 7)=VDC(18,1)/VMAX1
      PGB( 8)=VDC(15,1)/VMAX1
      PGB( 9)=VDC(14,1)/VMAX2
      PGB(10)=VDC(10,1)/VMAX2
      PGB(11)=ALPHA1
      PGB(12)=VDC(7,1)/VMAX1
      PGB(13)=VDC(8,1)/VMAX1
      PGB(14)=VDC(9,1)/VMAX1
      PGB(15)=TE
      PGB(16)=SPEED
      PGB(17)=THETA1
      PGB(18)=EFD
      PGB(19)=FLD
      PGB(20)=IPULS
      PGB(21)=P1
      PGB(22)=P2
      PGB(23)=Q1
      PGB(24)=Q2
      PGB(25)=CT(1)/IMAX2
      PGB(26)=CT(2)/IMAX2
      PGB(27)=CT(3)/IMAX2
      PGB(28)=CT(4)/IMAX2
      PGB(29)=CT(5)/IMAX2
      PGB(30)=CT(6)/IMAX2
      PGB(31)=IT1
      PGB(32)=IT2
      PGB(33)=CT(IT1)/IMAX2
      PGB(34)=CT(IT2)/IMAX2
      PGB(35)=AORD
      PGB(36)=VDC(4,1)/VMAX1
      PGB(37)=VDC(5,1)/VMAX1
      PGB(38)=VDC(6,1)/VMAX1
      PGB(39)=THETA
      PGB(40)=DELTA
```

```
C
      TIMER=TIMER+DELT
C
      RETURN
      END
C
C ########################################################################
C
      SUBROUTINE DSOUT
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/ TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/ STOR(ND10),NEXC
      COMMON /S4/ VAR(ND11),CON(ND12),PGB(ND13)
C
      RETURN
      END
C
C ########################################################################
C
      SUBROUTINE DCONT1(ID,AORD,SPEED)
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/  TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/  STOR(ND10),NEXC
      COMMON /S4/  VAR(ND11),CON(ND12),PGB(ND13)
C
C Variable declarations.
C
      REAL AINT,AORD,AORD0,ERROR,ID,ID0
      INTEGER INDEX
      REAL PI,PI_2,PI_6,SPD,SPEED,TID0
C
      IF(TIME.LT.DELT) THEN
C
       PI   = 3.141592654
       PI_2= PI/2.0
       PI_6= PI/6.0
C
C  SPD - Machine speed at TIME=0.0 (per unit)
C
       SPD   = VAR(2)
C
      ENDIF
C
      AORD0 = PI
C
      TID0  = 30.0
      IF(SPEED.LT.1.001) THEN
       ID0 = 0.95*(TID0-TIME)/TID0+0.05
       INDEX=0
      ELSE
```

```
        ID0 = 0.0
        INDEX=1
      ENDIF
C
      ERROR = ID0-ID
C
      AINT=-PI3(PI,20.0,-10.0,10.0,0.0,ERROR)
C
      AORD=AORD0+AINT
      IF(AORD.GT.PI)AORD=PI
      IF(AORD.LT. 0.0)AORD=0.0
      AORD=AORD+PI_6
C
      IF(INDEX.EQ.1)AORD=3.7
C
      RETURN
      END
C
C ######################################################################
C
      SUBROUTINE DCONT2(THETA,ALPHA1,DELTA,IPULS,IT1,IT2)
C
      INCLUDE 'emt.d'
      INCLUDE 'emt.e'
C
      COMMON /S1/  TIME,DELT,ICH,PRINT,FINTIM
      COMMON /S2/  STOR(ND10),NEXC
      COMMON /S4/  VAR(ND11),CON(ND12),PGB(ND13)
      COMMON /S10/ PULS(6),CT(6)
C
C Variable declarations.
C
      REAL AK,ALPHA1,ALPHA2,ALPHA3
      INTEGER IPULS,IT1,IT2,K
      REAL PI,PI_2
      INTEGER  PULS
      REAL THETA,THETA1,THETA2,THETA3,THETA4
C
      IF(TIME.LT.DELT)THEN
       PI    = 3.141592654
       PI_2  = 6.283185308
      ENDIF
C
      DO 1 I=1,6
       PULS(I)=0
1     CONTINUE
C
C THETA1 - Phase a angle + load angle.
C
      THETA1=THETA+PI
      IF(THETA1.GE.PI_2) THETA1=THETA1-PI_2
C
C THETA2 - Phase a angle, in degrees.
C
      THETA2=THETA1-DELTA
      IF(THETA2.LT. 0.0)THETA2=THETA2+PI_2
```

```
      IF(THETA2.GE.PI_2)THETA2=THETA2-PI_2
      THETA2=THETA2*180.0/PI
C
C THETA3 - New phase a angle, shifted to the natural commutation point.
C
      THETA3=THETA2-30.0
      IF(THETA3.LT.0.0) THETA3=THETA3+360.0
C
C THETA4 - The angle to determine the thyristors to be fired.
C
      THETA4=THETA3-ALPHA1
      IF(THETA4.LT.  0.0) THETA4=THETA4+360.0
      IF(THETA4.GE.360.0) THETA4=THETA4-360.0
C
      K=0
      IF(THETA4.GE.  0.0.AND.THETA.LT. 60.0) K=0
      IF(THETA4.GE. 60.0.AND.THETA.LT.120.0) K=1
      IF(THETA4.GE.120.0.AND.THETA.LT.180.0) K=2
      IF(THETA4.GE.180.0.AND.THETA.LT.240.0) K=3
      IF(THETA4.GE.240.0.AND.THETA.LT.300.0) K=4
      IF(THETA4.GE.300.0.AND.THETA.LT.360.0) K=5
C
      AK=K
      ALPHA2=AK*60.0+ALPHA1
      IF(ALPHA2.GE.360.0)ALPHA2=ALPHA2-360.0
      ALPHA3=AK*60.0+ALPHA1+15.0
      IF(ALPHA3.GE.360.0)ALPHA3=ALPHA3-360.0
C
      IF(ALPHA2.GT.ALPHA3)THEN
       ALPHA2=ALPHA2-100.0
       ALPHA3=ALPHA3-100.0
       THETA3=THETA3-100.0
       IF(ALPHA2.LT.0.0) ALPHA2=ALPHA2+360.0
       IF(ALPHA3.LT.0.0) ALPHA3=ALPHA3+360.0
       IF(THETA3.LT.0.0) THETA3=THETA3+360.0
      ENDIF
C
      IF(THETA3.GE.ALPHA2.AND.THETA3.LT.ALPHA3) THEN
       IPULS=1
      ELSE
       IPULS=0
      ENDIF
C
      IF(IPULS.EQ.1) THEN
C
       IF(K.EQ.0) GO TO 2
       IF(K.EQ.1) GO TO 3
       IF(K.EQ.2) GO TO 4
       IF(K.EQ.3) GO TO 5
       IF(K.EQ.4) GO TO 6
       IF(K.EQ.5) GO TO 7
2      PULS(1)=1
       PULS(2)=1
       IT1=1
       IT2=2
       GO TO 8
```

```
3        PULS(2)=1
         PULS(3)=1
         IT1=3
         IT2=2
         GO TO 8
4        PULS(3)=1
         PULS(4)=1
         IT1=3
         IT2=4
         GO TO 8
5        PULS(4)=1
         PULS(5)=1
         IT1=5
         IT2=4
         GO TO 8
6        PULS(5)=1
         PULS(6)=1
         IT1=5
         IT2=6
         GO TO 8
7        PULS(6)=1
         PULS(1)=1
         IT1=1
         IT2=6
8        CONTINUE
C
       ENDIF
C
       RETURN
       END
```

```
Datafile for pulsing with T-model line                     /TITLE
C
   1.0E-5  50.0E-1   25.0E-4                               /DELT,FINTIME,PRINT
   1                                                       /ONE SUBSYSTEM
  22                                                       /NUMBER OF NODES
   0.0                                                     /VOLTS
C
C  Load
C
  21  0    1.0E+6                                          /}
   1 21    1.0E+5                                          /}
   2 21    1.0E+5                                          /}
   3 21    1.0E+5                                          /}       LOAD
   4  1    1.0E+5                                          /}       SIDE
   5  2    1.0E+5                                          /}
   6  3    1.0E+5                                          /}
C
C  Inverter
C
  10  7    1.0E+6                                          /]
  10  8    1.0E+6                                          /]
  10  9    1.0E+6                                          /]     INVERTER
   7  0    1.0E+6                                          /]       SIDE
   8  0    1.0E+6                                          /]
   9  0    1.0E+6                                          /]
C
C  Transmision Line
C
  10   11   7.55                                           /R
  11   12   0.0    0.054                                   /L      LUMPED
  12    0   0.0    0.0       2.56                          /C    TRANSMISION
  12   13   0.0    0.054                                   /L       LINE
  13   14   7.55                                           /R
C
C  Converter
C
  14   15  1.0E+6                                          /}
  14   16  1.0E+6                                          /}
  14   17  1.0E+6                                          /}     CONVERTER
  15    0  1.0E+6                                          /}       SIDE
  16    0  1.0E+6                                          /}
  17    0  1.0E+6                                          /}
C
999                                                        /TERMINATES BRANCH DATA
C
C  Source
C
  18     0.001                                             /
  19     0.001                                             /
  20     0.001                                             /
C
999                                                        /TERMINATES SOURCE DATA
C
C  Transformer data
C
   2                                                       /NUMBER OF WINDINGS
```

```
  18  0   0.0  62.606719                                        /
  15 22   0.0  62.575415  0.0  62.606719                        /
888                                                             /
  19  0                                                         /
  16 22                                                         /
888                                                             /
  20  0                                                         /
  17 22                                                         /
C
999                                                             /TERMINATES TRANSFORMER DATA
999                                                             /TERMINATES T-LINE DATA
 -2.0   2.0                                                     /PRINTPLOT LIMITS
  30                                                            /NUMBER OF OUTPUT CHANELS
 1.0  1.0   0.0   0.10  60.0     0.0                            /VARS
C E0,  E1,   TF,    V0,    F,  SPEED
C
C  Machine's Parameters
C
 0.0279 0.0279 0.3268 0.0 0.0 0.0756 0.0394                     /X1,X2,XMD,X12D,X34D,X4D,X3D
 0.1393 0.0 0.1393                                              /XMQ,X12Q,X4Q
 0.042   0.042  2.25E-3 0.181  0.1109                           /R1,R2,R3D,R4D,R3Q
 0.663     376.99     0.0     30.0                              /H,OMO,D,GAMA
 0.0  1.0    1.0  1.0    2.0  0.99   3.0   0.98
 4.0  0.97    5.0  0.96   6.0  0.95  -1.0  -1.0                 /SATURATION DATA
14.14  0.02357  14.14  0.02357                                  /VBASE1,ABASE1,VBASE2,ABASE2
 0.0  0.0  0.0   0.0   0.0  1.0                                 /THETA,ID1,ID2,IQ1,IQ2,ID3
```

```
Datafile for pulsing with distributed line          /TITLE
C
   1.0E-5  50.0E-1   25.0E-4                        /DELT,FINTIME,PRINT
   1                                                /ONE SUBSYSTEM
  22                                                /NUMBER OF NODES
   0.0                                              /VOLTS
C
C  Load
C
  21   0    1.0E+6                                  /}
   1  21    1.0E+5                                  /}
   2  21    1.0E+5                                  /}
   3  21    1.0E+5                                  /}      LOAD
   4   1    1.0E+5                                  /}      SIDE
   5   2    1.0E+5                                  /}
   6   3    1.0E+5                                  /}
C
C  Inverter
C
  10   7    1.0E+6                                  /]
  10   8    1.0E+6                                  /]
  10   9    1.0E+6                                  /]    INVERTER
   7   0    1.0E+6                                  /]      SIDE
   8   0    1.0E+6                                  /]
   9   0    1.0E+6                                  /]
C
C  Transmision Line
C
  10   11   0.001                                   /R
  12   13   0.001                                   /R
  13   14   0.001                                   /R
C
C  Converter
C
  14   15  1.0E+6                                   /}
  14   16  1.0E+6                                   /}
  14   17  1.0E+6                                   /}    CONVERTER
  15    0  1.0E+6                                   /}      SIDE
  16    0  1.0E+6                                   /}
  17    0  1.0E+6                                   /}
C
999                                                 /TERMINATES BRANCH DATA
C
C  Source
C
  18     0.001                                      /
  19     0.001                                      /
  20     0.001                                      /
C
999                                                 /TERMINATES SOURCE DATA
C
C  Transformer data
C
   2                                                /NUMBER OF WINDINGS
  18  0  0.0  62.606719                             /
  15 22  0.0  62.575415  0.0  62.606719             /
```

```
888                                                        /
  19  0                                                    /
  16 22                                                    /
888                                                        /
  20  0                                                    /
  17 22                                                    /
C
999                                                        /TERMINATES TRANSFORMER DATA
C
C Distributed T. Line data
C
 1  0  1  1  1.6  100.0  150000.0  0.005  0.005           /
 12 11  9.553199E-1  1.292753E+3  2.205721E-4
 3.155568E-4  1.0                                          /
999                                                        /TERMINATES T-LINE DATA
 -2.0   2.0                                                /PRINTPLOT LIMITS
  30                                                       /NUMBER OF OUTPUT CHANELS
 1.0  1.0  0.0  0.10 10.0 60.0   10.0  0.9   0.0           /VARS
C E0,  E1,  TF,   V0,  TA,   F,   TOM,  SP,SPEED
C
C  Machine's Parameters
C
 0.0279 0.0279 0.3268 0.0 0.0 0.0756 0.0394                /X1,X2,XMD,X12D,X34D,X4D,X3D
 0.1393 0.0 0.1393                                         /XMQ,X12Q,X4Q
 0.042   0.042  2.25E-3 0.181  0.1109                      /R1,R2,R3D,R4D,R3Q
 0.663     376.99     0.0      30.0                        /H,OMO,D,GAMA
 0.0  1.0    1.0  1.0   2.0  0.99   3.0   0.98
 4.0  0.97    5.0  0.96   6.0  0.95  -1.0  -1.0            /SATURATION DATA
14.14  0.02357  14.14  0.02357                             /VBASE1,ABASE1,VBASE2,ABASE2
 0.0  0.0  0.0   0.0   0.0  1.0                            /THETA,ID1,ID2,IQ1,IQ2,ID3
```

```
Datafile for accelerating the machine                 /TITLE
C
   1.0E-5    100.0E-1    50.0E-4                      /DELT,FINTIME,PRINT
   1                                                  /ONE SUBSYSTEM
  22                                                  /NUMBER OF NODES
   0.0                                                /VOLTS
C
C  Load
C
  21  0    1.0E+5                                     /}
   1 21    1.0E+5                                     /}
   2 21    1.0E+5                                     /}
   3 21    1.0E+5                                     /}       LOAD
   4  1    1.0E+5                                     /}       SIDE
   5  2    1.0E+5                                     /}
   6  3    1.0E+5                                     /}
C
C  Inverter
C
  10  7    1.0E+6                                     /]
  10  8    1.0E+6                                     /]
  10  9    1.0E+6                                     /]     INVERTER
   7  0    1.0E+6                                     /]       SIDE
   8  0    1.0E+6                                     /]
   9  0    1.0E+6                                     /]
C
C  Transmision Line
C
  10  11    0.001                                     /R
  12  13    0.001                                     /R
  13  14    0.001                                     /R
C
C  Converter
C
  14  15   1.0E+6                                     /}
  14  16   1.0E+6                                     /}
  14  17   1.0E+6                                     /}     CONVERTER
  15   0   1.0E+6                                     /}       SIDE
  16   0   1.0E+6                                     /}
  17   0   1.0E+6                                     /}
C
999                                                   /TERMINATES BRANCH DATA
C
C  Source
C
  18     0.001                                        /
  19     0.001                                        /
  20     0.001                                        /
C
999                                                   /TERMINATES SOURCE DATA
C
C  Transformer data
C
   2                                                  /NUMBER OF WINDINGS
  18  0   0.0   73.597397                             /
  15 22   0.0   73.560598   0.0   73.597397           /
```

```
888                                                  /
  19  0                                              /
  16 22                                              /
888                                                  /
  20  0                                              /
  17 22                                              /
C
999                                                  /TERMINATES TRANSFORMER DATA
C
C Distributed T. Line data
C
 1  0  1  1  1.6  100.0  100000.0  0.005  0.005    /
 12 11  9.553199E-1  1.292753E+3  2.205721E-4
 3.155568E-4  1.0                                   /
999                                                  /TERMINATES T-LINE DATA
 -2.0   2.0                                          /PRINTPLOT LIMITS
  40                                                 /NUMBER OF OUTPUT CHANELS
  60.0     0.25    1.25     0.0     0.05             /VARS
C   F ,    SPD ,  EF0 ,   THETA , TFR
C
C  Machine's Parameters
C
 0.0279 0.0279 0.3268 0.0 0.0 0.0756 0.0394         /X1,X2,XMD,X12D,X34D,X4D,X3D
 0.1393 0.0 0.1393                                  /XMQ,X12Q,X4Q
 0.042   0.042  2.25E-3 0.181  0.1109               /R1,R2,R3D,R4D,R3Q
 0.663     376.99     0.0      30.0                 /H,OMO,D,GAMA
 0.0  1.0    1.0  1.0   2.0  0.99   3.0   0.98
 4.0  0.97    5.0  0.96   6.0  0.95  -1.0  -1.0     /SATURATION DATA
 9.617  0.0347  9.617  0.0347                       /VBASE1,ABASE1,VBASE2,ABASE2
 0.0  0.0  0.0   0.0   0.0  1.25                    /THETA,ID1,ID2,IQ1,IQ2,ID3
```