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DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A PC BASED SIMULATION OF AN STATOR VOLTAGE CONTROLLED INDUCTION MOTOR DRIVE

A Thesis Presented to
the Graduate School of Natural and Applied Sciences
Dokuz Eylül University

In Partial Fulfillment
of the Requirements for the Masters Degree
in Electrical and Electronics Engineering

by

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January, 1996
Bornova - İZMİR

THESIS ABSTRACT

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Master Of Science, January 1996
(B. Sc. Dokuz Eylül University, 1991)

61 Typed Pages
Supervised by Öğr. Gör. Dr. Reyat YILMAZ

In this thesis study, a power electronic simulation program ATOSEC5 was introduced and stator voltage controlled induction motor drive circuit is simulated using this software.

When a system is developed, the system is simulated on a computer using mathematical models of the system. Simulation is an important step, because the system performance can be analyzed without building the real system. The drive circuit can be tested and errors can be easily corrected. The results from the simulation is not the optimum solution for the best drive, but it gives some clues and saves time. Especially in power electronics, even any small errors in system design cannot be tolerated, so a powerful simulation software is needed.

Modeling induction motors and power switches like thyristors, power transistors, power MOSFETS, IGBTS is very important for the best simulation. ATOSEC5 is especially designed for power electronic circuit simulations so, when we compared this software with other simulation softwares this is the main advantage. Therefore, for this study, ATOSEC5 has been chosen.

At the first step of work, induction motor characteristics and speed control methods were studied. Stator voltage controlled speed adjustment was introduced.

At the second step, ATOSEC5 simulation software has been presented. Some using knowledge has been given.

At the third step stator voltage controlled induction motor drive system has been loaded into software and analyzed. Results were given.

ÖZET

Bu tez çalışmasında, bir güç elektroniği simulasyon programı ATOSEC5 tanıtılmıştır ve stator voltaj kontrollü asenkron motor sürücü devresi bu yazılım programı kullanılarak simüle edilmiştir.

Bir sistem geliştirilirken, sistemin matematiksel modelleri kullanılarak sistem bilgisayar yardımıyla simüle edilir. Simülasyon önemli bir aşamadır, çünkü, bu sayede gerçek sistem kurulmadan sistem performansı analiz edilebilir. Sürücü devre test edilebilir ve hatalar kolayca düzeltilebilir. Simülasyondan elde edilen sonuçlar en iyi sürme devresini bulmak için optimum sonuçlar olmayabilir, fakat bize bazı ipuçları verir ve zaman kazandırır. Özellikle güç elektroniğinde, sistem dizaynı yapılırken yapılacak küçük hatalar bile tolere edilemez. Bu yüzden güçlü bir simulasyon yazılımı kullanmak gereklidir.

Asenkron motorların ve tristör, güç transistörleri, güç MOSFET'leri ve IGBT gibi güç anahtarlarının matematiksel modellemesi iyi bir simülasyon sonucu elde etmek için çok önemlidir. ATOSEC5 özellikle güç elektroniği simülasyonu alanında dizayn edilmiştir, diğer yazılımlarla karşılaştırıldığında bu önemli bir avantajdır. Bu yüzden bu çalışmada ATOSEC5 programı tercih edilmiştir.

Çalışmanın ilk basamağında, asenkron motor karakteristkleri ve hız kontrol metodları incelenmiştir. Stator voltaj kontrollü hız ayarlaması tanıtılmıştır.

İkinci basamakta, ATOSEC5 simulasyon yazılımı anlatılmıştır, bazı kullanım bilgileri verilmiştir.

Üçüncü basamakta, stator voltaj kontrollü asenkron motor sürme sistemi yazılıma yüklenmiştir ve analiz edilmiştir. Sonuçlar verilmiştir.

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1. INTRODUCTION

Induction machines are used for many industrial drives where a simple, reliable and robust machine is the first requirement and where the use of non - synchronous speed drives is no disadvantage. Due to the advances of the power semiconductors and microcontrollers technology, the induction motor drive becomes popular and easy to implement.

In running up to speed these machines demand a reactive current which depresses the supply system voltage, but since motors are usually started individually this will not create excessive voltage drops unless large motors are started on relatively weak supplies, or overlapping sequential starts of several machines are required. However, when recovering from a supply system fault condition all the connected induction machines make a simultaneous demand for reactive current. In these circumstances the voltage drop may be do large as to cause certain motors to lose speed and eventually stall. It is principally in this area of induction motor performance that interest in the dynamic properties of the induction motor is focused. Predictive studies of post-disturbance transient response are necessary to ensure overall system stability and reliability.

The induction motor appears a relatively simple device. The reason lies in the simplicity of its construction. However, the small air gap necessary to limit the magnetizing current causes second order effects, negligible in other machines, to become of importance in induction machines. These second order effects vary in their importance over the speed range of the machine and, at normal working speeds and loading, they may be neglected. Under these circumstances, the motor may be modeled by using the traditional equivalent circuit, and for transient studies the two-axis generalized machine representation is normally used.

The generalized machine model and the equivalent circuit neglect all but the fundamental air gap electromagnetic field. For some applications, such as the consideration of steady-state running, they may be considered too complex, and for others, such as variable speed drive calculations, they may be considered inadequate.

There are two best known speed control methods of induction motor. One of them is frequency control using an inverter system, and the other is stator voltage control is which is relatively simple to develop. These methods are described in Chapter 2 briefly. In thesis study, stator voltage controlled induction motor drive is simulated using ATOSEC5 simulation software. Developing an induction motor drive system requires a theoretical base about obtaining three-phase sinusoidal voltage with less harmonics in all induction motor operation frequency range. If we use frequency control method, a high reliable inverter system is used to convert a DC input voltage to AC voltage. Switching data are used to drive the power semiconductor switches and they are calculated in the microcontroller which is calculated in real time.

Switching data are obtained from the generation methods such as most known PWM (Pulse Width Modulation) method or wide used Space Vector technique. In the stator voltage control method the power semiconductor switches are triggered at certain times to change the supply voltage level. By the means of removing some sections of power supply voltage, the r.m.s. value to the motor can be reduced and the speed adjustment can be made. In both of the methods, selecting the switching elements is very important step such as wide-known thyristors, power transistors, power MOSFETs or new developed IGBTs. Also induction motor parameters are to be considered to create the drive system effectively. All of these things can be simulated on a personal computer using the circuit models that are defined in a simulation software. Therefore, we can obtain the best drive circuit and then it can be easily adapted to the practical system.

AC machines detailed analysis with PC simulation programs are required for the prediction of the dynamic performance of machines. After simulation the best drive circuit can be selected. In power electronics, simulation is an important step to obtain AC motor drive system. The drive circuits are complex and the power switching devices costs are high. So, the simulation gives us important knowledge about our design.

In the third chapter, the ATOSEC5 simulation software was introduced. This program is designed to analyze power electronic systems.

In the fourth chapter, the stator voltage controlled AC drive was simulated using ATOSEC5 simulation software and the results were obtained.

2. INDUCTION MOTORS

2.1. Introduction

Induction motors are easy to construction and most wide motors in industry. Speed control of these machines is not easy as DC machines, we need to use developed microprocessors and digital technologies for different speed control methods.
The speed control methods depend on mathematical models of AC induction motor and drive circuit. If we know these models, the simulation of complete speed control system could be done on a personal computer. After that step the realization of the system is easy.

2.2. Magnetic Field Considerations

The discussion of the distribution of the flux and magneto motive force (mmf) waves in the induction machine will be limited to two - pole pitches for simplicity in illustrations. For every additional pair of poles around the periphery, the magnetic field is assumed to repeat itself. The discussion then is directly applicable to a two - pole machine. Only one full - pitch coil that produces the same fundamental mmf as the distributed phase winding will be shown. The outer member is the stationary member and becomes the upper member in developed views. The inner member is the rotating member and becomes the lower member in the developed views.

Consider the full - pitch coil on the stator Fig 2-1a carrying a current whose instantaneous direction is shown. If the magnitude of the coil current at this instant of time is i_a, the mmf across each air gap is Y ampere - turns and is given by,

$$Y = N_a \cdot i_a / 2 \qquad (2\text{-}1)$$

If the permeability of the iron is very large then all of the mmf appears across the two air gaps in series. This is a rectangular mmf wave around the periphery whose amplitude depend on the instantaneous current value and the turns per magnetic pole. If the number of poles in a machine is p (an even integer) and N_a is the effective turns per phase, then the amplitude Y is given by,

$$Y = N_a \cdot i_a / p \qquad (2\text{-}2)$$

The instantaneous amplitude of the fundamental component of this rectangular wave is

$$F_{pk} = \frac{4}{\pi} x \frac{N_a i_a}{p} \quad (2\text{-}3)$$

The current flowing in a phase winding of an induction motor, is normally sinusoidal so i_a will be,

$$i_a = I_{am} \cdot \sin(wt) \quad (2\text{-}4)$$

and F_{pk} becomes,

$$F_{pk} = \frac{4}{\pi} x \frac{N_a I_{am}}{p} \; Sin\,(w.t) \quad (2\text{-}5)$$

and

$$F_m = 4 \,.\, N_a \,.\, I_{am} / 3{,}14.p$$

then

$$F_{pk} = F_{am} \,.\, \sin(w.t) \quad (2\text{-}6)$$

The sinusoidal mmf distribution around the periphery of the machine is for the stated reference for the space angle Q as shown in Fig 2-1a and is,

$$F(t,Q) = F_{am} \cdot \sin(wt) \,.\, \sin(Q) \quad (2\text{-}7)$$

where the mmf across the air gap F (t,Q) is dependent on physical location. This may be calculated as

$$F(t,Q) = F_{am} \cdot [\cos(wt - Q) - \cos(wt + Q)] / 2 \quad (2\text{-}8)$$

Equation 2-8 states that F (t, Q) is composed of the superposition of two equal and constant - amplitude, counter - rotating magnetic fields. Figure 2-1c shows the two rotating amplitudes at a time when w.t = 90' and they coincide at a Q = 90'. This is the time and position when $F_{pk} = F_{am}$

A short time later the magnetic field amplitudes are in the physical location shown in Fig 2-1d. The designations F_f and F_b are arbitrarily designated forward and backward fields. That is,

$$F_f = - F_{am} \,.\, \cos(wt + Q) / 2 \quad (2\text{-}8a)$$

$$F_b = F_{am} \cdot \cos(wt - Q) / 2 \qquad (2\text{-}8b)$$

If it is desired to eliminate one of the component field in Fig 2-1c and 2-1d, it is apparent that one or more coils may be added which are displaced physically from coil *a* and carrying currents displaced in time from the current in coil *a* and with respect to each other.

If we consider a common case where a second coil is added displaced by 90' electrical in space and carrying a current displaces 90' electrical in time. This is recognized as a two - phase system. In Fig 2-1e only the stator is shown with the two equivalent coils. The magnetic field components are represented by vectors showing the locations of the amplitudes of these field components. In Fig 2-1e the current in coil *a* is a time maximum in the direction shown and the current in coil *b* is zero. One - fourth of a period later the current in a is zero, and the current in b is a time maximum. The positions of the component amplitudes for this case are shown in Fig 2-1f The coil *b* field components were deliberately not shown if Fig 2-1e Note that F_{bb} is directly opposed to F_{ab} and if they have equal amplitudes they will cancel each other. Also note that F_{af} and F_{bf} are coincident and thus produce a resultant amplitude of F_{af} plus F_{bf} or $2.F_{af}$, if the amplitudes are equal.

Figure 2-1g shows the component amplitudes a short time later. The clockwise rotating components continue to cancel while the forward or counterclockwise rotating fields continue to add. For the two phase stator winding, the following conditions should be understood for a single field to be rotating in a desired direction.

1.The phase windings must be in electrical space quadrature.

2.The winding currents must be in time quadrature

3.The time maximum space fundamental mmf and amplitudes of the two phases must be equal.

4.The reverse the direction of the resultant field, one of the currents must be shifted through 180' in time.

5.The amplitude of the resultant field is aligned on the axis of *a* phase winding at the instant the current in the winding has a maximum value.

6.If the two phase winding are identical, the currents must have equal amplitudes. This is called a symmetrical stator winding.

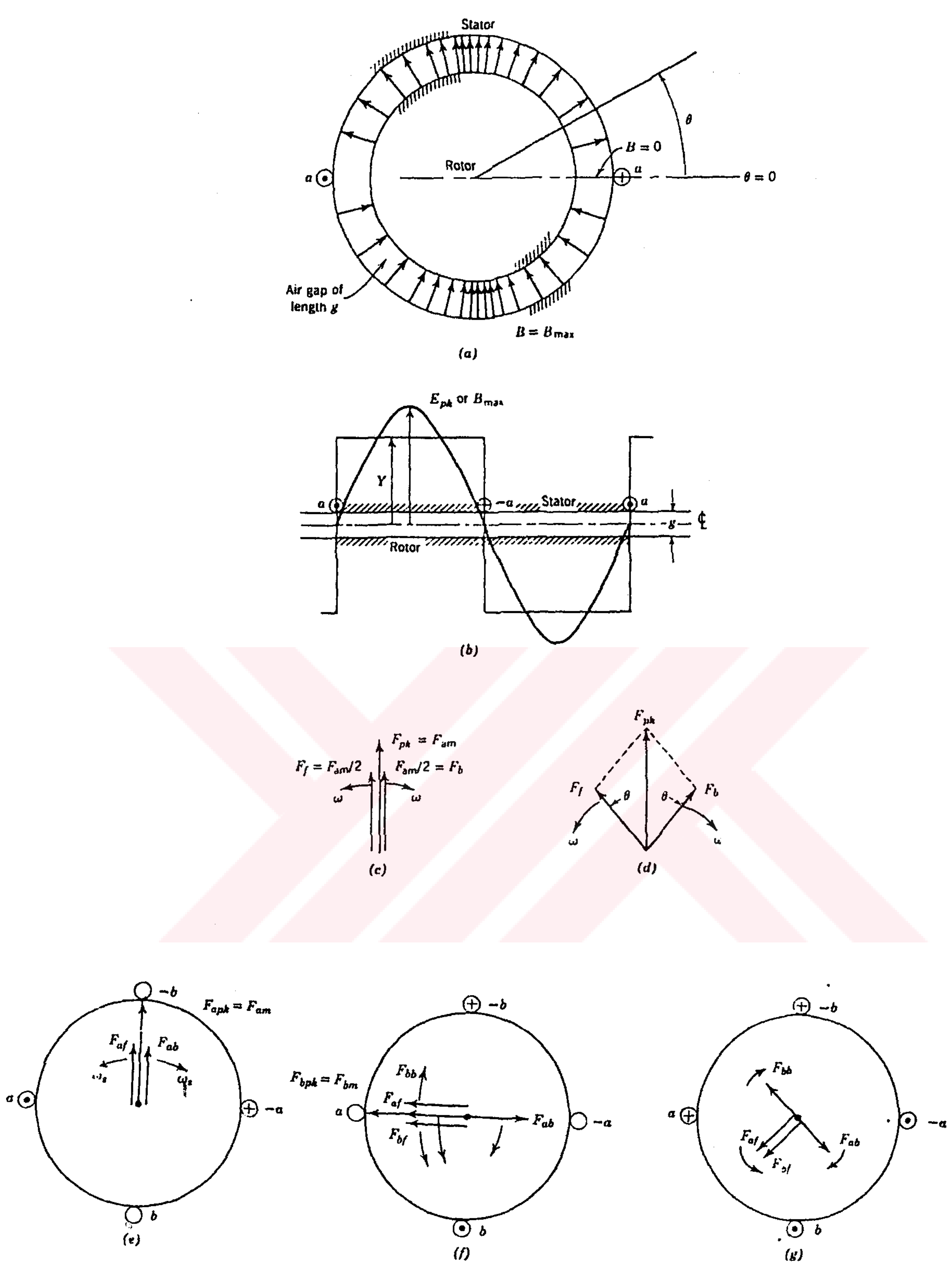


Fig 2-1 Development of forward and backward fields **(a)** Fundamental flux density distribution **(b)** Developed view of magnetic field of (a). **(c)** f and b components when current in coil is a time maximum. **(d)** f and b components when Q = w.t **(e)** Current in (a) is at a time maximum **(f)** Current in (a) is zero, in (b) is a time maximum; all field components are shown **(g)** Component field position 45' later in time than in (b).

The previous method of analysis may be extended to any number of phases. As an additional illustration the case of the three phase symmetrical induction machine will be presented when balanced three phase voltages are applied to the stator coils. Phase sequence is *a - b - c* and the magnitude of each of the three coils fundamental mmf amplitudes as functions of time are;

$$F_{apk} = F_{am} \cdot \sin(w.t)$$

$$F_{bpk} = F_{am} \cdot \sin(w.t - 120')$$

$$F_{cpk} = F_{am} \cdot \sin(w.t + 120') \qquad (2\text{-}8c)$$

Each of the phase winding produce a component of mmf at each location around the air gap. Thus,

$$F_a(t, Q) = F_{am} \cdot [\cos(w.t - Q) - \cos(w.t + Q)] / 2$$

$$F_b(t, Q) = F_{am} \cdot [\cos(w.t - Q) - \cos(w.t + Q - 240')] / 2$$

$$F_c(t, Q) = F_{am} \cdot [\cos(w.t - Q) - \cos(w.t + Q + 240')] / 2 \qquad (2\text{-}8d)$$

The resultant of the instantaneous mmf at any point Q in the air gap at any instant of time is given by the summation of the Eqs (2-8d) and is

$$F_T(t, Q) = F_a(t, Q) + F_b(t, Q) + F_c(t, Q)$$

$$F_T(t, Q) = 3. F_{am} \cdot \cos(w.t - Q) / 2 \qquad (2\text{-}8e)$$

Once again under symmetrical machine winding conditions with balanced polyphase a constant amplitude magnetic field is obtained moving in the air gap with a velocity of w electrical rad/sec. If either unsymetrical winding are placed in the stator or unbalanced voltages are applied to symmetrical windings, the backward fields do not cancel and thus two counter rotating fields are obtained. This condition can be analyzed by the method of symmetrical components and in general, a stator having a symmetrical winding consisting of M number of phases must have the coils displaced in time by 360/m electrical degrees. The amplitude of the resulting field will be $(M/2).(F_{am})$, where F_{am} is the maximum fundamental amplitude of the phase effective coil *a*.
Continuing with the balanced stator condition, the flux density distribution in the air gap (as a function of Q) is given by

$$B(Q) = \frac{M}{2} \times \frac{F_{am}}{g} \times \mu_0 \sin(Q) \qquad (2\text{-}9)$$

If the radial length of the air gap *g* is much smaller than the radius of the rotor, then the flux density may be considered constant across the air gap and was the assumed condition of Eq 2-9. This magnetic field crossing the air gap links the rotor windings as well as the stator winding as shown in Fig 2-2a.

Figure 2-2a shows in developed form the air gap, the fundamental stator mmf and flux density distribution. The direction of the magnetic field movement is also shown with the rotor moving in the same direction but at a smaller velocity than the field. The induced voltages in the rotor conductors are shown as crosses and dots with the size of the sign proportional to the instantaneous induced voltage. The rotor winding is assumed to be the squirrel cage type, that is, conducting bars inserted in axial slots and directly connected together on both ends by low impedance conductors. Thus current flow in these rotor conductors with magnitudes determined by the induced voltages and the respective conductor impedance. The induced voltages and the stator field are moving to the right with relative velocities of w_s with respect to the stator and $(w_s - w_r)$ with respect to the rotor. The stator conductors see source frequency, and the rotor conductors see a frequency dependent on the relative velocity. If $w_r = w_s$, then the rotor frequency of induced voltages and currents is zero. For the condition of small relative velocity, the rotor currents are essentially in time phase with the rotor voltages. Thus the crosses and dots in Fig .. represents the magnitudes of both conductor voltages and currents. Since the currents are distributed sinusoidally around the periphery of the rotor, they produce a sinusoidally distributed magnetic field in the air gap whose amplitude is space displaced from the current maximum by 90' electrical. This space distributed wave is shown in Fig 2.2a as $F_2(Q)$ or $B_2(Q)$.
As $(w_s - w_r)$ increases in magnitude the rotor currents are no longer in time phase with the rotor induced voltages. They lag in time by the rotor impedance angle. The torque is given for two sinusoidal mmf displaced by δ as,

$$T_g = K \cdot F_{pk1} \cdot F_{pk2} \cdot \sin \delta \qquad (2\text{-}10)$$

where δ is equal to 90' + Q_r for the induction motor. Thus the torque expression may be written as

$$T_g = K \cdot F_{pk1} \cdot F_{pk2} \cdot \cos Q_r \qquad (2\text{-}11)$$

Notice that as the relative velocity (w_s - w_r) becomes very large, Qr approaches 90' as a limit in the absence of capacitance effects. Thus the developed torque approaches zero as the relative velocity becomes very large.

It is frequently more convenient to combine the stator and the rotor mmf waves which yields the resultant mmf wave having an amplitude of F_r. This resultant mmf produces the actual air gap flux density distribution

$$B_r(Q) = \frac{F_r}{g} \times \mu_0 \sin(Q) \qquad (2\text{-}12)$$

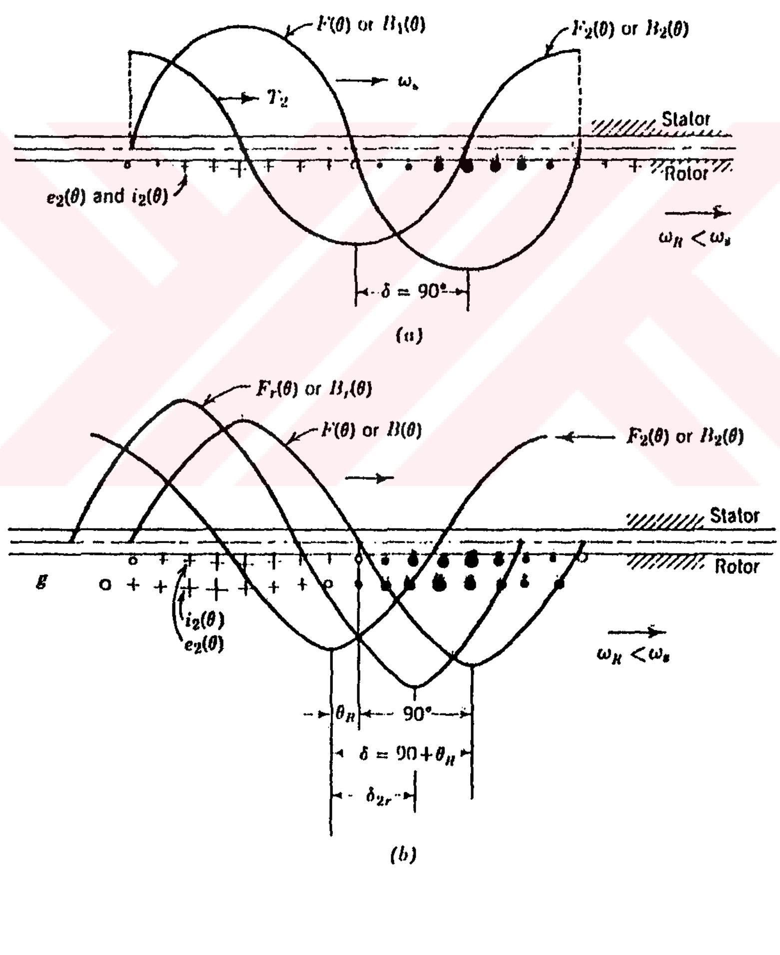


Fig 2-2 Air gap relations for induction motor. **(a)** Voltage, current, and field relations for (w_s - w_r) small **(b)** Relations for (w_s - w_r) relatively large

Q is measured from the resultant zero flux density location. The resultant flux per pole may be obtained by integrating over the pole area

$$\Phi_r = \frac{2}{p}\int_0^r \frac{F_r}{g} \times \mu_0 \, Sin\,(Q).l_r \, dQ \tag{2-13}$$

$$\Phi_r = 2\,\frac{F_r}{g} \times \mu_0 l_r \,\frac{2}{p} \tag{2-14}$$

for a pole machine. The torque expression may now be written as

$$T_g = K' F_{k2}\,\Phi_r \,Sin\,(\delta_{2r}) \tag{2-15}$$

The torque angle δ_{2r} is shown in Fig 2-2b with the resultant $F_r(Q)$ or $B_r(Q)$ representation. The subscript on δ states explicitly that the angle is measured from the rotor mmf wave to the resultant mmf wave.

With respect to Fig 2-1, the necessary conditions for the backward rotating fields to cancel were that $[F_{am}] = [F_{bm}]$ and that the currents in the two coils be displaced in time by 90' electrical. For control applications of the two phase induction motor, a constant voltage is applied to winding *a* called the reference winding and a variable voltage of the same frequency is applied to winding *b* called the control winding. Generally the two voltages are in time quadrature and are assumed to be such in the first analysis. Figure 2-1b and 2-1c are repeated in Fig 2-3 when the control voltage is one half the reference voltage. For the symmetrical motor, the current in winding *b* is one half that in winding *a*. Thus

$$F_{bmax} = F_{amax}/2 \tag{2-16}$$

From inspection of Fig 2-3, parts *a* and *b*, it is seen that the forward field amplitude has been reduced and that the backward field is not canceled. The result is that there are two counter - rotating stator mmf waves, each of which has a constant amplitude. The correlation with the symmetrical components can be shown as follows for I_a leading I_b by 90' and in magnitude is twice I_b. When I_b is placed on the reference

$$I_{af} = (j.I_a + j.I_b)/2 = 3.j.I_b/2 \tag{2-17}$$

$$I_{ab} = (j.I_a - j.I_b)/2 = j.I_b/4 \tag{2-18}$$

$$I_{bf} = -j.I_{af} = 3.I_b/2 \tag{2-19}$$

$I_{bb} = +j \cdot I_{ab} = I_b / 4$ (2-20)

the resultant amplitude of the forward field is

$$F_{sf} = F_{af} + F_{bf} = \frac{4}{\pi}\left[\frac{1}{2} N_a (\sqrt{2}) \frac{3}{2} I_b + \frac{1}{2} N_b (\sqrt{2}) \frac{3}{2} I_b\right] \quad (2\text{-}21)$$

$$F_{sf} = \frac{4}{\pi} \sqrt{2}\, N_a \frac{3}{2} I_b \quad (2\text{-}22)$$

where $N_a = N_b$

$$F_{ab} = F_{ab} - F_{bb} = \frac{4}{\pi}\left[\frac{1}{2} N_a (\sqrt{2}) \frac{1}{4} I_b + \frac{1}{2} N_b (\sqrt{2}) \frac{1}{4} I_b\right] \quad (2\text{-}23)$$

$$F_{ab} = \frac{4}{\pi} \sqrt{2}\, N_a \frac{1}{4} I_b \quad (2\text{-}24)$$

Thus the symmetrical components of the currents lead directly to the two counter rotating fields with the positive sequence currents producing only the forward field and he negative or backward sequence currents producing only the backward field. Each of these fields reacts with the respective rotor fields to produce torque's that act in the direction of the respective field motion. The torque for the forward field is schematically shown in Fig 2-3c.

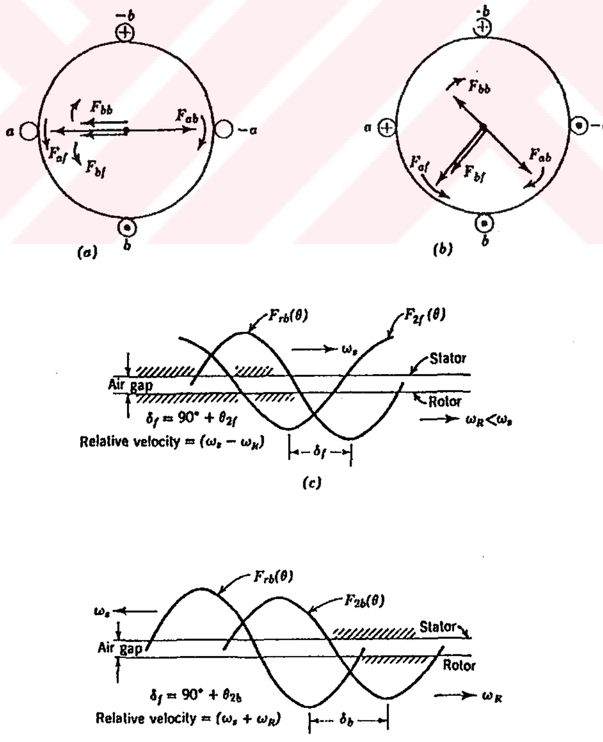


Fig 2-3 Two rotating field representations **(a)** Components when current in (b) is a maximum. **(b)** 45' later in time **(c)** Forward field components **(d)** Backward field components.

2.2. Rotor Resistance and Reactance Considerations

The general requirements of an induction motor are
1.High efficiency under normal running conditions.
2.Sufficiently large starting torque's must be developed in order to accelerate large inertia loads in reasonable periods when normal load torque's exist.
3.Starting currents should not be excessive when line voltage is applied for starting.
These requirements are inherently contradictory. High efficiency under normal running conditions requires small values of rotor resistance. S times the air gap power is dissipated in the rotor circuits, and the slip S is dependent on the magnitude of rotor resistance for a given developed torque. But small values of rotor resistance increase the magnitude of line current when the motor is being started. It is noticed that starting current can be reduced by increasing the rotor circuit leakage reactance. Further consideration of this possibility shows that the maximum torque is reduced, which reduce both the starting torque and short time overload capability. Thus, as is the usual case, the rotor circuit resistance and leakage inductance values are based on compromise.
One type of induction motor involves no compromise and that is the wound rotor motor with the rotor winding terminals brought outside of the machine by means of sliding contacts. As a result, these terminals can be shorted for normal running conditions, which leads to efficient operation. The requirements for large starting torques and low starting current are both accomplished by adding resistance to the rotor circuits at start and gradually removing the resistance as the motor / load combination accelerates.

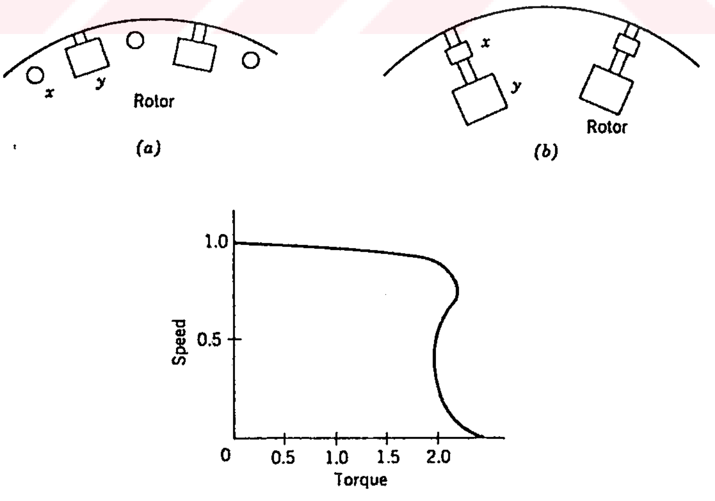


Fig 2-4 Double cage rotor winding **(a)** and **(b)** Two geometries of the double - cage type of construction **(c)** Resulting speed - torque curve.

An additional benefit is obtained since a large portion of the rotor I^2R loss is dissipated in the external resistance, which reduces the internal heating of the motor during the starting period. It should also be noted that maximum developed torque may be maintained throughout the accelerating period if a continuously variable resistance is used in the rotor external circuits. The main disadvantage of the wound rotor motor as compared with the squirrel cage motor its appreciably greater cost.
In the rotor winding of a squirrel cage motor, the circuit terminals are not available and, as a result, resistances and their variations must be build into the rotor conductor at the time of manufacture. Since the maximum developed power and torque are essentially determined by the leakage reactances, only small variations are permissible, and they are generally limited in their magnitude so that maximum developed torque is not less than approximately two times rated torque. What must be done with the rotor conductors is to obtain relatively large resistances at starting when the rotor frequency is large and to have the rotor resistance small when the rotor frequencies are small. The first and perhaps most obvious method to accomplish this is to provide two squirrel cage windings. This method is extensively used and the basic physical configuration is presented in Fig 2-4a and 2-4b The small conductors labeled *x* are the high resistance, low leakage conductors that provide the good starting torques. The larger conductors labeled *y*, provide the high efficiency operation under normal (low slip) running conditions. The general shape of the speed torque characteristic was first shown in Fig 2-4c.

Another method for varying the rotor circuit resistance is to make use of the principle of eddy currents in the conductor to increase the effective resistance when the rotor frequencies are large, that is, at starting. One of the simplest physical configurations to accomplish this is the "deep bar" arrangement shown in Fig 2-5a.

The dashed lines represent the slot leakage flux distribution due to the current in the rotor bar. Notice that the area of the conductor at the bottom has more flux encircling it than the areas at the top. Consequently with time varying currents in the bar, the lower currents exist in a larger impedance circuit than the currents near the top. As a consequence, the current may be said to be crowded to the top, resulting in a greater effective resistance.

The higher the frequency the greater is this effect. The practical range of resistance expressed as a ratio is about 2.35 to 1 from standstill or line frequency to d-c value of resistance. The typical shape of the speed torque characteristic for the deep bar rotor winding is shown in Fig 2-5b. A word of caution is necessary here. Since both the rotor resistance and the leakage reactance are frequency dependent.

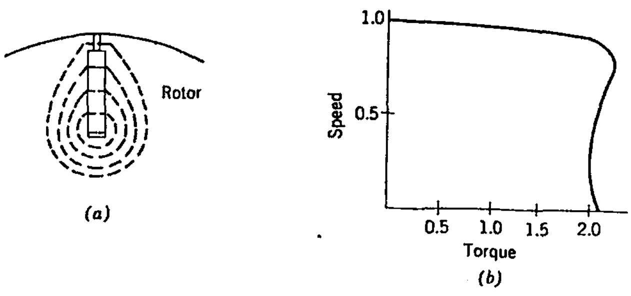


Fig 2-5 Deep - bar rotor winding (a) Deep - bar construction (b) Speed - torque

2.3. Induction Motor Equivalent Circuit

Induction motor rotor consists of axial conductors shorted at the end by circular connectors to form a squirrel cage. The stator is identical to the stator of a synchronous motor.

The rotor must always rotate at a different speed from the synchronous speed for a voltage, and hence current and torque to be induced in the rotor. The relative speed of the rotor to the synchronous speed of the stator flux is known as the slip *s* (Slip will range between 0 and 1).

$$s = \frac{\text{synchronous speed - rotor speed}}{\text{synchronous speed}} = \frac{N_{syn} - N_{rotor}}{N_{syn}} \qquad (2\text{-}25)$$

The motor equivalent circuit [5] for one phase of the rotor is given in Figure 2-6a where Rr' is the resistance, the Xr' is the leakage reactance of the rotor windings, and Er is the induced phase voltage when the speed is zero (or s=1). In Figure 2-6b where Rs is the resistance, the Xs is the leakage reactance of the stator windings. The complete circuit model with all parameters referred to the stator is shown in Figure 2-6c where Rm represents the resistance for excitation loss and Xm is the magnetizing reactance.

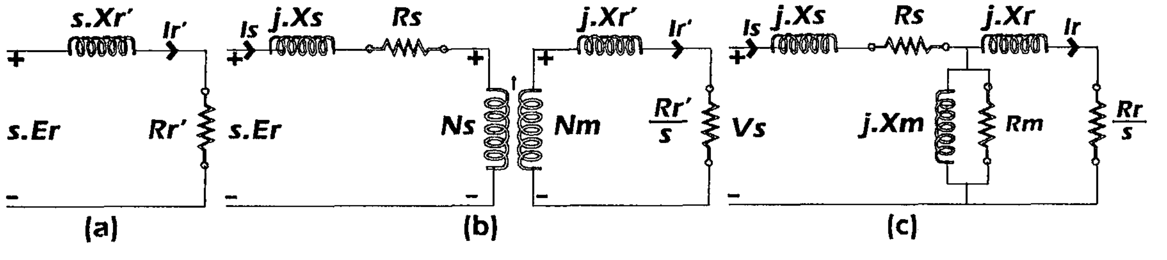


Fig. 2-6. a) Rotor Circuit b) Stator and Rotor Circuit c) Equivalent Circuit

2.4. Motor Characteristics

As the rotor speed approaches synchronous speed, the inductive reactance (proportional to slip frequency) is less, hence the current is closer in phase to the voltage, resulting in a better power factor in the stator. The output power (neglecting friction and iron loss) must be given by the same torque times the rotor speed, giving

Rotor output power = $T.w_r = T.(1\text{-}s).w_{syn}$ (2-26)

Expressing the rotor speed w_r in rad/s,

$w_r = (1\text{-}s).\ w_{syn}$ (2-27)

If we are to examine the torque - speed characteristic of a particular motor at different fixed supply frequencies, then the effect of the different frequencies must be considered.

In any magnetic circuit, the induced voltage is proportional to the flux level and the frequency hence, to maintain optimum flux level in a machine, the ratio,

(voltage / frequency = constant) (2-28)

Typical torque-speed curves are shown in Fig. 2-7, where it can be observed that the shapes are similar, with the maximum torque value independent of frequency. The running region of cage induction motor is normally with a small slip at just below its synchronous speed. An efficient means of speed adjustment is possible by variation of the supply frequency, provided the ratio of voltage to frequency is maintained reasonably constant. At the very lowest speeds, the supply voltage has in practice to be increased slightly to compensate for the stator impedance voltage drop.

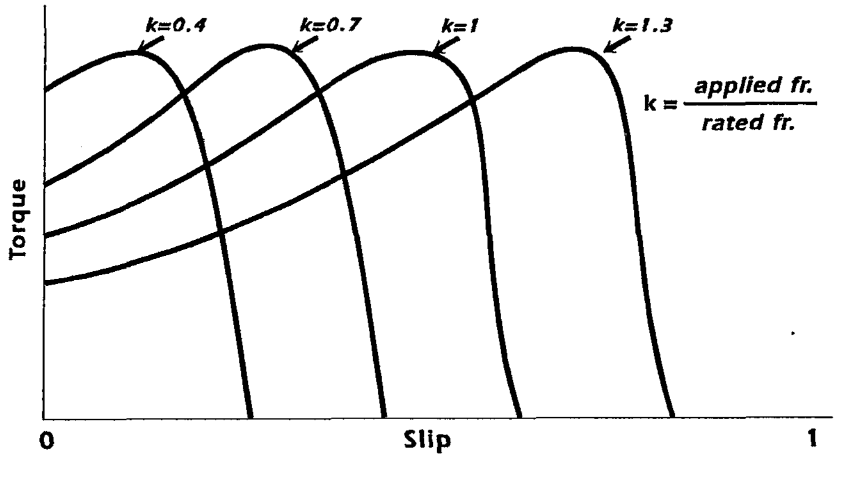


Fig 2-7. Induction motor torque-speed characteristic.

The current demanded by the induction motor for a direct-on-line start at fixed frequency has a magnitude of approximately six times the normal full-load current. With a fixed frequency source, this starting current can only be reduced by voltage reduction. However, using the inverter drives described later, it is possible to start at low frequency, then raise the frequency to accelerate the motor. If the voltage, at fixed frequency, to an induction motor is reduced, the slip is increased in order to maintain the same torque. The torque to be proportional to the square of the voltage.

2.5. Speed Control Methods

The operating region of I.M. is normally with a small slip at just below its synchronous speed. At this speed, the developed torque is proportional to slip and the speed decreases with torque. The speed and torque of I.M. can be varied by *the supply frequency* and *the stator voltage control* [5]. The I.M. needs to have a constant flux in the rotor and stator to generate maximum torque. Therefore the volts/hertz ratio between the stator voltage and frequency of stator voltage must be constant.

2.5.1. Stator Voltage Control

The effect is shown in Fig. 2-8 where it can be seen that a narrow range of speed adjustment is possible by voltage reduction. The disadvantage are those of loss efficiency, the increase in rotor losses leading to possible overheating and the reduction in the maximum torque.

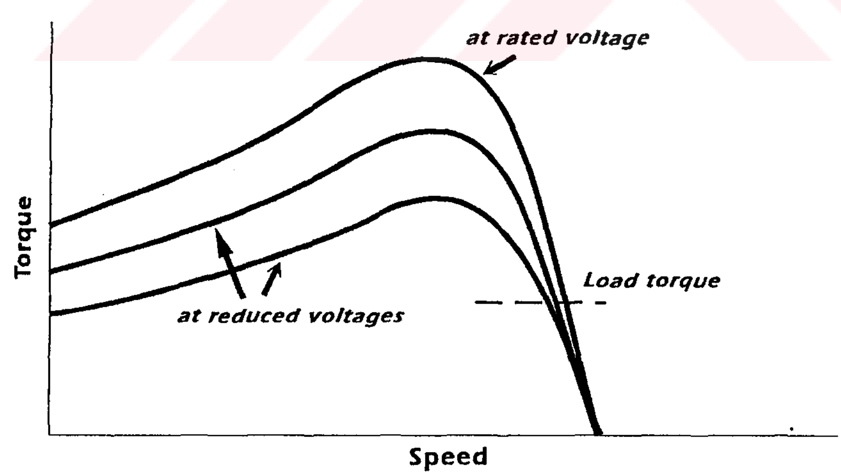


Fig 2-8. Torque speed characteristics at reduced voltage, fixed frequency.

If the voltage, at fixed frequency, to an induction motor is reduced, the slip is increased in order to maintain the same torque. The torque to be proportional to the square of the voltage. The effect is shown in Fig. 2-8 where it can be seen that a narrow range of speed adjustment is possible by voltage reduction. The disadvantage are those of loss efficiency, the increase in rotor losses leading to possible overheating and the reduction in the maximum torque.

In Figure 2-9, thyristors used in fully controlled arrangement where firing delay of the thyristors removes sections of the supply voltage, so reducing the r.m.s. value of the voltage to the motor.

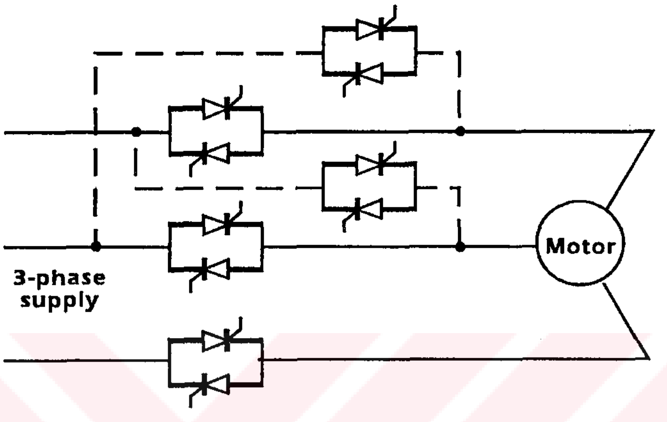


Figure 2-9. Speed adjustment by supply voltage control

2.5.2. Frequency Control (Inverters)

A simple inverter scheme is shown in Figure 2.10 [5]. D.C. voltage feed to inverter is constant and capacitor holds the voltage constant. The six switches are fired at certain times to require an AC voltage at the outputs. The firing angles are adjusted to obtain variable frequency of the AC voltage. The switches are not ideal, they take a small amount of time to turn-off. Therefore, the output AC voltage contains harmonics, but the induction motor low-pass filter characteristics makes AC output voltage closer to the sinusoidal voltage.

Inverters are widely used in industrial applications such as variable speed AC motor drives, induction heating, uninterruptable power supplies.

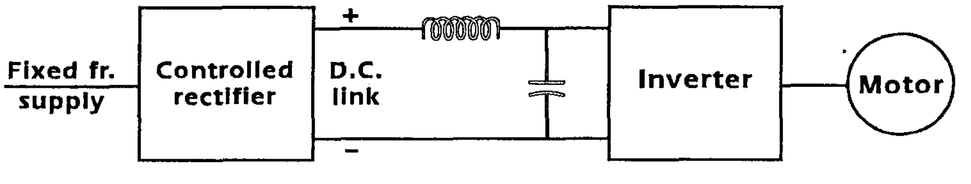


Figure 2-10. Inverter circuit

3. ATOSEC5 SIMULATION SOFTWARE

3.1. Introduction

Atosec5 simulation software helps to analyze any power electronic converter containing semiconductor switches and other usual linear circuit elements; voltage sources, current sources, resistors, self and mutual inductors and capacitors.

The standard simulator can handle a maximum of 40 state variables, a maximum of 15 switches (thyristors, transistors, diodes, hysteresis control - based switches, PWM switches). The post - processing module of AtoSec5 (Ato5PPM) is used to plot any of the circuit variables and to perform the harmonic analysis of any circuit voltage or current.

3.2. Simulation Programs

Power electronic converter circuits contain non-linear elements such as semiconductor switches. These switches can change state, from blocking to conduction, or vice versa, depending on their control signals. In Atosec simulator, a semiconductor device is modelled as a binary inductor. The system equations are obtained in state variable form in Atosec simulator as

$$dX / dt = \underline{AX} + \underline{BU} \qquad (3\text{-}1)$$

The dimensions of the state A and imout B matrices remain the same irrespective of the state of conduction of the semiconductor switches because a constant topology method is used for the formulation of system equations. Further, the state and input matrices corresponding to a particular state of the circuit, characterized by a distinct combination of conduction / blocked states of the different switches present in the system, can easily be obtained without going through elaborate computations.

SACSOTR is another simulation program that makes use of a state variable approach for the formulation of system equations. In this program a semiconductor switch is modelled as a binary resistor. Although a constant topology method is used for the computation of system equations, the state input matrices of the system are to be computed completely following elaborate steps for each particular state of the system, characterized by a combination of conducting / blocked states of the semiconductor switches. Further, in this simulation program, the output equation Y has to be computed corresponding to each state of the system

$$\underline{Y} = \underline{PX} + \underline{QU} \qquad (3\text{-}2)$$

The output equation usually represents voltages across semiconductor devices that are in the clocked state and the currents through those switches that are in the conduction state. In the Atosec simulator, the output equations need not be

computed separately. This is due to the fact that the currents through the inductors modeling semiconductor switches are made state variables and the voltages across them are also available as co-state variables. This therefore simplifies the number of computation steps in the Atosec simulator.
In general, the order of the system is higher in the Atosec simulator than the Sacsotr simulator; this is due to the fact that each semiconductor switch is to be modeled by a circuit containing LRC elements in the Atosec simulator; therefore, for each semiconductor switch present in the system, the order of the system increases by 2. This implies that the Atosec simulator takes longer for the solution of system equations.

The SPICE simulator uses a hybrid method of formulation of system equations. Detailed models are used for the description of parameters of each semiconductor device. Spice belongs to a class of general - purpose simulation program that is specially suited to the analysis and design of integrated circuits.

ECAP simulator uses a state variable approach for the formulation of system equations. A semiconductor switch can be modelled using E, C, R, L, J and switch type elements.

3.3. Preparation of Data For Atosec5 Simulation

In order to use Atosec5 simulator, the user has to prepare a file containing data for a circuit under study. The allowable circuit elements are voltage sources, capacitors, resistors self and mutual inductors, semiconductor switching elements and current sources. The modelling elements for semiconductor switches and their typical values are shown in Fig 3.1.

Nedit.exe module permits the preparation of a data file suitable for Atosec5 simulator in an interactive manner. Atosecg.exe module is a graphic interface module which permits the preparation of the schematic circuit diagram and the data file of a circuit under study suitable for the Ato5sim.exe module. The user can also use any available Editor program to prepare the data for the Atosec5 simulator in the form of an ASCII file.

Before the preparation of data for the simulator, draw the circuit under study. Assign arbitrary names for the edges (branches), names for nodes. Assign any directions of current flow through all the elements of the circuit; for unidirectional semiconductor switches, assign directions following the normal current flow through the device if the device would be in conduction. Prepare the data for the circuit following the sequence given below;

*Data for the description of the circuit
*Data for the initial conditions
*Data for controlled sources

*Data for additional state variables, additional sources and definition of control variable
*Total number of semiconductor switches
*Data for sources; original and additional sources
*Additional data for semiconductor switches
*Data for solution control
*Data for visualization of curves during computation

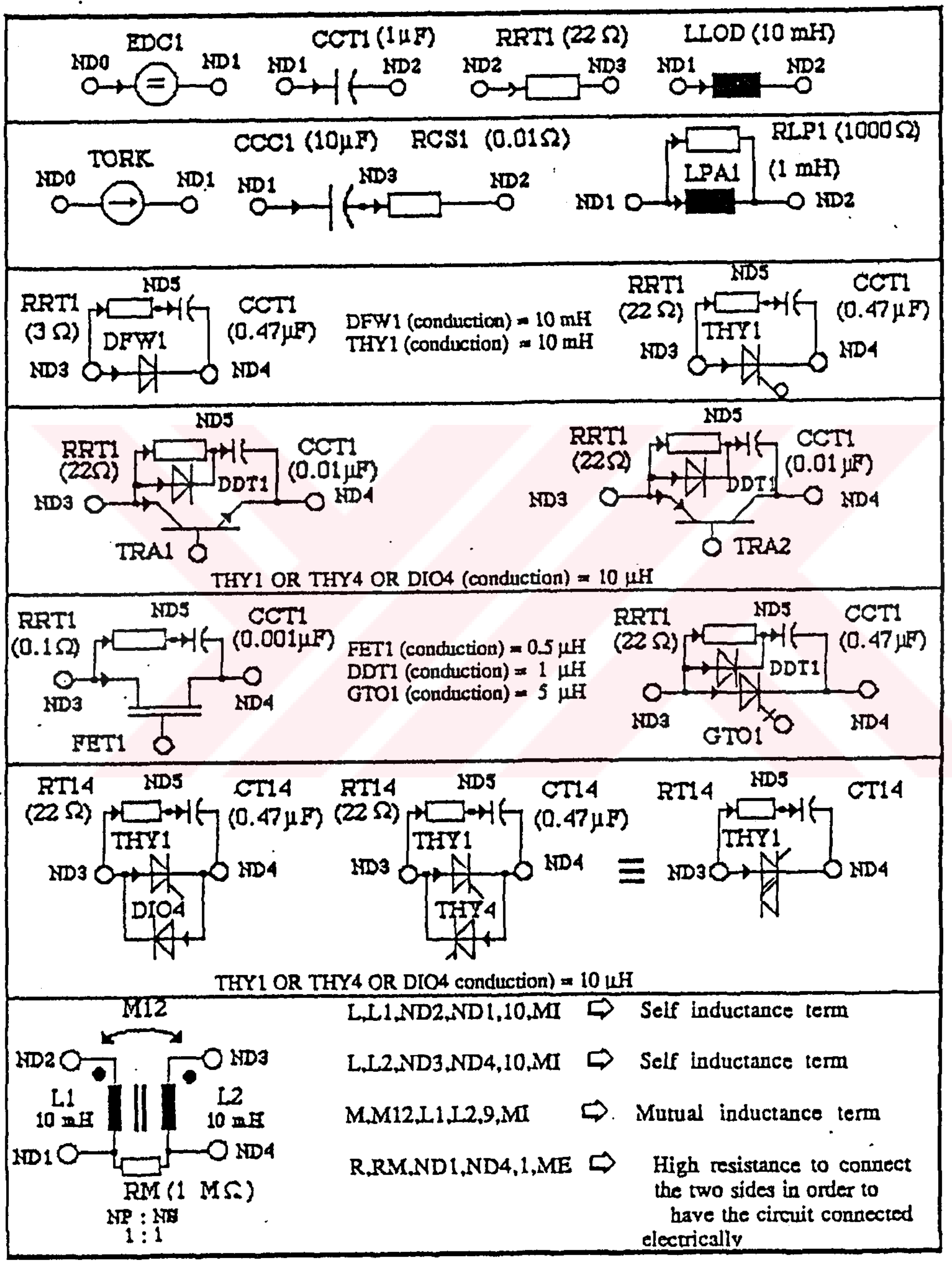


Fig 3.1. Various circuit elements and their description of edges

3.3.1. Data for the description of the circuit

The description of the topology of the circuit elements can be given in any arbitrary manner.
Each edge (branch) of the circuit is described in one line in the following order;

TYPE, BRNH, FRN, TON, VALUE, EXP

Type represents the code for each one of the following types of elements;

E voltage source
C capacitor
R resistor
S thyristor
T transistor, bipolar or Fet or Gto switch
D diode
L inductor
J current source
M mutual inductance

BRNH	represents the name of the edge; any arbitrary, but distinct and valid Fortran variable name not exceeding four characters can be assigned as name of an edge
FRN	represents the name of the from - node; any arbitrary but distinct and valid Fortran variable name not exceeding three characters can be assigned to designate the node from which the edge current is oriented. In the case of mutual inductance, the name of the first inductance that is coupled is given
TON	represents the name of the to-node; any arbitrary but distinct and valid Fortran variable name not exceeding three characters can be assigned to designate the node to which the current is oriented. In the case of mutual inductance, the name of the second inductance that is mutually coupled to the first one is given
Value	denotes the magnitude of the element value; for values smaller than 0.001 and higher than 1000, the next parameter EXP representing the permissible abbreviations must be used; otherwise, EXP need not be difened
EXP	represents the allowable exponents KI: Kilo, MI: Milli, MU: Micro, ME: Mega

After all the edge lines have been enumerated, the last line should be followed by a line having the symbol star "*": This indicates the end of description of all the edges present in the circuit.

As an example, if we give the edge description data for the various circuit elements shown in Fig 3.1,

For the voltage source EDC1 connected between nodes ND0 and ND1 and oriented from node ND0 to node ND1	E, EDC1, ND0, ND1.

For the capacitor element CCT1 of capacitance 1 F connected between nodes ND1 and ND2	C, CCT1, ND1, ND2, 1, MU.
For the resistor element RRT1 of resistance 22 Ohms connected between nodes ND2 and ND3	R, RRT1, ND2, ND3, 22
For the inductor element LL0D of inductance 10 mH connected between nodes ND1 and ND2	L, LL0D, ND1, ND2, 10, MI.
For the current source TORK connected between ND0 and ND1	J, TORK, ND0, ND1
For the capacitor CCC1 (10 F) and series resistor RCS1 (0.01 Ohm) combination	C, CCC1, ND1, ND3, 10, MU R, RCS1, ND3, ND2, 0.01
For the inductor LPA1 (1 mH) and parallel resistor RLP1 (1000 Ohms)	L, LPA1, ND1, ND2, 1, MI. R, RLP1, ND1, ND2, 1, KI

*For semiconductor switches,
Any semiconductor switch is modelled by a finite value of inductance in parallel with a snubber circuit. The following formula can be used for calculating the finite inductance modelling of a semiconductor while in conduction,

$L_{semiconductor} = V_{FOM} \cdot t_{on} / 2.3\, I_F$ where, (3-3)

V_{FOM} represents the maximum allowable device forward voltage
t_{on} represents the turn-on time of the device
I_F represents the device (average or r.m.s. value) current

Typical values of snubber circuit are indicated as follows;

Diode (rectifier type) DFW1 (simulated as an inductor having an inductance value of 10 H while in conduction) with snubber circuit (CCT1 = 0.47 F and RRT1 = 3 Ohms)	D, DFW1, ND3, ND4, 10, MU R, RRT1, ND3, ND5, 3 C, CCT1, ND5, ND4, 0.47, MU
Thyristor (rectifier type) THY1 (simulated as an inductor having an inductance value of 10 H while in conduction) with snubber circuit (CCT1 = 0.47 F and RTT1 = 22 Ohms)	S, THY1, ND3, ND4, 10, MU R, RRT1, ND3, ND5, 22 C, CCT1, ND5, ND4, 0.47, MU
Bipolar NPN transistor TRA1 (simulated as an inductor having an inductance value of 1 H while in conduction) with polarized snubber circuit (CCT1 = 0.01 F, RRT1 = 22 Ohms and DDT1, simulated as an inductor having an inductance value of 1 H while in conduction)	T, TRA1, ND3, ND4, 1.0, MU D, DDT1, ND3, ND5, 1, MU R, RRT1, ND3, ND5, 22 C, CCT1, ND5, ND4, L, 0.01, MU
Bipolar PNP transistor TRA2 (simulated as an inductor having an inductance value of 1 H while in conduction) with polarized snubber circuit	T, TRA2, ND3, ND4, 1, MU D, DDT1, ND3, ND5, 1, MU R, RRT1, ND3, ND5, 22 C, CCT1, ND5, ND4, 0.01, MU

Field effect transistor FET1 (simulated as an inductor having an inductance value of 0.5 H while in conduction) with snubber circuit	T, FET1, ND3, ND4, 0.5, MU R, RRT1, ND3, ND5, 0.1 C, CCT1, ND5, ND4, 0.001, MU
GTO switch GTO1 (simulated as an inductor having an inductance value of 5 H while in conduction) with polarized snubber circuits	T, GTO1, ND3, ND4, 5, MU D, DDT1, ND3, ND5, 1, MU R, RRT1, ND3, ND5, 22 C, CCT1, ND5, ND4, 0.47, MU
Anti parallel-connected diode and thyristor with snubber circuit,	S, THY1, ND3, ND4, 10, MU D, DIO4, ND4, ND3, 10, MU R, RT14, ND3, ND5, 22 C, CT14, ND5, ND4, 0.47, MU
Anti parallel-connected thyristors with snubber circuit or a triac with snubber	S, THY1, ND3, ND4, 10, MU S, THY4, ND4, ND3, 10, MU R, RT14, ND3, ND5, 22 C, CT14, ND5, ND4, 0.47, MU
Two winding transformer 2:1	L, L1, ND2, ND1, 10, MI L, L2, ND3, ND4, 2.5, MI M, M12, L1, L2, 4.5, MI R, RM, ND1, ND4, 1, ME

3.3.2. Data for the initial conditions

After giving the description of all the edges, the initial conditions for all state variables are specified; that is, we have to specify the initial voltages for the capacitors and initial currents for the inductors present in the circuit.
If all the initial values are zero, it is enough to indicate in a line the code 0; on the contrary, if there are non-zero initial conditions for some state variables, then it is sufficient to specify the values for these state variables as follows;

*First line must give the data for the number of state variables, NSV, for which the initial conditions are given; edge name (BRN) and value of the initial condition (ICV). 5 pairs of parameters (BRN, ICV) can be given in the first line.

*If there are more than 5 initial conditions to be specified, then additional lines must be used giving only edge name (BRN) and the value of the initial conditions (ICV) up to a maximum of 5 pairs of parameters (BRN, ICV) per line

3.3.3.Data for controlled sources

After specifying data for initial conditions, the description of any controlled sources present in the circuit should be given as follows: the first line gives the comment and the number of controlled sources. This line is followed by the description of each controlled source using one line per source. If there are no controlled sources present in the circuit, only one line having a zero (0) entry should be given.

3.3.4.Data for additional state variables

It is possible to augment the state equations of the system by inclusion of additional state variables and additional sources. This feature enables the user to include additional state equations corresponding to regulation circuit.

3.3.5.Total number of semiconductor switches

The next data following the information pertaining to additional state variables etc. contains the total number of semiconductor switches.

3.3.6.Data for sources

The data for original additional sources are described as follows: SOUDAT (M1,6)
TYPE, MAG, FREQ, PHI, OS, PW where,
TYPE represents the code of various types of permissible sources (Fig. 3.2)

1 d.c. sources
2. sinusoidal source
3. cosinusoidal source
4. pulsed source
5. saw tooth wave
6. sine-modulated sine wave
7. rectified sinusoidal wave

MAG	represents the amplitude of the source
FRE Q	represents the frequency, in type 7, this represents the frequency of the full sinusoidal wave
PHI	represents the phase angle in degrees
OS	represents the offset for sources of type 1,2,3,4 or 5; this represents the carrier frequency for type 6 source
PW	represents the pulse width in time units for type 4 source or the carrier frequency f_2 for type 6 source

Type 0 $a_7.x_7 * a_8.x_8$ and $a_9.x_9 * a_{10}.x_{10}$
Type 9 $(x_7.u_{13} + x_8.u_{14} + x_9.u_{15}) . a_{10} / x_{10}$

These special sources are defined in conjunction with the choice of suitable control parameter PRMT (13) value. The coefficients a_7, a_8, a_9 and a_{10} and code numbers of the state variables x_7, x_8, x_9 and x_{10} are defined as data following definition of 90 as the additional state variable line.

3.3.7.Additional data for semiconductors

For each semiconductor, additional data must be provided. In each case synchronizing voltages, initial state, holding current level, minimum device voltage for turn-on, turn-off time requirement for thyristors and the gate or base drive pulse width must be given. These data are to be given in the following manner,

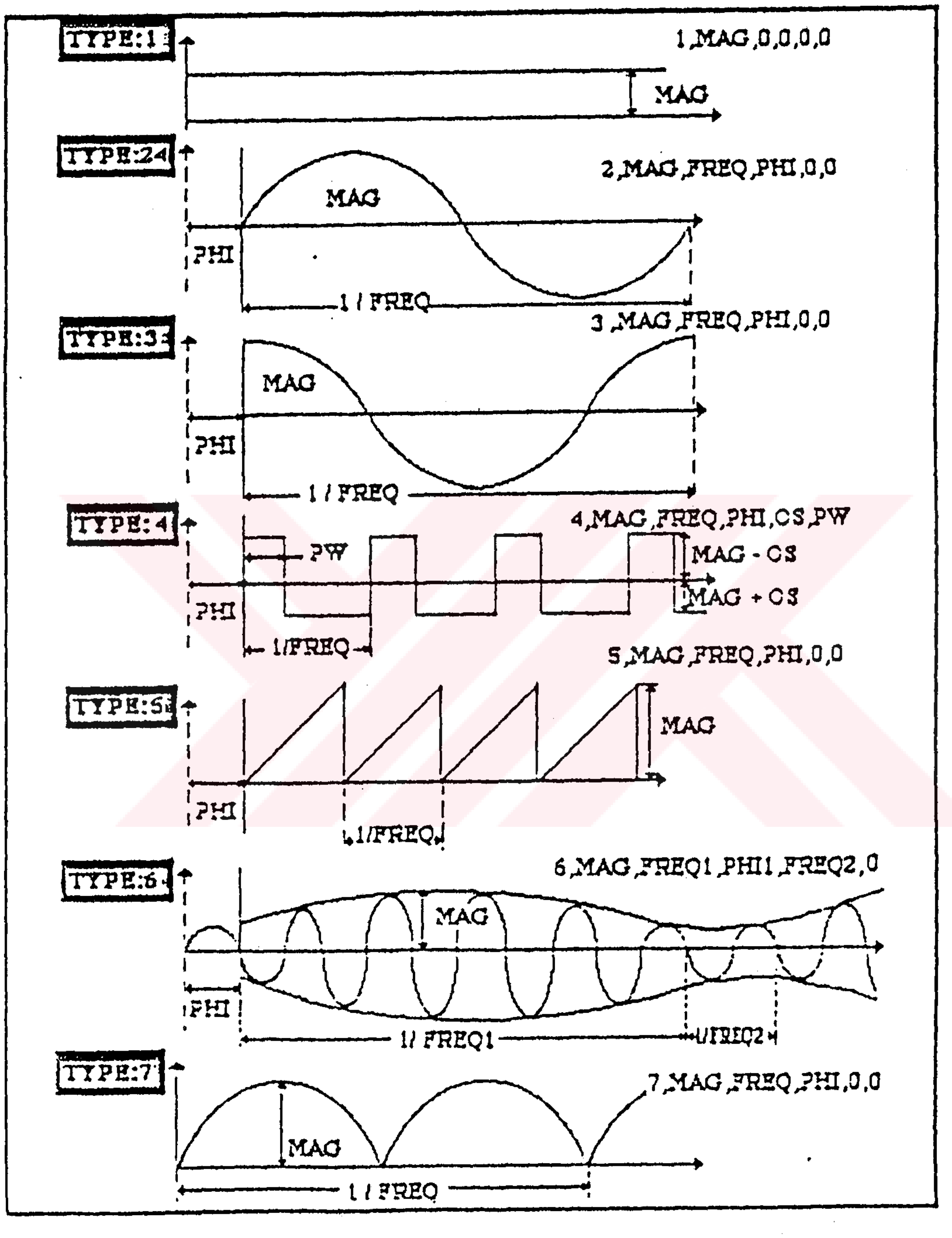


Fig 3.2 Permissible Sources For Atosec5 Simulator

Synchronizing voltages;
For each one of the semiconductors, the synchronizing voltages are defined in the first line: SOUDAT (M 1,6)

TYPE, MAG, FREQ, PHI, OS, PW where,

Type represents one of the code numbers given below with the following significance (Table 3.1)

1	Diode
2	Thyristor with sinusoidal wave form used as a reference for the detection of the firing instant
3	Bipolar or Mosfet transistor or GTO thyristor; ramp reference voltage is used for type 3 switch with fixed pulse width or with pulse width controlled by the control voltage defined by PARA(9)
4	Special type switches: thyristor type 411/412, transistor type 4 switch using special reference voltages (user defined)
5	Thyristor with half ramp reference voltage used for the detection of the firing instant.
6	Pulse width modulated (PWM) switch
7	PWM switch complementary to type 6
8	Any special type transistor switch: user defined subroutine
9	Any special type transistor switch: user defined subroutine complementary to type8

The significance of other parameters are defined in Table 3.1

Initial states;
After defining the synchronizing (reference) voltages, the initial states for all the semiconductor elements are given in one line with the following significance
1. if a semiconductor is initially conducting
0. if a semiconductor is initially blocked
Holding current;
For each one of the semiconductors, the next lines give the values of the holding current levels of device current in Amperes below which a semiconductor should block.
Minimum device voltage for turn-on;
For each one of the semiconductors, the next set of lines gives the values of device voltage above which it can turn on
Gate or base drive pulse width;
For each one of the semiconductors, the next set of cards gives the values of the gate pulse width in degrees for thyristors. GTO switches, the base drive pulse width in the case of bipolar transistors. This parameter is ignored for computation in the case of

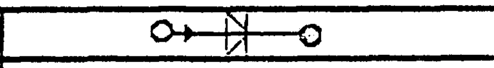
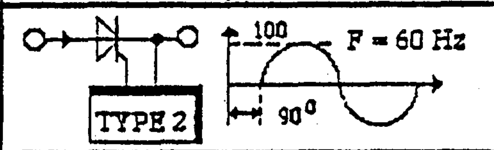
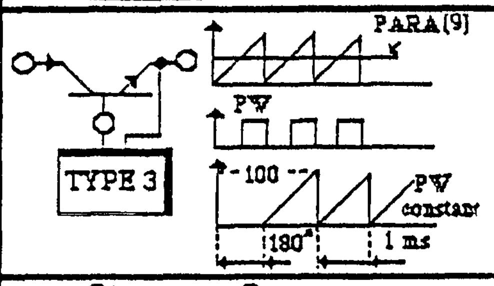
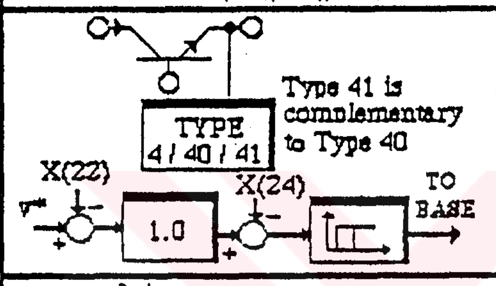
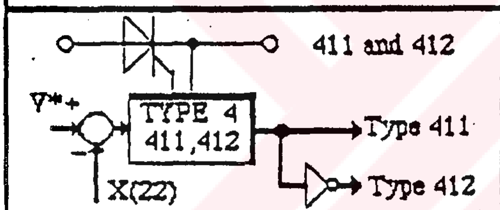
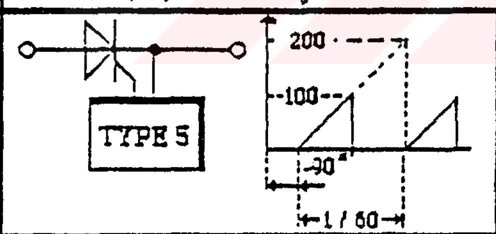
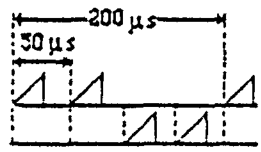
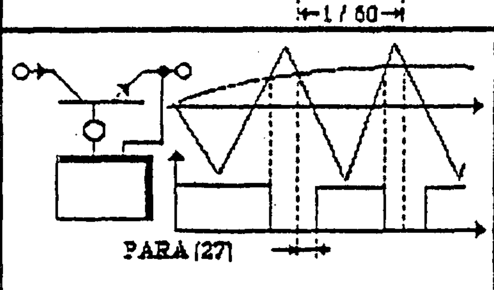
1		DIODE : 1,0,0,0,0,0
2		THYRISTOR WITH SINUSOIDAL SYNCHRONIZING VOLTAGE : 2,100,60,-90,0,0
3		NPN TRANSISTOR WITH RAMP REFERENCE VOLTAGE 3,100,1E3,-180,0,0 NPN TRANSISTOR WITH PULSE WIDTH CONTROLLED BY PARA(9) 3,100,1E3,0,0,30 COMPLEMENTARY TO ABOVE : 3,100,1E3,0,0,31
4		NPN TRANSISTOR (SPECIAL SWITCH) : USER-DEFINED; SEE SUBROUTINE EXTEIR 40,100,60,-90,22,24 POS. TYPE 4 or 4,100,60,-90,22,24 41,100,60,-90,22,24 NEG. TYPE 41 V* : 100 SIN (2π60t-90°) X(22) and X(24) are state variables
		THYRISTOR TYPE 411 OR 412 WITH SPECIAL TYPE SYNCHRONIZING VOLTAGE : 4,100,60,0,22,411 4,100,60,0,22,412 X(22) is state variable 22
5		THYRISTOR CONTROL WITH HALF RAMP SYNCHRONIZING VOLTAGE :  5,200,60,-90,0,0 5,360,20E3,0,51,5E3 5,360,20E3,0,52,5E3
6		PWM SWITCH TYPE 6 AND PWM SWITCH COMPLEMENTARY TO SWITCH TYPE 6, TYPE 7 6,100,60,-90,0,0 7,100,60,-90,0,0 f_m = 60 Hz; f_c = PARA(26)*f_m Amplitude of carrier wave : PARA(25) f_c/f_m = PARA(26) Dead time TD = PARA(27)

Table 3.1 Description of Synchronizing Voltages for Semiconductor Switches

diode, type 6, 7, 8, 9 switches and it can be made zero (0). For type 3 switch, if the pulse width is controlled by the control voltage then this parameter can be made zero.

Turn-off time requirement;

For each one of the semiconductors, the next set of lines gives the values of the turn-off time requirement. For bipolar or MOSFET transistors or GTO thyristors or diode switches, these values can be zero (0) as this parameter is not used for these devices.

3.3.8. Data for solution control

The parameters are denoted as PRMT or PARA parameters. The data are given in 4 lines with 9 entries per line. The significance of these parameters is as follows;

PRMT (1)	Initial time in seconds
PRMT (2)	Final time in seconds; if PRMT(28) is non zero, then PRMT(2) represents the period of the steady state solution
PRMT (3)	Step length in seconds
PRMT (4)	Set to zero
PRMT (5)	Set to zero
PRMT (6)	Set to zero
PRMT (7)	Printing step, a number identifying the number of step lengths after which the results are written in Tape4 (*.Tp4 file in PC), which can later be used for plotting etc.
PRMT (8)	Definition of allotted computer processing time in seconds for the computation of numerical solution. This is not used for personal computers. This value must be non zero for mini/mainframe computers
PRMT (9)	Value of the constant control voltage used for switches of types 2, 3 and 5. For switches of types 1, 4, 6, 7, 8 and 9, this parameter is not used.
PRMT (10)	Error amplitude used for the determination of semiconductor firing instant; this value could be critical in certain problems resulting in skipping of firing instants.
PRMT (11)	Set to zero
PRMT (12)	Set to zero
PRMT (13)	If this value is 0, then no special law is used for the definition of control voltage; control voltage is defined by PRMT(9). If this value is 1, then the control voltage is computed from; $a_1.x(N1) + .. + a_6.x(N6) + a_{11}.u(N11) + a_{15}.u(N15)$. If this value is 9, then the control voltage is computed from $a_1.x(N1) + .. + a_6.x(N6) + a_{11}.u(N11) + a_{12}.u(N12)$
PRMT (14)	Set to zero
PRMT (15)	Set to zero

PRMT (16)	Set to zero
PRMT (17)	Lower bound for control voltage, when calculated from special control law.
PRMT (18)	Upper bound for control voltage, when calculated from special control law.
PRMT (19)	Set to zero
PRMT (20)	△F, when used with a three phase variable frequency ac source that can be used with the induction motor drive problem; otherwise must be made zero(0).
PRMT (21)	Final time is defined to be PRMT(2) * PRMT(21); this is used only for the study of induction motor drive problem; otherwise must be made zero (0).
PRMT (22)	△A, when used with the induction motor drive starting problem; otherwise must be made to zero (0).
PRMT (23)	Set to zero
PRMT (24)	Set to zero
PRMT (25)	Amplitude of the carrier wave for type 6 and type 7 switches
PRMT (26)	Carrier frequency to modulating frequency ratio for type 6 and type 7 switches
PRMT (27)	Delay time before turn-on of type 6 ad type 7 switches. These parameters are used in conjunction with type 6 and type 7 switches only.
PRMT (28)	If this is zero, then the transient state is computed. It this is not equal to zero, then the number specified represents the number of iterations for the computation of steady state solution
PRMT (29)	Set to zero
PRMT (30)	If 0, no weighting factor is used for adjusting initial values for the next iteration. This is used only for the computation of steady state solution.
PRMT (31)	Accuracy specified to verify for the convergence of steady state solution
PRMT (32)	Set to zero
PRMT (33)	Hysteresis amplitude used in type 4 switch
PRMT (34)	Set to zero
PRMT (35)	Set to zero
PRMT (36)	Set to zero

3.3.9. Output Files

After the preparation of data for a circuit (for example Exam1.Dat), the data is stored in the Atosec5 directory. Use Ato5SIM module to study the simulation of the circuit;

-Define the name of the data file (for example, Exam1.Dat)

-Define the name of the Tape4 file (for example, Exam1.Tp4)
-Define the name of the Tape3 file (for example, Exam1.Tp3)

In the current version for personal computers, the command is:
Ato5SIM Exam1. As and when the computation progresses, the user can visualize the curves for the variables that had been defined in the data file (only on the PC version).

In mainframe computers, the data is executed in batch mode using the simulation module.

TAPE 6 (output) Results:

The output file Tape 6 resulting from the execution of a set of data for a given problem using AtoSec5 Simulator contains the following:

-A listing of edges after the simulation processes it: priorities are assigned for E, C, R semiconductor switches L, J type elements.
-The input data as read for sources, semiconductor switches and solution control parameters.
-The initial values for the state variables

3.3.10. Diagnostic Error Messages

In case of abnormal termination, various types of diagnostic messages are issued which would help the user to identify the errors committed in the preparation of data. For example, if a hanging node is present in the circuit indicating that a node has only one edge connected to it, then the following message appears on the output file:

"The node, xxx, has only one edge"

At the end of reading all the edge description cards, the execution is terminated by the indication "Stop 001".
Another type of error could occur while giving data for controlled source or additional state variables. At this time, the error message would be:

"There is an error in xxxth controlled source card"

This indicates that the name of the edge given as the controlled variable does nor correspond to th name of a source branch or the name of the edge given as controlling branch is not in the list of state variables. The list of state variables is available on Tape 3. the processing then stops and is indicated by "Stop 002".

The message "There is an error in xxxth additional state variable card" indicates that the name of the edge used, is not in the list of state variables; when this kind of error occurs, the processing stops after reading all the cards pertaining to the additional state variables. This is also indicated by "Stop 002". The user is warned that there are no other error messages available should there be any omission of data in other parameters or sequence, after the definition of controlled sources.

3.3.11. TAPE3 Files

This file contains two very useful sets of information which are required for the preparation of additional data and interpretation of results. The first set contains the list of state variables and their code numbers. The code numbers are required for the analysis of computed results such as harmonic analysis of wave forms, finding the final values of the state variables at the final time, plotting etc. the code numbers for other variables can also be inferred as follows;
Let there be N state variables and Ns sources;

X1, ..., Xn represent the state variables (voltage across capacitor elements and inductor currents)

CX1, ..., CXn represent the co - state variables (current through capacitor elements and voltage across inductor elements).

S1, ..., SNs represent the actual sources present in the system.

These code numbers are used for the plotting of computed results.
The second set of important results in the Tape 3 file is the semiconductor switch over table. this table prints all the time instants at which a change of state for at least one of the switches has occurred. The results contain rows of the time instants and the states of all the semiconductor switches (as many 0's or 1's as there are number of semiconductor switches). The column entries correspond to the semiconductor elements in the same order in which they have been enumerated in the data giving the description of the edges.

3.3.12. TAPE4 Results

TAPE4 contains all the results of computation for all state variables, co - state variables, derivatives of state variables, and original sources at all instants of time as defined by control parameter PRMT(7). These results are used for plotting, harmonic analysis etc. using the post processing module Ato5PPM.

3.3.13. Restrictions for the Power Converter Circuit

3.3.13.1. Limitations on the Number of Elements

The following restrictions have been imposed on the number of elements, in order to limit the memory space used and to enable network solution using a time sharing computer terminal. As such, these restrictions are neither on the method of formulation nor on the solution of the problem:

*the total number of edges is limited to 150
*the total number of vertices is limited to 40
*the total number of semiconductors is limited to 15
*the total number of any one of the elements C, or R, or L is limited to 40
*the total number of state variables or sources is limited to 50
As a rule, the word used in the computer must be at least of 32 - bit size.

3.3.13.2. Topological Restrictions

There should not be any cutset that contain only inductors and current sources.
There should not be any cutset containing only inductors and semiconductors. This restriction is generally overcome by taking into account the Rt - Ct protection circuit across any semiconductor device.
There should not be any loop containing only capacitors and voltage sources.

3.3.13.3. Restrictions Placed on the Controlled Sources and Additional State Variables

When the controlled sources are present, the controlling quantity should always be a state variable (i.e. current through inductor or voltage across capacitor). Among the inductors forming a cutset, the program always makes the first inductor listed as a tree branch and as such that current will not be a state variable so, proper ordering of inductors is essential if the currents through some of them control some controlled sources.

One way of avoiding all inductor cutsets is to add a high value resistor across each inductor taking the Q factor into consideration. Similarly, an all capacitor loop can be avoided by adding a small resistor in series with the capacitor by taking into account the leakage factor for the capacitor element.

3.4. Source code for Atosec5

The source code of the Atosec5 software is in FORTRAN 77. The simulation program is called Ato5 Sim which computes the solution of the simulated system. The parameters of the simulation program are set as follows:

M1 = 40
NBITS = 25
M2 = 150
NWRDS = M2 / NBITS

The parameter M1 signifies the maximum number of state variables that can be studied using the simulator. the current version allows a maximum of 40 state variables. If the total number of state variables for a system exceeds 40, then the parameter M1 should be set at the desired value subject to availability of memory in the computer that is used for simulation.

The parameter M2 signifies the maximum number of branches that is allowed for the simulator. The current version allows a maximum of 150 branches. If the total number of branches for a system exceed 150, then parameter M2 should be set at the desired value subject to availability of memory in the computer used for the simulation study.

The parameter NBITS represents the number of bits that are used for the representation of nodes in a given word machine.

The parameter NWRDS represents the number of words that are used for the representation of incidence matrix and fundamental cutset matrix. This parameter is automatically chosen from the values given for M2 and NBITS.

The main program contains labeled common commands which contain the variables that are used in the common blocks. The significance of the various dimensioned variables are as follows:

X(M1)	State variables
XDOT(M1)	derivatives of state variables
A(M1)	co - state variables
STATE1(M1,M1)	state1 (A1) matrix
STATE2(M1,M1)	state2 (B1) matrix
STATEA(M1,M1)	stateA (A) matrix
STATEB(M1,M1)	stateB (B) matrix
RLCINV(M1,M1)	capacitor - inductor (LC) matrix
SOURCE(M1,M1)	source (U) vector

The state equations for the system are written in terms of these variables:

[RLCINV] [XDOT] = [STATE1] [X] + [STATE2] [SOURCE] (3-4)

or

[XDOT] = [STATEA] [X] + [STATEB] [SOURCE] (3-5)

In short form Eq (3-4) and (3-5) are written as:

[LC] [X] = [AX1] [X] + [B1] [U] (3-6)

[X] = [A] [X] + [B] [U] (3-7)

The significance of other dimensioned variables are:

TSTAT (M1)
Vector containing the time instants at which change of state occurs for the semiconductor devices
SOUDAT (M1,6)
Array representing data for sources and reference / synchronizing voltages for semiconductor devices
THSP (M1,4)
Array representing additional data for semiconductor devices
THSP (M1,1)
Holding current for the semiconductor devices
THSP (M1,2)
Minimum voltage required for turning on the semiconductor devices
THSP (M1,3)
Gate / base pulse width specification (in degrees) for semiconductor devices
THSP (M1,4)
Recovery time specification (in time units) for semiconductor devices
WKA (M1)
Table containing time instants at which semiconductor change to conducting states
FPX (M1,M1), FPXINV (M1,M1), FPX1 (M1,M1)
are arrays that are used during the computation of steady state in subroutine SOL
XJO (M1), XCORR (M1), XTO (M1)
are vectors that are used to store initial, corrected and final values of the state variables in subroutine SOL.
NRC(M1),SRC(M1),CH(2700),VALUE(250)
are vectors that are used during the formulation of the tree for the graph of the circuit.

NSTAT(M2)
table that is used to store the conduction/blocking states of the semiconductor devices at a given instant.
INC(M2,NWRDS)
incidence matrix/fundamental cutset matrix.

The main simulation program ATO5SIM calls subroutine MAINPR which in turn calls five principal subroutines:
TREEF,STATE,LCINVT,CONSOR,SOLVE

Subroutine TREEF computes the fundamental cutset matrix from the topological description of a circuit. After processing data for the description of the circuit in terms of the different nodes and branches, this subroutine formulates the incidence matrix and then a modified proper tree.

Subroutine STATE computes the state equations using the fundamental cutset matrix.

Subroutine LCINVT computes the capacitor-inductor matrix which is then used to formulate the state equation form.

Subroutine CONSOR is used to read data for controlled sources, additional state variables and additional data for semiconductor devices.

Subroutine SOLVE is used to read data for the parameters of the solution such as initial time, step length, final time, etc. and to solve numerically the state equations.

4. STATOR VOLTAGE CONTROLLED INDUCTION MOTOR DRIVE USING ATOSEC5

The squirrel - cage induction motor is basically a simple, cheap and reliable machine which can provide excellent characteristics where nearly constant speed is required. The speed of a typical induction motor fed from a constant frequency supply may typically vary by less than 5% over the range of normal load and supply voltage variations. This basic characteristic of the induction motor, to run at a virtually constant speed close to the synchronous speed, has long been a challenge to designers who have sought to devise variable speed schemes using induction motors. One of the simplest speed control methods that can be used is based on the stator voltage control. The variable ac voltage can be obtained by using a thyristor ac regulator.

A typical three phase ac regulator is shown in Figure 4.1. The ac regulator consists of three pairs of anti parallel connected thyristors feeding a star connected RL load. A well-known equivalent circuit for the induction motor is used for each one of the three phases which takes into account the stator and rotor resistances, stator and rotor leakage inductances, and the mutual inductance. AC motor parameters are chosen as follows; 1325 RPM, 1/3 HP, 220 V, 375 W.

Table 4.1 shows the list of data for the ac regulator fed induction motor used for the Atosec simulator. The simulation results are obtained using this base file. The desired changes are applied to this file and different graphic outputs are given.

In the third chapter the semiconductors parameters are explained. For thyristor firing technique, type 5 thyristor control with half ramp synchronizing voltage is selected. Parameters are listed as,

TYPE,MAG,FREQ,PHI,OS,PW

The parameters are given in DATA FOR SYNCHRONIZING VOLTAGES FOR SEMICONDUCTORS section in Table 4.1. MAG parameter stands for magnitude of the ramp and effects the thyristor firing width. If this parameter is made smaller than the original value, 360, the firing width is decreased. Therefore the magnitude of the voltage that is applied to the motor is decreased so the speed can be adjusted. The FREQ parameter determines the AC supply voltage frequency and it was selected as 50 Hz. The PHI parameter determines the thyristor's firing angles and they are chosen using 60 deg intervals between them. The OS and PW parameters are selected as 0.

Table 4.2 includes the list of state variables and the semiconductor switch over table. List of state variables are very important when we want to get the simulation results, because the ATOSEC5 software programs evaluates the state variable numbers, not the device's labels. Only the voltage sources are used with their original names. If we

want to obtain voltage of one of the devices, the C initial letter is appended to the number of the state variable. If the currents are used, no letter is appended.
Semiconductor Switchover Table in table 4.2 shows one 20 milliseconds period for triggering. This table is created by the ATOSEC5 simulator from the Type 5 thyristor control method to realize how the triggering system works. The "1" shows the related thyristor is fired at this time. For example at 4.8 msec, thyristor 1 is triggered, and at 5.3 msec none of the thyristors are triggered. At 5.35 msec, the thyristor 1 is triggered again which is determined by the type 5 thyristor control method.

Figure 4.2. gives the plotted results for the following variables:

Thyristor 1 current, X_4
Voltage across thyristor 1, CX_4
Phase voltage of the ac motor, $CX_{19} + 7.2X_{13} + CX_{13}$
Line current of the ac supply mains, X_{13}

We study the steady state operation of the induction motor under constant speed. The aim of this study is to predict the steady state operation of the induction motor based on the familiar equivalent circuit.
In this analysis, the MAG parameter is selected as 360. Up to the 20 msec, the initial results can be seen. After that time the steady state outputs can be evaluated. The Thyristor 1 current, X4, is approximately 1.2 Ampere maximum value and remains several msecs. When we compare the thyristor 1 current with the voltage across thyristor 1, CX4, it can be seen that when thyristor conducts the voltage is nearly zero. The positive pulse on the voltage graphic shows the turn-on condition and the negative pulse shows the turn-off condition.
The phase voltage of the ac input to the motor is computed as the sum of the voltage across the mutual inductor, MUTA (co-variable CX_{19}), the voltage drop across the stator resistor (7.2 X_{13}), and the voltage drop across the stator leakage inductor (co-variable CX_{13}). The phase voltage is a new version of the AC line voltage that some parts are removed. This changes the rms value of the voltage that can be seen from the ac motor. The ac motor has a low-pass filter characteristic, so the harmonics of the processed voltage waveform can be filtered by the nature of inductance of the motor. Also the same harmonics are included by the line current due to the ac motor voltage waveform harmonics. All the variables can be analyzed comparatively in time domain.

Figure 4.3. gives the plotted results for the same variables that are used in the previous simulation. The adjustments were made in the base file DATA FOR SYNCHRONIZING VOLTAGES FOR SEMICONDUCTORS section as follows:

5, 310, 0.050, -00, 0, 0

5, 310, 0.050, -060, 0, 0
5, 310, 0.050, -120, 0, 0
5, 310, 0.050, -180, 0, 0
5, 310, 0.050, -240, 0, 0
5, 310, 0.050, -300, 0, 0

The only difference is the MAG parameter has a value of 310. Therefore, the triggering width is decreased. As a result of width adjustment, the ac motor rms voltage value is decreased. Also the rms line current smaller than the previous value. The waveform changes can be easily seen with comparing the previous graphic waveforms.

Figure 4.4. gives the plotted results for the following variables:

Phase 1 voltage, -S1
Phase 1 voltage of the ac motor, $CX_{19} + 7.2X_{13} + CX_{13}$
Phase 2 voltage of the ac motor, $CX_{20} + 7.2X_{14} + CX_{14}$
Phase 3 voltage of the ac motor, $CX_{21} + 7.2X_{15} + CX_{15}$

The modification must be made at the end of the program as;

-S1, $CX_{19} + 7.2X_{13} + CX_{13}$, $CX_{20} + 7.2X_{14} + CX_{14}$, $CX_{21} + 7.2X_{15} + CX_{15}$

As can be seen from the figure, the phase voltages of the ac motor are the same but they have 120 deg phase difference like the one between the phase voltages. The Phase 1 voltage of the ac motor has the same form with the Phase 1 voltage, -S1. But, the ac motor voltage has some harmonics.
ATO5PPM program can analyze the harmonic contents of the variables. The original phase voltage -S1 was analyzed an the result is given in Figure 4.5. Only it has main harmonic if we think that the line voltage is pure sinusoid.
The motor phase voltage harmonic analysis result is given in the Figure 4.6. As can be evaluated, some harmonics have a magnitude in the descending order. Due to the 3 phase system nature, the even harmonics are eliminated. The harmonic content analysis shows that we have acoustic noise, but motor filters the unwanted harmonics. Therefore, motor rotates at different speed with slight changes due to the inefficiency of the stator voltage control method. Also, in Figure 4.7. the line current harmonics are given.
When the stator voltage is decreased, speed can be adjusted, but at the same time torque would get smaller. This is not the ideal situation. Also, due to the limited speed adjustment, this is not wide - used method. The frequency control technique using inverter logic must be preferred. But, to keep the "voltage / frequency" voltage constant, the stator voltage control also can be applied to the system.

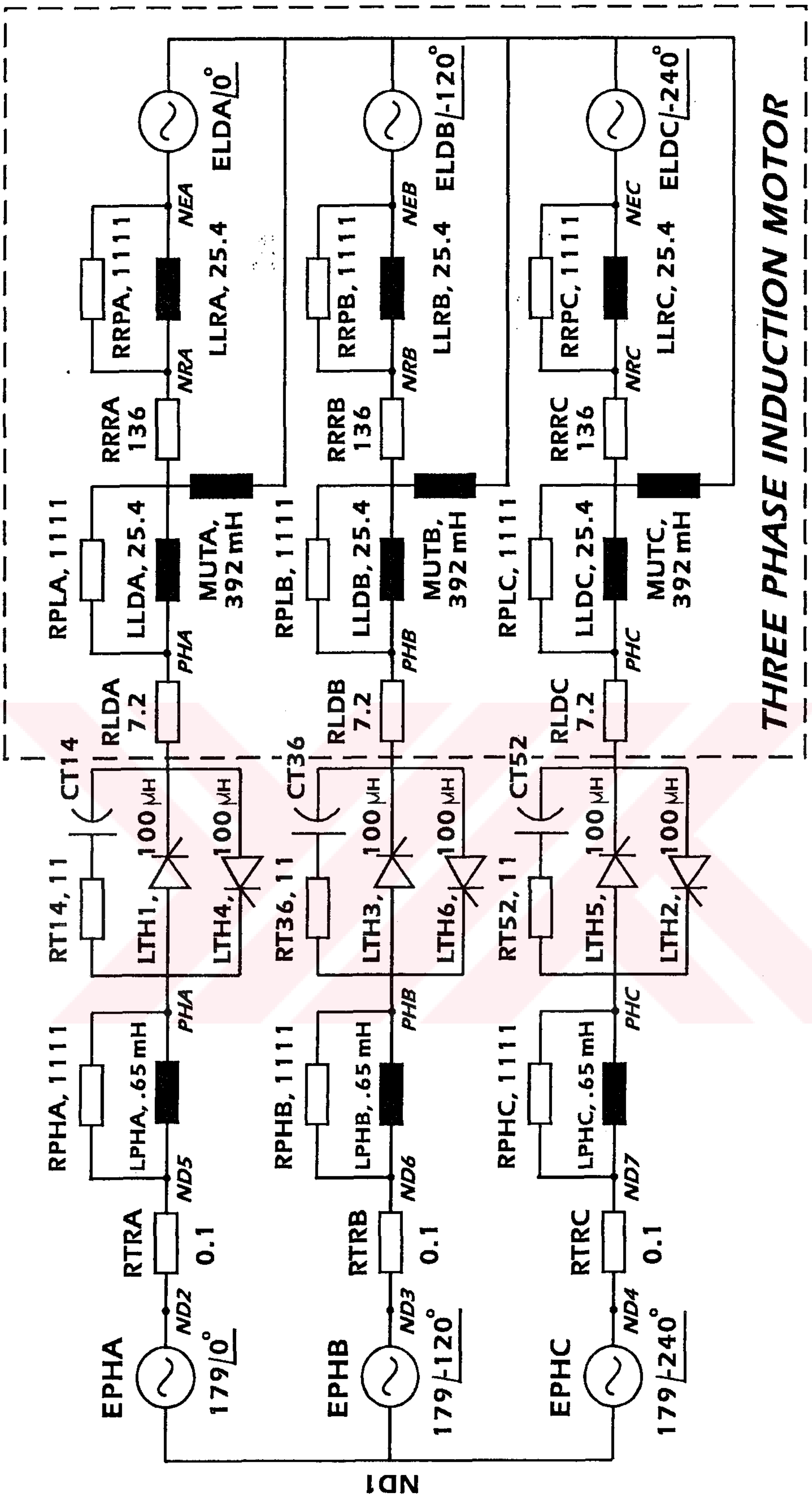


Figure 4.1. Three-phase ac regulator-fed induction motor circuit

```
$ -----------------------------------------------------------------
$ BEGIN ENUMERATION OF EDGES DATA.
$ -----------------------------------------------------------------
E, EPHA, ND1, ND2
E, EPHB, ND1, ND3
E, EPHC, ND1, ND4
R, RTRA, ND2, ND5, 0.1
R, RTRB, ND3, ND6, 0.1
R, RTRC, ND4, ND7, 0.1
S, LTH1, PHA, PAA, 0.1
S, LTH2, PCC, PHC, 0.1
S, LTH3, PHB, PBB, 0.1
S, LTH4, PAA, PHA, 0.1
S, LTH5, PHC, PCC, 0.1
S, LTH6, PBB, PHB, 0.1
R, RT14, PHA, N14, 11.
R, RT36, PHB, N36, 11.
R, RT52, PHC, N52, 11.
C, CT14, N14, PAA, 0.0002
C, CT36, N36, PBB, 0.0002
C, CT52, N52, PCC, 0.0002
R, RLDA, PAA, NSA, 7.2
R, RLDB, PBB, NSB, 7.2
R, RLDC, PCC, NSC, 7.2
L, LPHA, ND5, PHA, 0.65
L, LPHB, ND6, PHB, 0.65
L, LPHC, ND7, PHC, 0.65
R, RPHA, ND5, PHA, 1111
R, RPHB, ND6, PHB, 1111
R, RPHC, ND7, PHC, 1111
L, LLDA, NSA, NMA, 25.4
L, LLDB, NSB, NMB, 25.4
L, LLDC, NSC, NMC, 25.4
R, RPLA, NSA, NMA, 1111
R, RPLB, NSB, NMB, 1111
```

```
R, RPLC, NSC, NMC, 1111
R, RRRA, NMA, NRA, 136
R, RRRB, NMB, NRB, 136
R, RRRC, NMC, NRC, 136
L, LLRA, NRA, NEA, 25.4
L, LLRB, NRB, NEB, 25.4
L, LLRC, NRC, NEC, 25.4
R, RRPA, NRA, NEA, 1111
R, RRPB, NRB, NEB, 1111
R, RRPC, NRC, NEC, 1111
E, ELDA, NEA, NNN
E, ELDB, NEB, NNN
E, ELDC, NEC, NNN
L, MUTA, NMA, NNN, 392
L, MUTB, NMB, NNN, 392
L, MUTC, NMC, NNN, 392
$ ----------------------------------------------------------------
$ END OF ENUMERATION OF EDGES DATA.
$ ----------------------------------------------------------------
*
$ ----------------------------------------------------------------
$ DATA FOR INITIAL CONDITIONS.
$ ----------------------------------------------------------------
0
$ ----------------------------------------------------------------
$ DATA FOR CONTROLLED SOURCES.
$ ----------------------------------------------------------------
0
$ DATA FOR ADDITIONAL STATE VARIABLES.
$ ----------------------------------------------------------------
0
$ ----------------------------------------------------------------
$ TOTAL NUMBER OF SEMICONDUCTORS.
$ ----------------------------------------------------------------
06
```

```
$ ------------------------------------------------------------------
$ DATA FOR SOURCES.
$ ------------------------------------------------------------------
2, -179, 0.05, 0, 0, 0
2, -179, 0.05, -120, 0, 0
2, -179, 0.05, -240, 0, 0
$ ------------------------------------------------------------------
$ DATA FOR SYNCHRONIZING VOLTAGES FOR SEMICONDUCTORS.
$ ------------------------------------------------------------------
2, 00, 0.050, -00, 0, 0
2, 00, 0.050, -120, 0, 0
2, 00, 0.050,-240, 0,0
5, 360, 0.050, -00, 0, 0
5, 360, 0.050, -060, 0, 0
5, 360, 0.050, -120, 0, 0
5, 360, 0.050, -180, 0, 0
5, 360, 0.050, -240, 0, 0
5, 360, 0.050, -300, 0, 0
$ ------------------------------------------------------------------
$ INITIAL STATES FOR SEMICONDUCTORS.
$ ------------------------------------------------------------------
0, 0, 0, 0, 0, 0
$ ------------------------------------------------------------------
$ HOLDING CURRENT VALUES FOR SEMICONDUCTORS.
$ ------------------------------------------------------------------
0.1, 0.1, 0.1, 0.1, 0.1, 0.1
$ ------------------------------------------------------------------
$ MINIMUM VOLTAGE FOR FIRING SEMICONDUCTORS.
$ ------------------------------------------------------------------
2, 2, 2, 2, 2, 2
$ ------------------------------------------------------------------
$ GATE OR BASE PULSE WIDTH.
$ ------------------------------------------------------------------
120, 120, 120, 120, 120, 120
$ ------------------------------------------------------------------
```

$ TURN-OFF TIME REQUIREMENT.
$ ---
0.02, 0.02, 0.02, 0.02, 0.02, 0.02
$ ---
$ CONTROL PARAMETERS
$ ---
0, 60, 0.05, 0.05, 0, 0, 1, 158, 90, 4, 120, 0.2, 0, 0, 0, 0, 0, 0
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0
S_3-S_1, $CX_{19} + 7.2X_{13} + CX_{13}$, $-S_1$, X_{13}, CX_4, X_4

Table 4.1. Program Data

State Variables

State Variable	Name
1	CT14
2	CT36
3	CT52
4	LTH1
5	LTH2
6	LTH3
7	LTH4
8	LTH5
9	LTH6
10	LPHA
11	LPHB
12	LPHC
13	LLDA
14	LLDB
15	LLDC
16	LLRA
17	LLRB
18	LLRC
19	MUTA
20	MUTB
21	MUTC

Semiconductor Switchover Table

T = 4.80000	1	0	0	0	0	0
T = 5.30000	0	0	0	0	0	0
T = 5.35000	1	0	0	0	0	0
T = 5.40000	0	0	0	0	0	0
T = 8.15000	0	1	0	0	0	0
T = 8.30000	1	1	0	0	0	0
T = 11.4500	1	1	1	0	0	0
T = 11.9500	0	1	1	0	0	0
T = 14.8000	0	1	1	1	0	0
T = 15.7500	0	0	1	1	0	0
T = 18.1500	0	0	1	1	1	0
T = 19.1500	0	0	0	1	1	0
T = 21.4500	0	0	0	1	1	1
T = 22.3500	0	0	0	0	1	1
T = 24.8000	1	0	0	0	1	1

Table 4.2. State Variables List and Thyristor Switchover Table

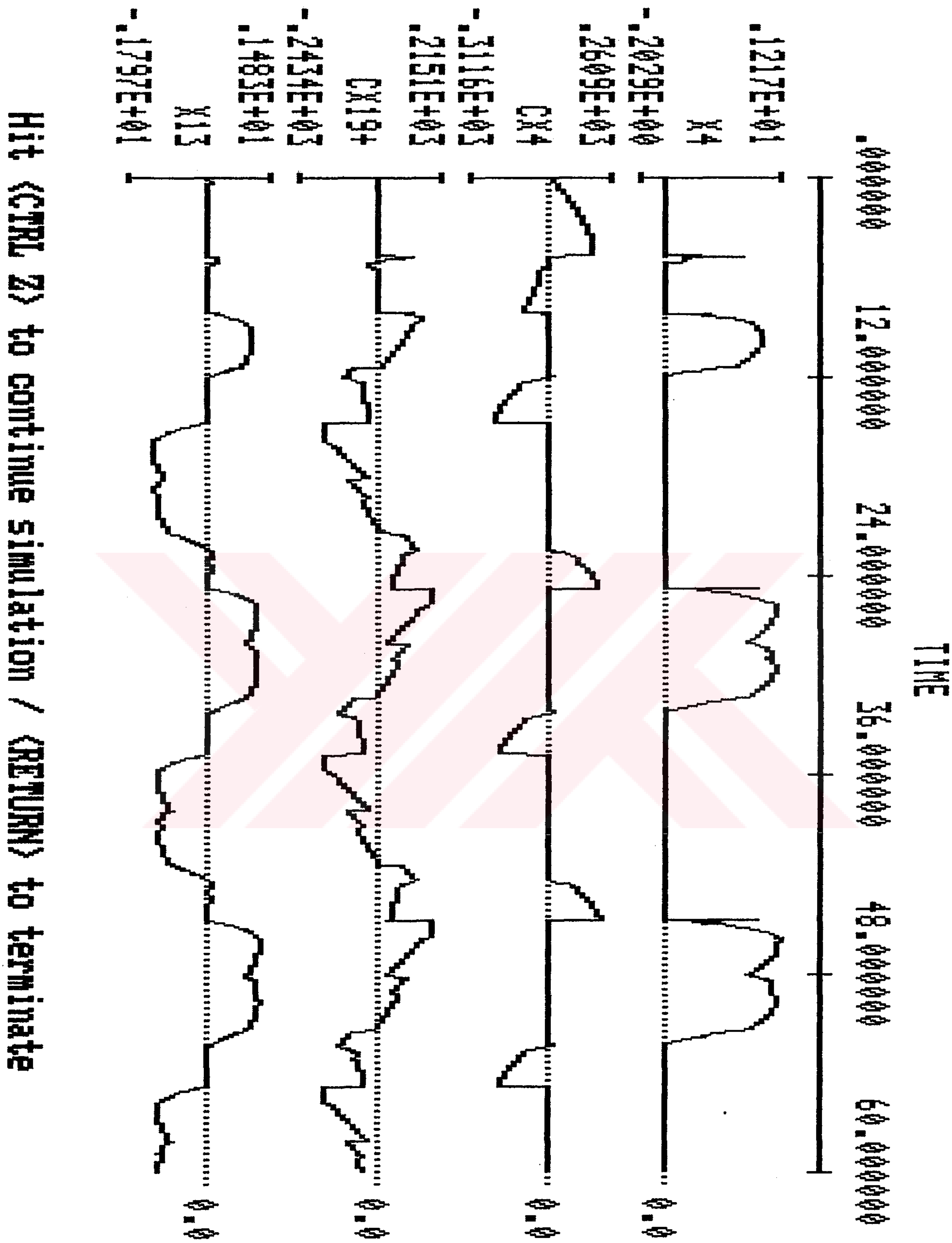


Figure 4.2. ATOSEC5 simulation result 1

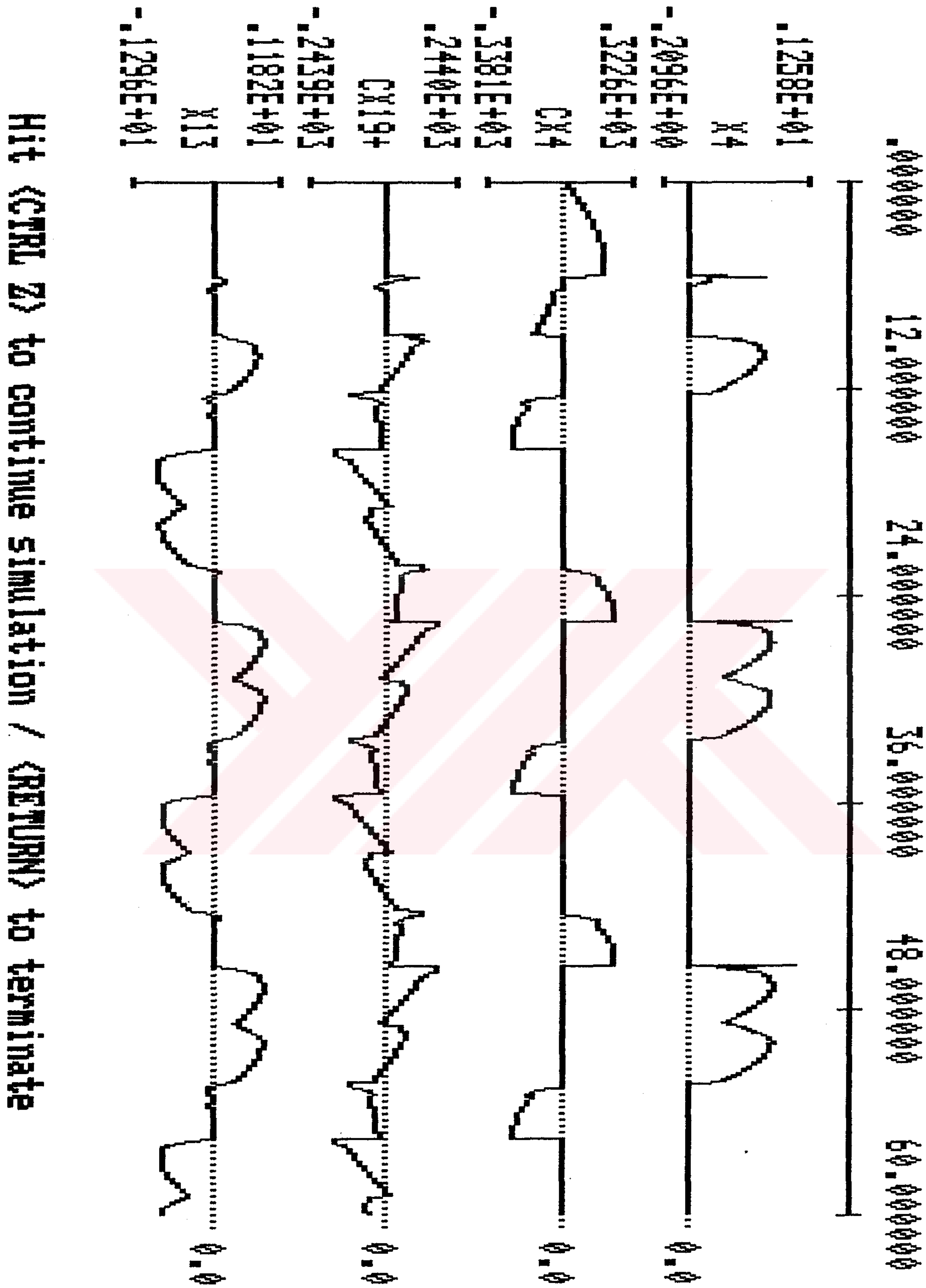


Figure 4.3. ATOSEC5 simulation result 2

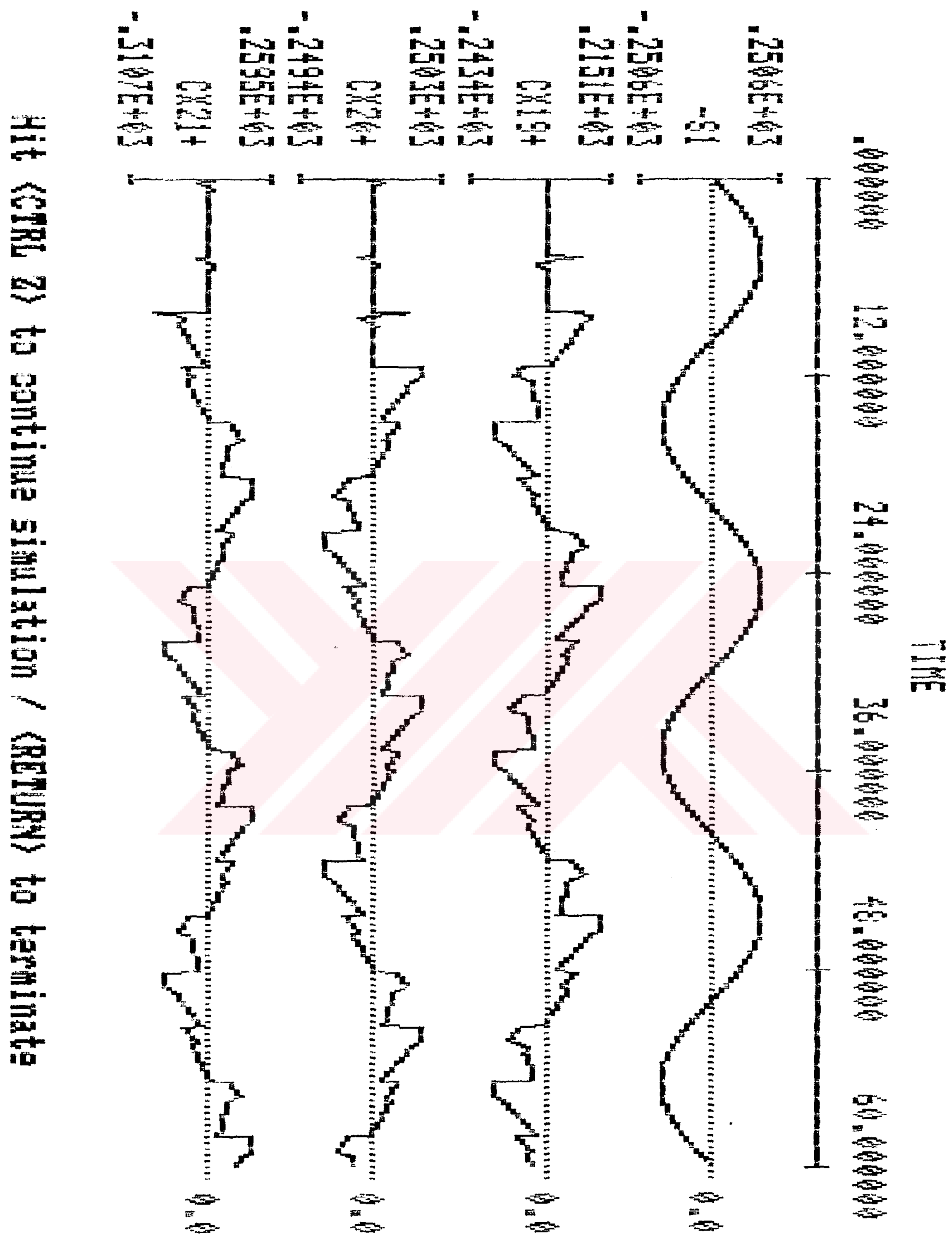


Figure 4.4. ATOSEC5 simulation result 3

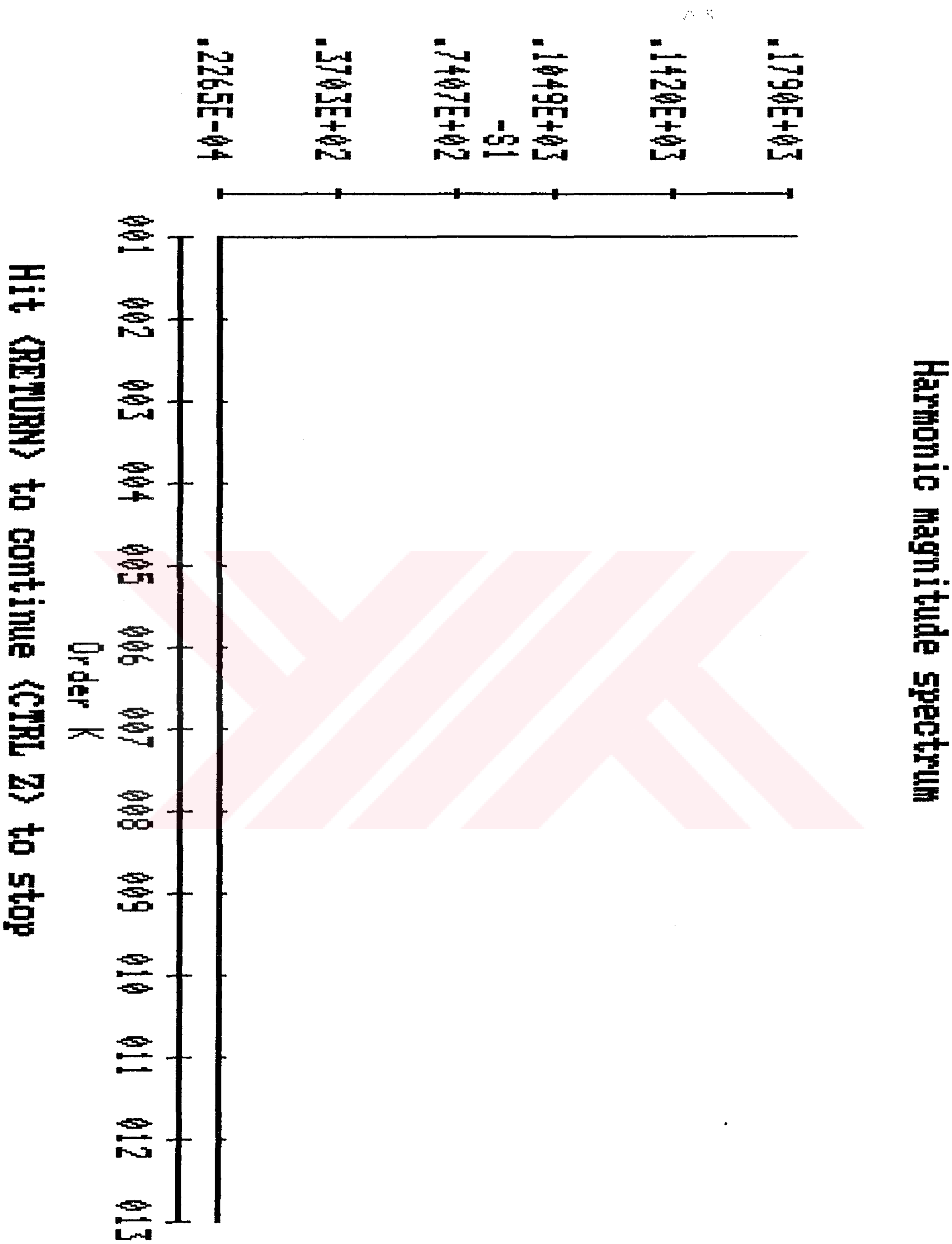


Figure 4.5. The ac supply voltage harmonic analysis

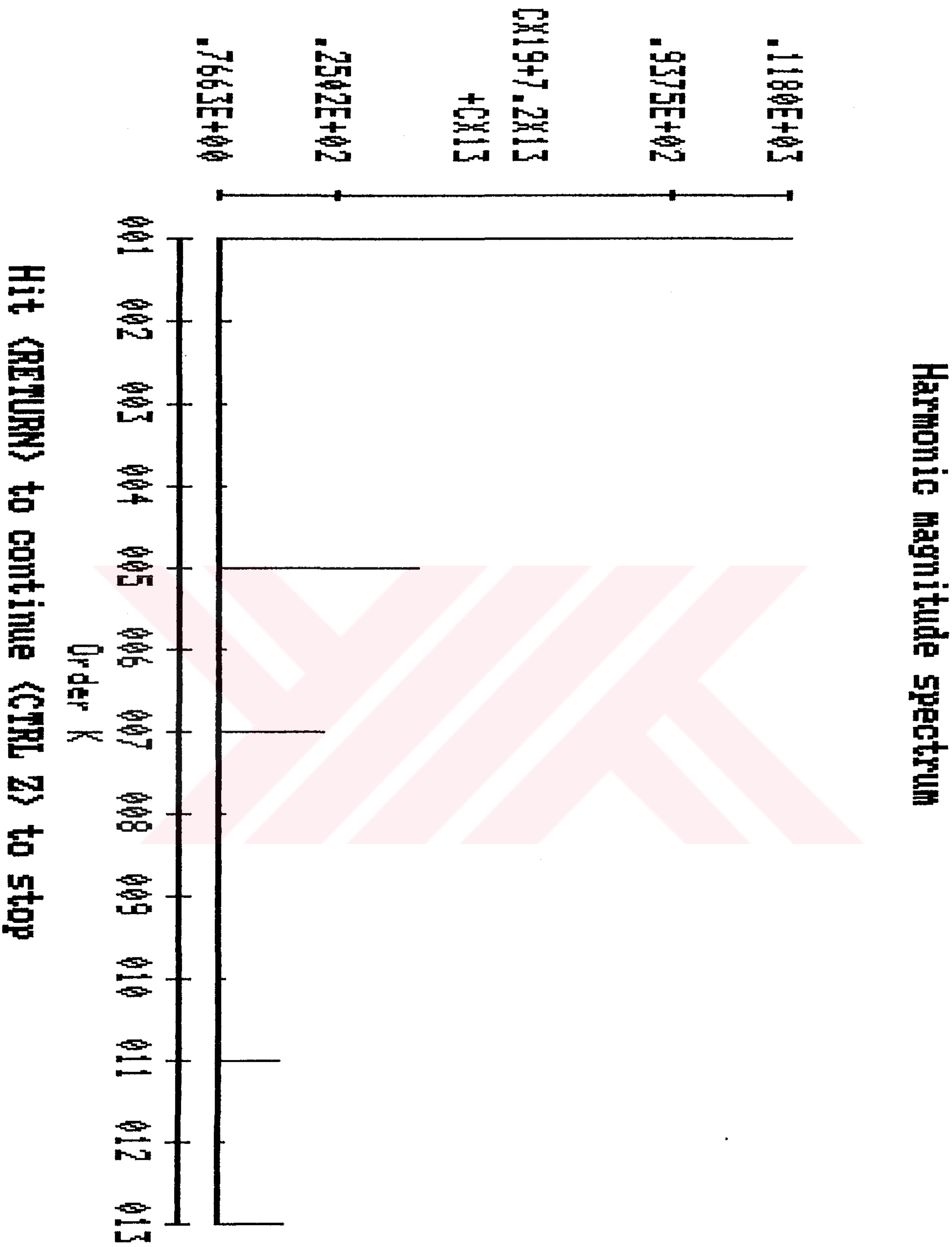


Figure 4.6. The ac motor voltage harmonic analysis.

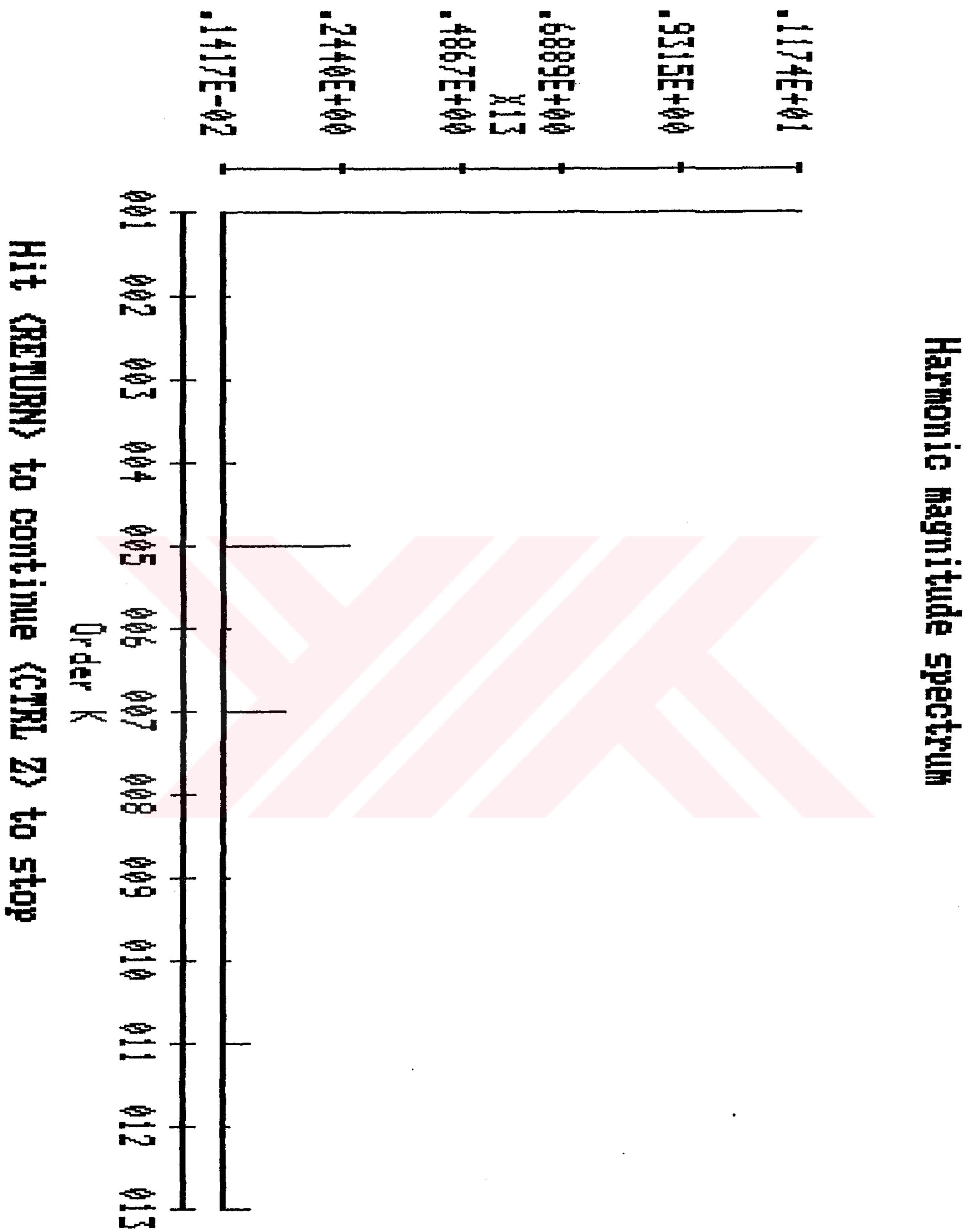


Figure 4.7. The line current harmonic analysis.

5. CONCLUSION

In this thesis study, an induction motor speed control is applied on a simulation software and some results are obtained that is close to the known theoretical results. These results are voltage and current graphics of the three phase ac regulator and they were given in Chapter 4.

In the thesis study, the ATOSEC5 power electronic circuits simulation software is used. The most important reason to select this simulation software is it's ability of analyzing power semiconductor devices successfully. In order to design generally electronic circuits in SPICE simulation software, the new additional features of this software enables also power electronic systems as well.

In the thesis, ATOSEC5 simulation software was introduced and briefly shown the usage of software efficiently. To determine the software abilities, the steps of analyzing process were explained to understand how to solve a problem. A stator voltage controlled induction motor drive is selected as a power electronics problem and the results were obtained.

Also some comparisons are made with other simulation softwares. When the simulation was performed, some inefficiencies were detected. At first, problem circuit entering module is not user friendly development environment. Secondly, simulation module and the graphics module are not easily interconnected to each other because of the state variables' assignment. Some difficulties are appeared when we try to link the simulation results to the graphics module. Thirdly, state variables are limited, therefore complex problems may not be easily implemented to the simulation software because of number of nodes limitations. The fourth; the source code is created by using the Fortran 77 language, so the program development enviroment is not powerful to use, and the processing speed is not high as well in C language. At the fifth step, more than four signals can not be seen on one graphic screen and comparing the results of more signal waveforms with the others is not possible. Also, the gate control signals' waveforms that applied to the switching elements such as thyristors cannot be seen graphically. But, this is important to compare the output voltage and current signals with the gate signals respectively. The effects of turn-on and turn-off activities of the power semiconductor switches must be analyzed comparatively with the output signals. At last, on-line help facility is not available, at first glance may be this is not required but it makes easier to use the development area efficiently without using manuals.

In spite of usage difficulties, the ATOSEC5 simulation software is an efficient media to analyze power electronic circuits and we can realize how our system works. The results can be considered as close to the real practical results more accurately due to the special circuit modeling feature. The program graphic outputs can be easily obtained using ATO5SIM program. Also, some features in the ATO5SIM program enables these graphic outputs processed by an external graphic program. Printouts can easily be taken either usage of the graphic program like GRAPHER or using Print Screen hotkey. If the second printout option is preferred, initially "GRAPHICS GRAPHICS" DOS command must be executed. Beside, the harmonic analysis feature of the ATO5SIM program is very helpful for design efficiency.

The phase voltage of the AC input to the motor includes harmonics and its not similar to a sinusoidal form. This depends on thyristor firing angles and inductive operation. Stator voltage controlled AC motor speed adjustment is not a wide-used method. Speed adjustment area is small and its around somewhere close to the synchronous speed of induction motor. Frequency adjustment of the line voltage is better than stator voltage control, but this method is more complex. Frequency adjustment using inverter circuit also must be supplied with the stator voltage control. At start-up, the line voltage must be low due to the excessive current drawn by ac motor load. Also, when the speed adjusted in a wide area the voltage / frequency ratio must be kept constant.

A relatively basic problem is selected to show the abilities of the software. As more complex problems; a more popular Space Vector PWM generation method, and indirect or direct vector control (known as flux control) of the induction motor systems can be simulated using this software. It is very important help to analyze these more complex problems without using a real development enviroment. Also the simulation results can be compared with the real time results to see the ability of the ATOSEC5 simulation software as a future thesis study.

The help of simulation softwares can be expressed in two ways. First, the drive circuits can be built easily with examining all the circuit conditions. This enables to find best circuit that satisfies the results. Secondly, the results of the simulations gives us a chance to understand how our system works and these results can be easily evaluated.

6. REFERENCES

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