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Degree project

Simulation of 3ph induction motor in Matlab with Direct and Soft starting methods

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Abstract

Asynchronous machines are considered nowadays the most commonly used electrical machines, which are mainly used as electrical induction motors. Starting the induction motor is the most important and dangerous step. The theory behind this project is based on representing the real motor by a set of equations and values in Matlab using the subsystem feature, forming a corresponding idealistic motor in a way where all the physical effects are similar. The motor is started under different loads in two methods: Direct and Soft starting. Each method is studied and discussed using supporting simulation of currents, torque, speed, efficiency and power factor curves.

Acknowledgement

I am grateful to God for the support, good health and wellbeing that were necessary to complete this project. I feel deeply honored expressing my sincere thanks to Matz Lenells for providing valuable insights leading to the successful completion of my project. I take this opportunity to express gratitude to all of the department faculty members for their help and support. I also thank my loving family and friends for the encouragement, support and attention through this venture.

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Chapter 1: Introduction

Asynchronous machines are considered nowadays the most commonly used electrical machines, which are mainly used as electrical induction motors and sometimes as generators. This is mainly due to the simplicity of composition, low price, light weight, high reliability, easy to command and control performance and not containing parts that could easily breakdown compared with DC machines and synchronous machines.

Starting the induction motor is the most important and dangerous step, where the motor properties play a major role in the evaluation of all electrical motors, and these properties are defined by the following factors:

Starting torque

Starting current

Transient state

Smoothness of the starting

Simplicity and economics of starting

Problem formulation

In this study, a couple of methods of starting three-phase motors will be discussed and compared through curves of currents, torque, speed, efficiency and power factor. These methods are Direct and Soft starting. The discussion will be based on a Matlab simulation of different loading cases of the induction motor. The induction motor model is created according to a group of standard equations (current, voltage, power, efficiency, speed) [1, p 388] or [2, p 167-p 200] and values developed and edited in the laboratory.

Chapter 2: A General Outline of Induction Motors

2.1   The 3ph induction motor structure:

A. Stator

The stator is formed from thin plates with a thickness of (0.35 - 0.5 mm) of Ferromagnetic iron [1, p48]. These plates are painted before being assembled with insulating materials to reduce Eddy currents losses. The inner part of the stator has a cylindrical shape filled with insulated copper inductors that form the stator windings. These windings form a balanced three-phase circuit connected in either star or delta formation.
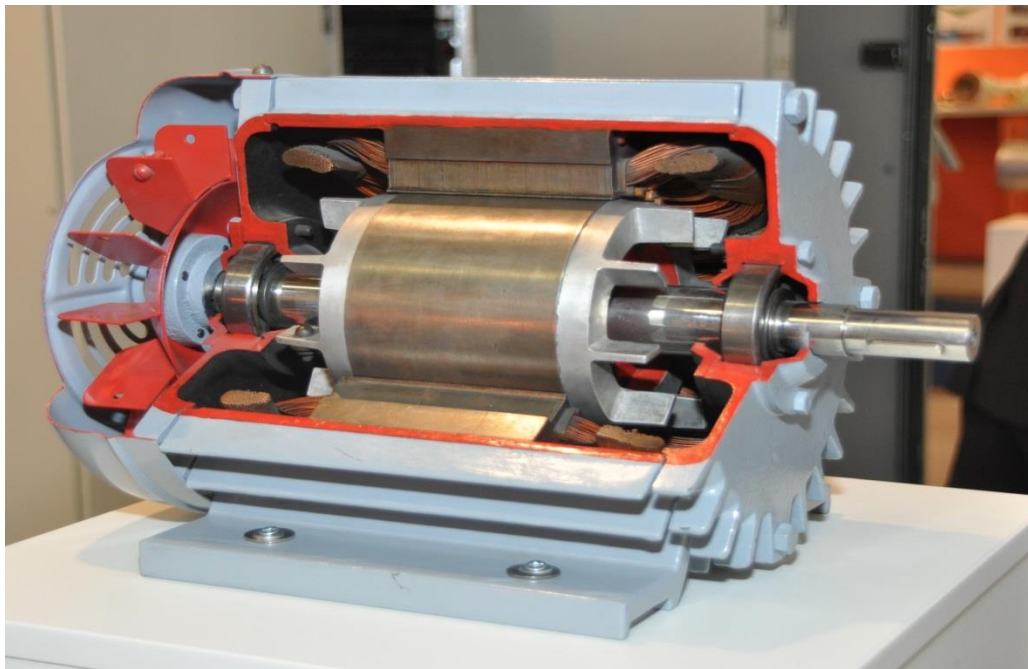

Figure 2.1 Induction motor structure
[Source:https://en.wikipedia.org/wiki/Electric_motor#/media/File:Rotterdam_Ahoy_Europort_2011_(14).JPG]

B. Rotor

This part is also formed from thin plates of Ferromagnetic iron assembled together to form a cylindrical shape which has slots on its outer surface.

As in the stator, the rotor coils can also be a three-phase circuit or a multi-phase circuit. The endings of the phases of the rotor coils are connected in star formation and fixed on the axis of the machine.

Rotors are sorted in terms of the type of its coils into two types:

B.1. Squirrel cage Rotor

In this case an uninsulated aluminum or copper bar is found in each slot where both endings are shorted with rings made of the same material as the bars .The bars and the rings form a square cage shape, which is opened at its end .Most induction motors - especially small and medium capacity ones -are designed this way, where the square cage represents a multi-phase coil connected in star formation at which the number of phases and slots are equal. This kind of rotors is shown in figure 2.2 and in figure 2.3 (C).
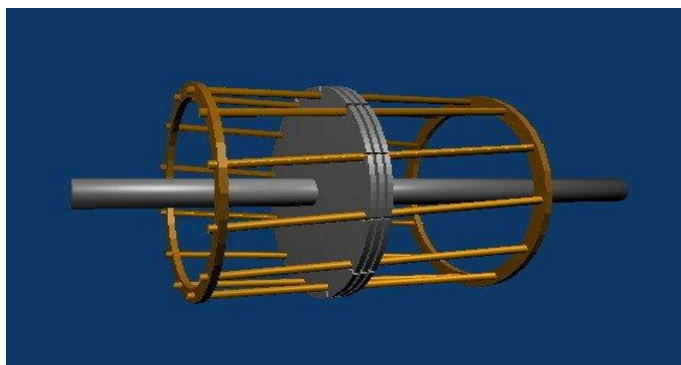
Figure 2.2 A square cage rotor

B.2. Slip Ring Rotor:

In this case, isolated copper inductors are fixed in the slots connected in series as 3ph groups forming a stable circuit.

The endings are normally connected in star formation where the star point is fixed to the rotor's body or to the axis of rotation.

On the other hand, the beginnings of the inductors are assembled with isolated copper slip rings that are installed to the rotor's axis and shorted through external resistances (starting resistances).

The rotor's windings are formed to have a number of magnetic poles equal to the number of poles in the stator. This kind of rotors is shown in figure 2.3 (A).
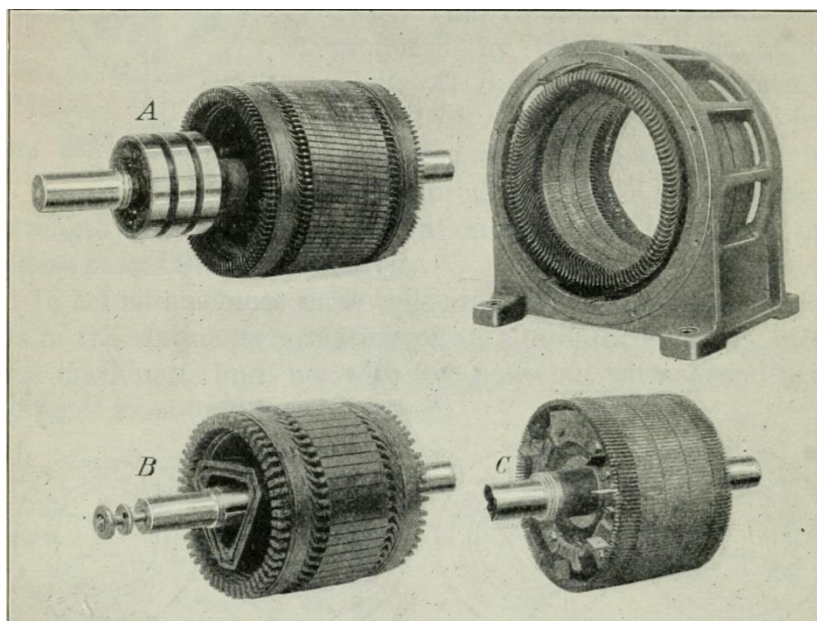

Figure2.3 Different kind of rotors

C. Air-Gap:

The rotor is set apart from the stator by an air-gap which is design to be as small as possible (0.4-0.5 mm) to reduce the leakage flux and the no-load current, enhancing the power factor and the efficiency. In case of large capacities this air-gap gets larger (few mm).

2.2 Basic Theory of Three Phase Induction Motors:

When the stator windings are connected to a three-phase balanced network, a rotating magnetic field is generated -due to current passage through its coils- in a speed that corresponds to the electrical source frequency where the source is connected to the stator.

If the rotating magnetic field creates a pair of poles (N, S) on the stator surface this corresponds to one cycle of the alternative current AC, in this case the number of pole pairs (P) equals (1) [1, p 88].

$$f_1 = n_1/60 \qquad (1)$$

If the stator has a number of pole pairs (P>1), then the rotating magnetic field frequency will be larger by a factor of (P).This means that the axis of the rotating magnetic field will revolve 360 degrees for every (P) number of the AC cycle as shown in the equations below [1, p 88]:

$$f_1 = P.n_1/60 \qquad (2)$$

Then:

$$n_1 = \frac{60.f_1}{P} \qquad (3)$$

The rotating magnetic field passes through the stator and the rotor windings inducing electromotive forces (E_1, E_2). Since the rotor windings are connected to form a closed circuit, a current (I_2) passes through those windings.

As a result to the interplay between I_2 and the rotating magnetic field, mechanical forces $(F = B \cdot I \cdot L)$ and electromagnetic torques comes into existence.

These forces and torques revolve the motor in a speed n (rpm), which has the same direction of the magnetic field created by the passage of the electrical current through the stator windings.

The values of E_2 and I_2 and their frequency of altering depend on the speed of the intersection between the rotating magnetic field and the rotor windings. The speed (n) is less than (n_1) due to the losses in the rotating magnetic field spent to overcome the various losses in the machine.

The frequency of (E_1, E_2) depends on the deference between the synchronous speed (n_1) and the motor speed (n) which is called the slip (S) as shown in the equation bellow [1, p89] :

$$S\% = \frac{n_1 - n}{n_1} . 100\% = \frac{\omega_1 - \omega}{\omega_1} . 100\% = \frac{\Omega_1 - \Omega}{\Omega_1} . 100\% \qquad (4)$$

Where:

- (Ω_1) is the mechanical angular speed of the magnetic field rotation and is given by [1, p 90]:

$$\Omega_1 = \frac{2.\pi.n_1}{60} \qquad (5)$$

- (ω_1) is the electrical angular speed of the magnetic field rotation and is given by [1, p 90]:

$$\omega_1 = \Omega_1 . P = \frac{2.\pi.n_1}{60}. P = 2.\pi.f_1 \qquad (6)$$

- (Ω) is the mechanical angular speed of the motor and is given by [1, p 90]:

$$\Omega = \frac{2.\pi.n}{60} \qquad (7)$$

- (ω) is the electrical angular speed of the motor. Therefore [1, p91]:

$$n = (1 - S).n_1 \qquad (8)$$

$$\omega = (1 - S).\omega_1 \qquad (9)$$

The rotor does not revolve synchronically with the magnetic field ($n \neq n_1$) and this is where the name "Asynchronous motors" comes from. This type of motors is also called "induction motors" because the current that passes through the rotor is created in an inductive way that is not given from an external source.

In order to calculate (f_2) for (E_2), (I_2) and a speed ($n_1 - n$) it is found that [1, p92]:

$$f_2 = \frac{(n_1 - n).P}{60} \qquad (10)$$

But:

$$S = \frac{n_1 - n}{n_1} \qquad (11)$$

Therefore:

$$f_1 = \frac{P.n_1}{60} \qquad (12)$$

The electromotive forces (emf) induced in the stator and rotor winding are given by the equations [1, p 95]:

$$E_1 = 4.44 \cdot f_1 \cdot W_{ph1} \cdot \phi \cdot K_{W1} \qquad (13)$$

$$E_{2S} = 4.44 \cdot f_2 \cdot W_{ph2} \cdot \phi \cdot K_{W2} \qquad (14)$$

Where (E_{2S}) is the emf induced in the rotor windings when revolving with a slip (S) and is also given by the equation [1, p 95]:

$$E_{2S} = 4.44 \cdot f_2 \cdot W_{ph2} \cdot \phi \cdot K_{W2} = 4.44 \cdot S \cdot f_1 \cdot W_{ph2} \cdot \phi \cdot K_{W2} = S \cdot E_2 \qquad (15)$$

The values of the slip (S) are determined by the mechanical load applied to the rotation axis. It increases proportionally with the load (the speed decreases).

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But if the motor would revolve in the synchronous speed ($n = n_1$) and in the same direction ($S = 0$), the magnetic field would not have crossed the rotor winding, therefore no emf would have been induced in the rotor and no current would have passed in the rotor windings. Thus, neither mechanical forces nor rotating torques would have come into existence.

As a conclusion, the induction motor should revolve in a speed less than the synchronous speed in order for it to work as a motor, therefore its domain is limited by the following conditions [1, p 96]:

$$n_1 > n > 0 \qquad (16)$$

$$1 > S > 0 \qquad (17)$$

Chapter 3: The general theory of electrical machines:

This theory is based on representing the real machine with a corresponding idealistic machine in a way where all the physical effects are similar. This idealistic machine is symmetrical (has two poles and two phases) and has two pairs of identical windings on perpendicular axes in both the stator and the rotor. The windings are fed by two AC currents that are shifted by (90°) from each other according to time as shown in Figure (3.1) The idealistic machine is treated as a two poles machine because the magnetic flux distribution is repeated after each pair of poles, no matter how many poles there are in the real machine [1, p 15].

In the idealistic machine, the electrical and the geometrical axes are identical. This property simplifies detecting the rotor's position with reference to the stator during transient state. This transient state has a very complicated physical effect, which makes it almost impossible to mathematically study the machine without applying some theories and assumptions. The complexity is caused by the nonlinearity of the magnetization curve and the elements of the machine, and their dependence to the currents passing through the windings. Another factor of the complexity is the nonsinusoidal curve of the windings electromagnetic force which alters according to the working system of the machine.
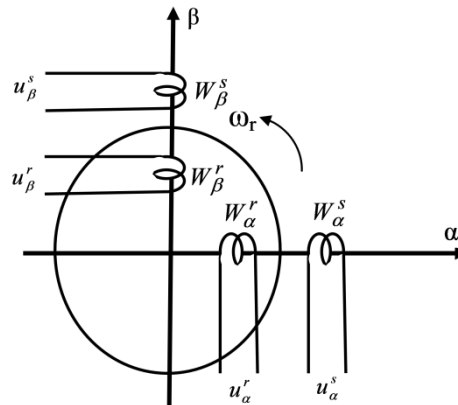

Figure (3.1) The ideal machine circuit

Considering the previous obstacles, it is found that the mathematical study would lead to nonlinear equations that are hard to analyze. Therefore, the basic factors are approximated whereas subsidiary factors are totally neglected. Applying these steps would lead to an analyzable idealistic machine which has the following specifications [1, p 19]:

- The air-gap is steady.
- The winding are distributed on the circumference of the rotor and the stator in a way that ensures a steady distribution for the current, and a sinusoidal distribution for the electromotive force.
- The magnetic circuit is unsaturated.
- The absolute resemblance between the stator and the rotor windings.
- The windings leakage flux is independent from the rotor location.
- The reluctance of the stator and rotor should be neglected.

In all electrical machines, studies in [1, p 21] show that the magnetic fields in both of the rotor and the stator are static with respect to each other. Furthermore, this is a crucial condition of power conversion.

When running electrical machines, a few phenomena occur and it is required to represent these phenomena as mathematical equations in order to study the machine. These equations depend on each other, but one can, anyway, consider them to belong to one of three groups which describe [1, p 22]:

- The windings voltages.
- The torques on the axis of the machine.
- The mechanical motion.

In order for these equations to be written in a standard way, it is important to consider the following [1, p 23]:
- The positive direction of the current passing through the windings is from the windings ending towards its beginning.
- The electromotive force has the same positive direction as the current.
- The positive direction of the magnetic flux is the direction of the flux coming out of the rotor.
- The positive direction of the winding axes and the electromagnetic force is the same positive direction of the current.
- The positive direction of the machine revolution, the electromotive force and the angles calculation is counter clockwise.

To be able to study the mathematical model, it is customary to choose one of the following rectangular coordinates that are commonly used in this case [1, p 24]:

1. The coordinates system of (α) and (β) which is fixed on the stator.
2. The coordinates system of (d) and (q) which is fixed on the rotor and revolves with it in the same speed.
3. The coordinates system of (u) and (v) which is fixed on optional coordinates and revolves in an optional speed as well.

The power conversion process in electrical machines does not depend on choosing the coordinates system. However, it is preferred to use the (α) and (β) coordinates system to study power conversion equations, because the voltage equations in the stator have a minimum number of terms. Furthermore, the observer is static in reference to the stator and the frequency of the network voltage in this coordinates system.

Chapter 4: Simulating and starting the 3ph induction motor in Matlab

A. The induction motor model:

In order to simulate the induction motor in Matlab, the motor is represented by a set of equations and values according to the following steps:

1. The motor equations on the coordinates system $(\alpha - \beta)$ are set as:

1.1 Currents equations [1, p 388] or [5, p 45] (note (6) in the appendix):

$$\frac{di_\alpha^s}{dt} = \frac{1}{Ls} u_\alpha^s - \frac{Rs}{Ls} i_\alpha^s - \frac{M}{Ls} \frac{di_\alpha^r}{dt} \qquad (18)$$

$$\frac{di_\beta^s}{dt} = \frac{1}{Ls} u_\beta^s - \frac{Rs}{Ls} i_\beta^s - \frac{M}{Ls} \frac{di_\beta^r}{dt} \qquad (19)$$

$$\frac{di_\alpha^r}{dt} = -\frac{Rr}{Lr} i_\alpha^r - \frac{M}{Lr} \frac{di_\alpha^s}{dt} - \omega_r i_\beta^r - \omega_r \frac{M}{Lr} i_\beta^s \qquad (20)$$

$$\frac{di_\beta^r}{dt} = -\frac{Rr}{Lr} i_\beta^r - \frac{M}{Lr} \frac{di_\beta^s}{dt} + \omega_r i_\alpha^r + \omega_r \frac{M}{Lr} i_\alpha^s \qquad (21)$$

Where:

i_α^s : The stator current represented on the axis alpha.

i_β^s : The stator current represented on the axis beta.

i_α^r : The rotor current represented on the axis alpha.

i_β^r : The rotor current represented on the axis beta.

u_α^s : The stator voltage represented on the axis alpha.

u_β^s : The stator voltage represented on the axis beta.

u_α^r : The rotor voltage represented on the axis alpha.

u_β^r : The rotor voltage represented on the axis beta.

$M = Lm$: the constant of mutual induction.
Rr: the rotor resistance.
Rs: the stator resistance.
Ls: the stator inductance.
Lr: the rotor inductance.
$Wrb = Wr$: the angular velocity.

1.2 Torque and Speed equations [1, p 389] or [4, p18]:

$$T_{em} = \frac{3}{2} pM (i_\beta^s i_\alpha^r - i_\alpha^s i_\beta^r) \qquad (22)$$

$$\frac{d\omega_r}{dt} = \frac{p}{J}(T_{em} - T_m) \qquad (23)$$

Where:

T_b: the nominal torque.
T_m: the load torque.
p: the number of pairs of poles.
J: the moment of inertia.
T_{em}: the electromagnetic torque.

1.3 Input and Output Power equations [1, p 390]:

$$p_s(t) = p_\alpha^s + p_\beta^s = 3/2(u_\alpha^s i_\alpha^s + u_\beta^s i_\beta^s) \qquad (24)$$

$$q_s(t) = q_\alpha^s + q_\beta^s = 3/2(u_\beta^s i_\alpha^s - u_\alpha^s i_\beta^s) \qquad (25)$$

$$s(t) = \sqrt{p_s^2 + q_s^2} \qquad (26)$$

$$p_2(t) = T_{em}.\Omega_r = T_{em}.\frac{\omega_r}{p} \qquad (27)$$

1.4 Efficiency and Power factor equations [1, p 394]:

$$\eta = \frac{p_2(t)}{p_1(t)} \qquad (28)$$

$$Cos\varphi_1 = \frac{p_1(t)}{s(t)} \qquad (29)$$

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Where:

P_n: real power in kw.

p_α^s : The stator real power represented on the axis alpha.

p_β^s : The stator real power represented on the axis beta.

q: reactive power.

q_α^s : The stator reactive power represented on the axis alpha.

q_β^s : The stator reactive power represented on the axis beta.

s: apparent power.

$p_1(t)$: the electrical power (input of the motor).

$p_2(t)$: the mechanical power (output of the motor).

$Cos\varphi_1$: the power factor.

η : the efficiency.

Ω_r :the mechanical angular speed.

2. On the other hand, the currents passing throw the phases of the induction motor are given by [1. P 395] or [2, p 199]:

$$i_A^s = i_\alpha^s \qquad (30)$$

$$i_B^s = -\frac{1}{2}i_\alpha^s + \frac{\sqrt{3}}{2}i_\beta^s \qquad (31)$$

$$i_C^s = -\frac{1}{2}i_\alpha^s - \frac{\sqrt{3}}{2}i_\beta^s \qquad (32)$$

3. The equations are represented and simulated by means of the block diagram shown in figure (4.1).

The model and the code are built according to the following values which were experimentally chosen. The model is a combination of standard models that were implemented according to standard equations [2, p 167]. This process is quite complicated and can not be explained in this report:

$$P_n = 18.5\,kW \qquad R_s = 0.159\Omega \qquad M = 0.0489\,H$$
$$2p = 4\,pole\,s \qquad R_r = 0.16\Omega \qquad J = 0.234\,kg.m^2$$
$$U_n = 220V \qquad L_s = 0.05\,H \qquad I_b = 52A$$
$$n_b = 1500\,rpm \qquad L_r = 0.051H \qquad T_b = 125Nm$$
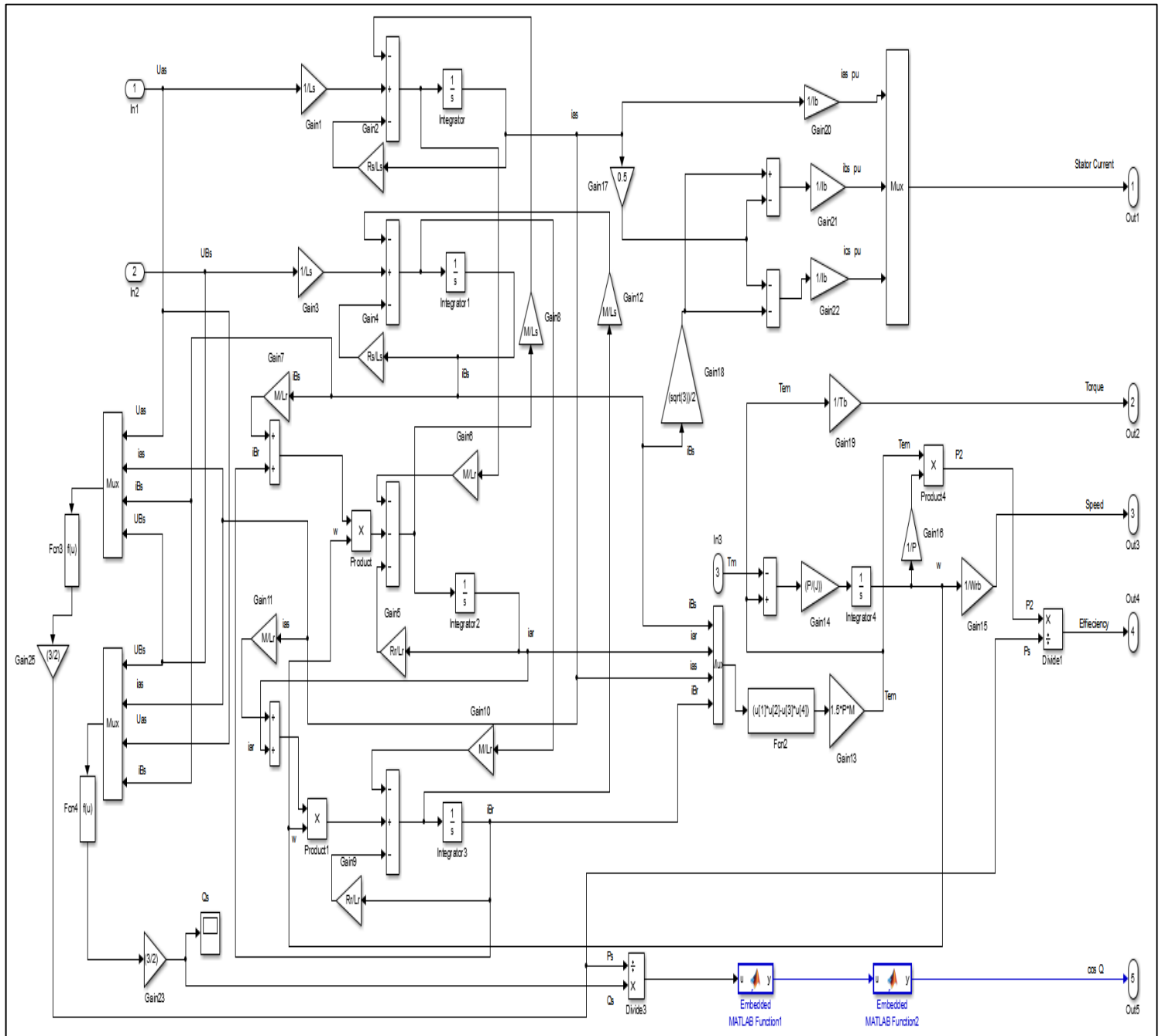$$\omega_{rb} = 314rad/\sec \qquad f = 50Hz$$

Figure (4.1) Block diagram (1) for the induction motor model in Matlab as a subsystem

B. Simulating starting curves in No-load \ Load cases:

To be able to compare the states of the motor with each other, a new block diagram -based on the previous one- is made. This new block shown in figure (4.2) is built in Matlab using the subsystem method as explained in the following steps:

- A new model is opened from:

$$\text{File} \ \rightarrow \text{New} \ \rightarrow \text{Model}$$

- From the library browser, the option (ports & subsystem) is taken.
- The (subsystem) icon is dragged into the opened model and then double-clicked.
- The following icons -which represent the subsystem content-, would appear.

- The line between in_1 and out_1 is deleted.
- The number of inputs and output is determined applying the (copy& paste) feature.
- The induction motor model is pasted into the subsystem page, excluding the inputs and the outputs.
- The outputs of the (subsystem) are set to be the following:

(Currents, Torque, Speed, Efficiency, Power factor), where every output is connected to a (scope).
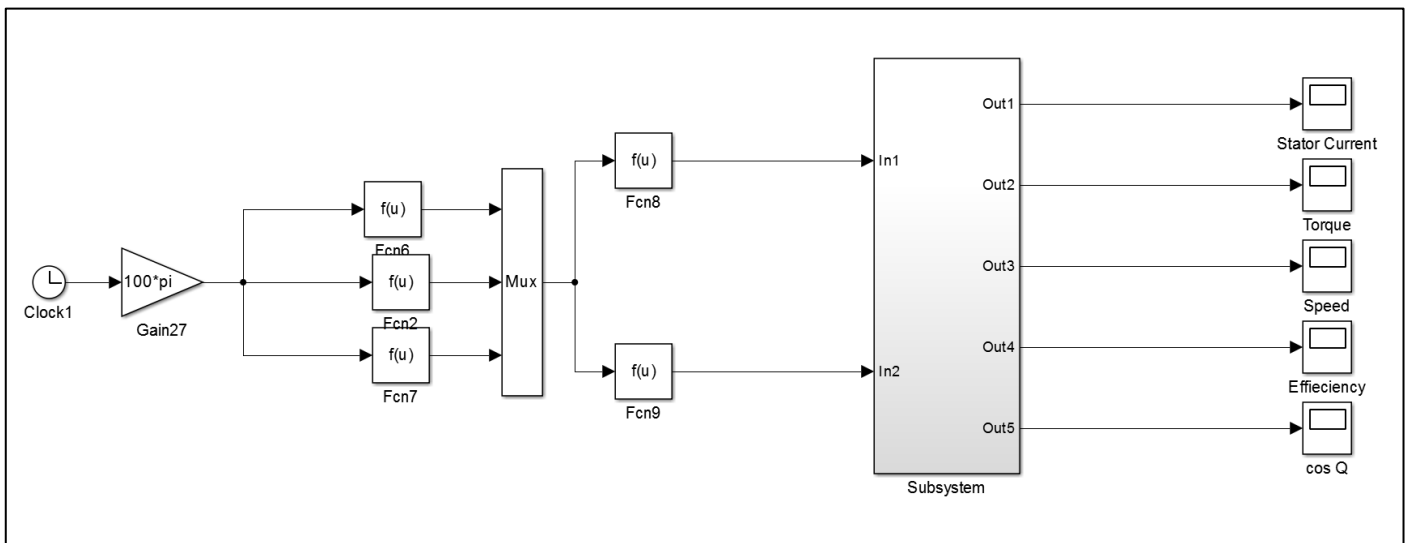
Figure (4.2) Block diagram (2) for the induction motor model in Matlab as a subsystem

Note: The symbol (In3) in figure (4.1) represents the load torque (T_m), which could be introduced either in figure (4.1) as a constant in the subsystem, or as a third input in figure (4.2).

Note: In all the following simulations, the horizontal axis represents the time by seconds, while the vertical is per unit.

C. Direct starting method

This method is quite simple and cheap, because the motor is started directly without any external equipment.

C.1 Direct starting curves in the No-load case:

In this case the load torque (T_b) is set to zero.

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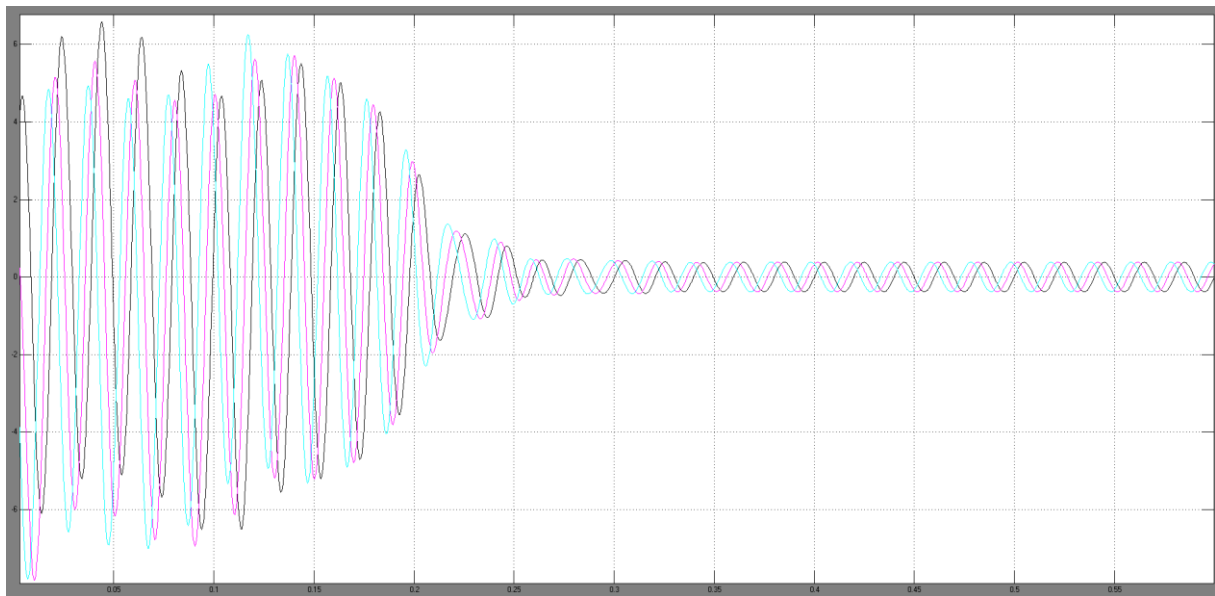
Figure (4.3) Starting currents curves in the No-load case
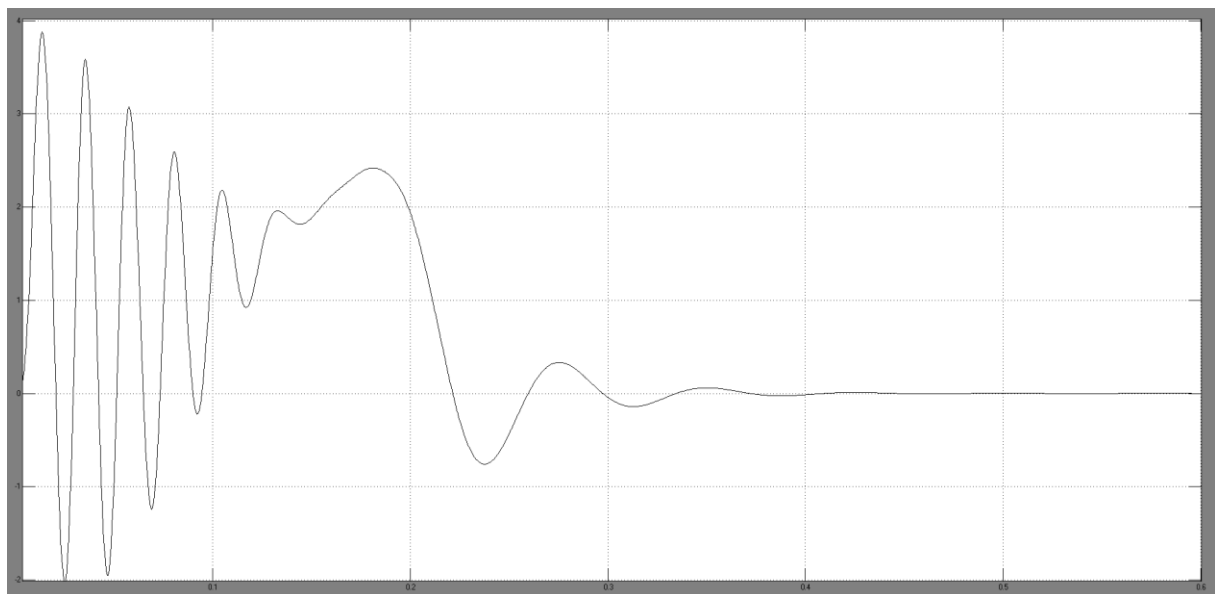
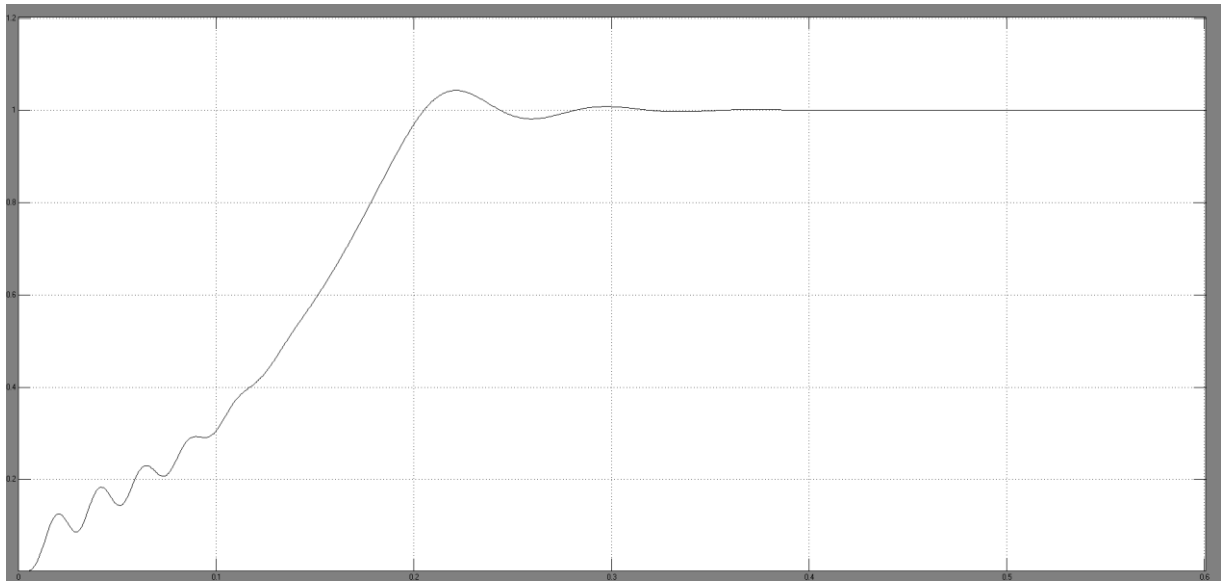Figure (4.4) Starting torque curve in the No-load case

Figure (4.5) Starting speed curve in the No-load case

The following table shows the values of the starting current, the starting torque and the transient state period. For example, the value of the starting current is the largest value at the positive pulse, and so is the value of the starting torque. All of the previous variables values are obtained during the transient state, which is the time needed to reach stationarity. Stationarity is reached when the speed curve reaches a certain value and gets steady. For example, in figure (4.5) the speed reaches stationarity at about (0.4).

No-load test reaults table:

Ist (pu)	Tst (pu)	Transient (s)
6.3	3.8	0.4

Table (4.1)

C.2 Direct starting curves in the 75% of nominal load case:

In this case the load torque value will be set to (93.75 Nm), which is 75% of the nominal value.
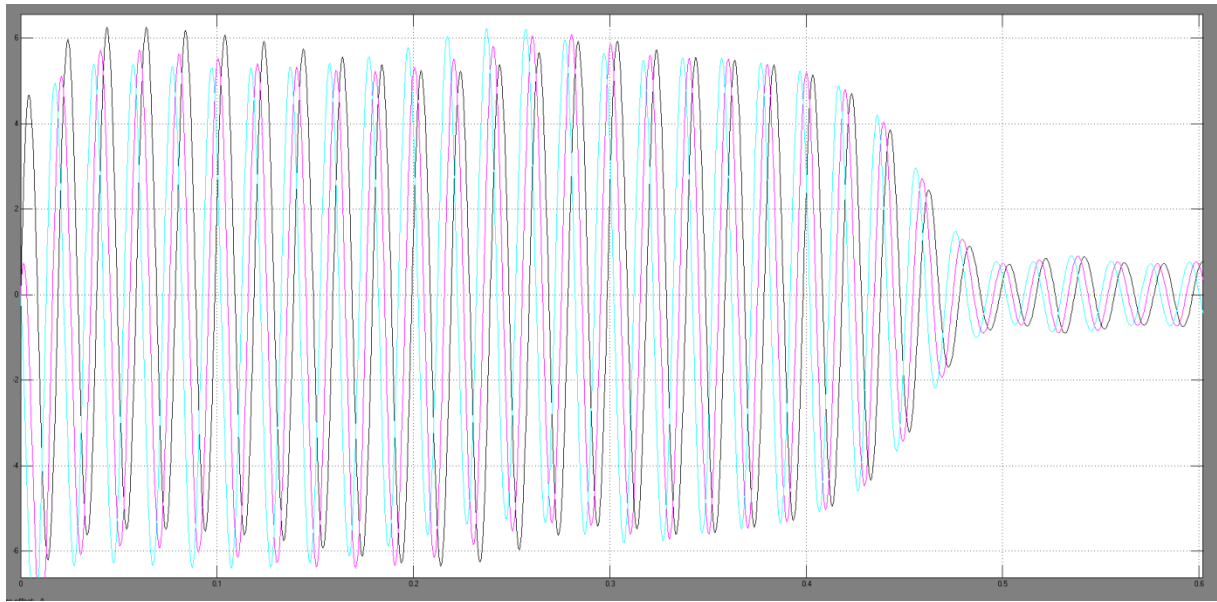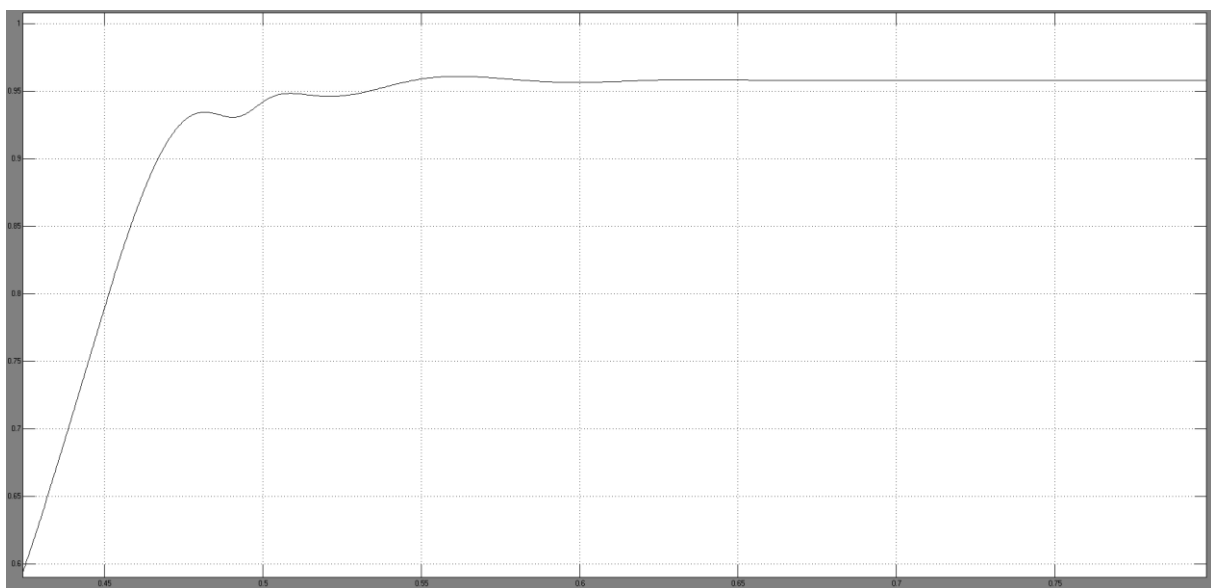
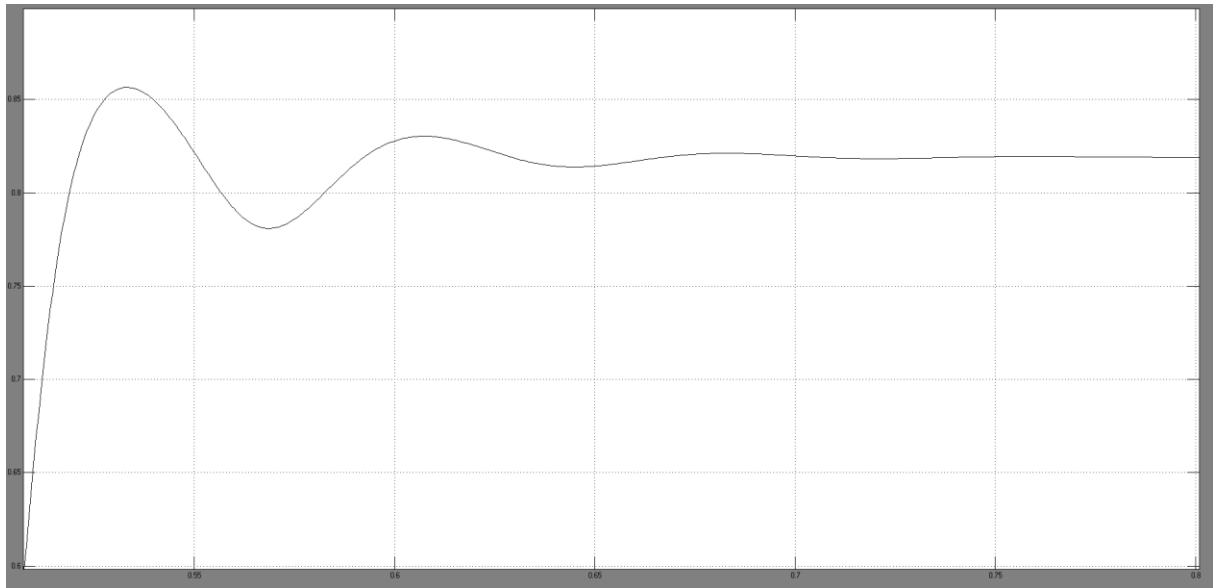Figure(4.6) Starting currents curves in 75% of the nominal load case
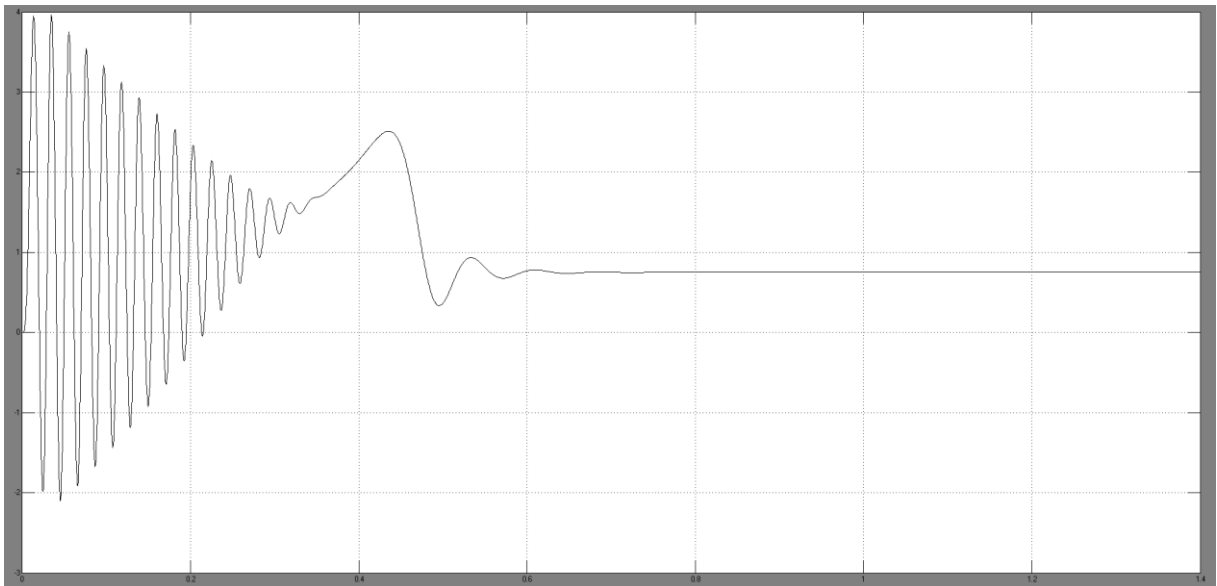
Figure(4.7) Starting torque curve in 75% of the nominal load case
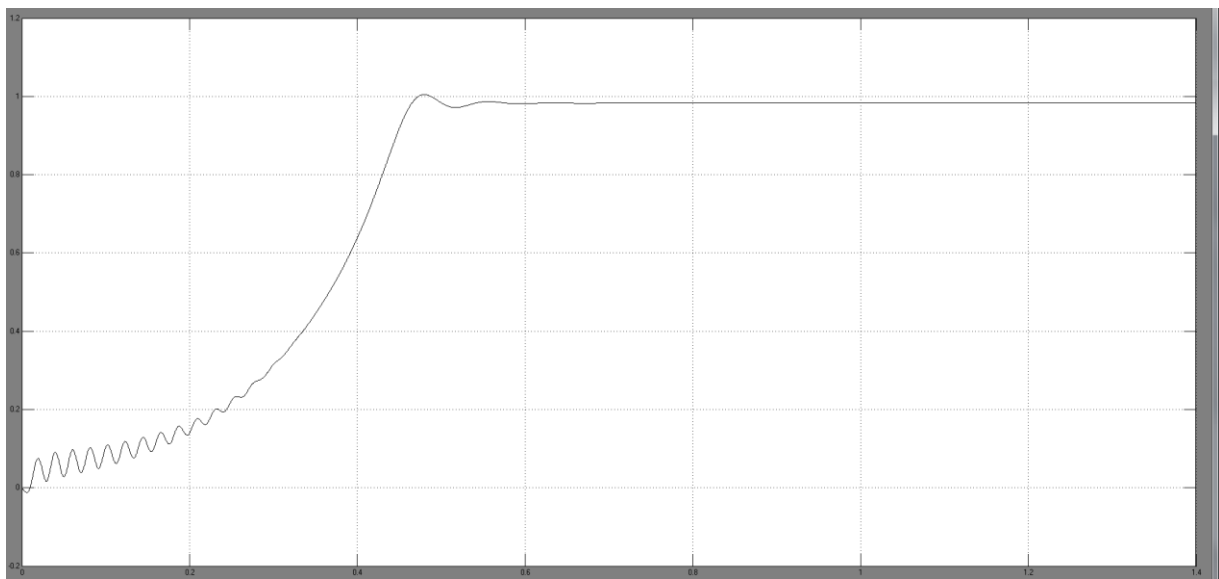
Figure(4.8) Speed curve in 75% of the nominal load case

Figure(4.9) Efficiency curve in 75% of the nominal load case

Figure(4.10) Power factor curve in 75% of the nominal load case

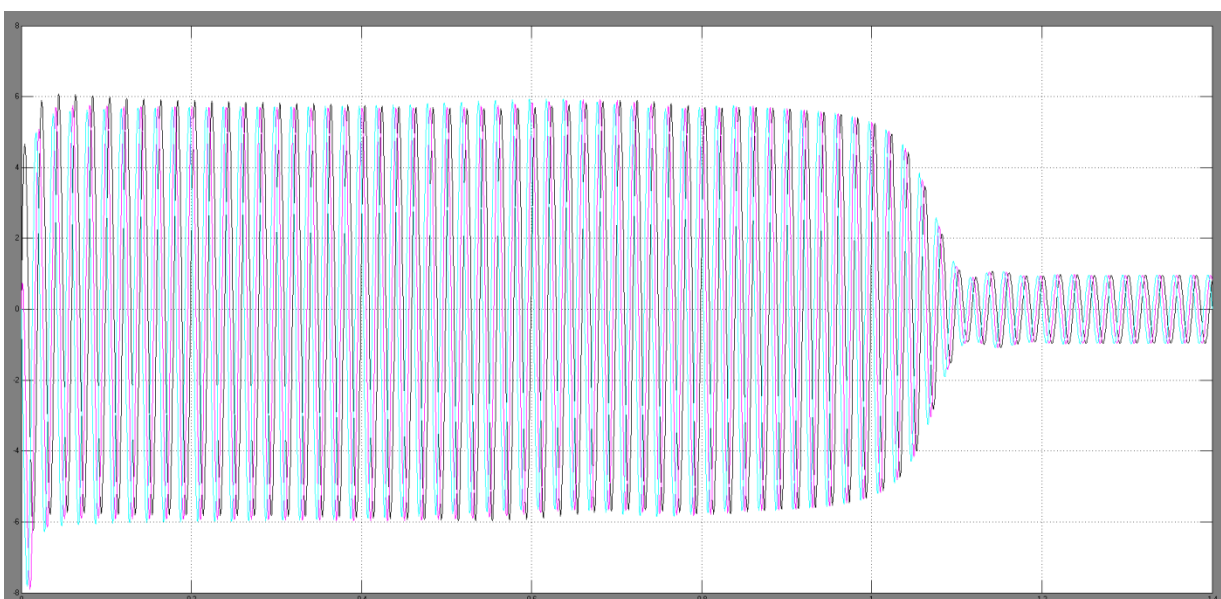Note: The efficiency and the power factor values are taken after the curves reach stationarity.

75% nominal load test reaults table:

Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
6.1	3.95	0.6	96	82

Table (4.2)

C.3 Direct starting curves in the nominal load case:
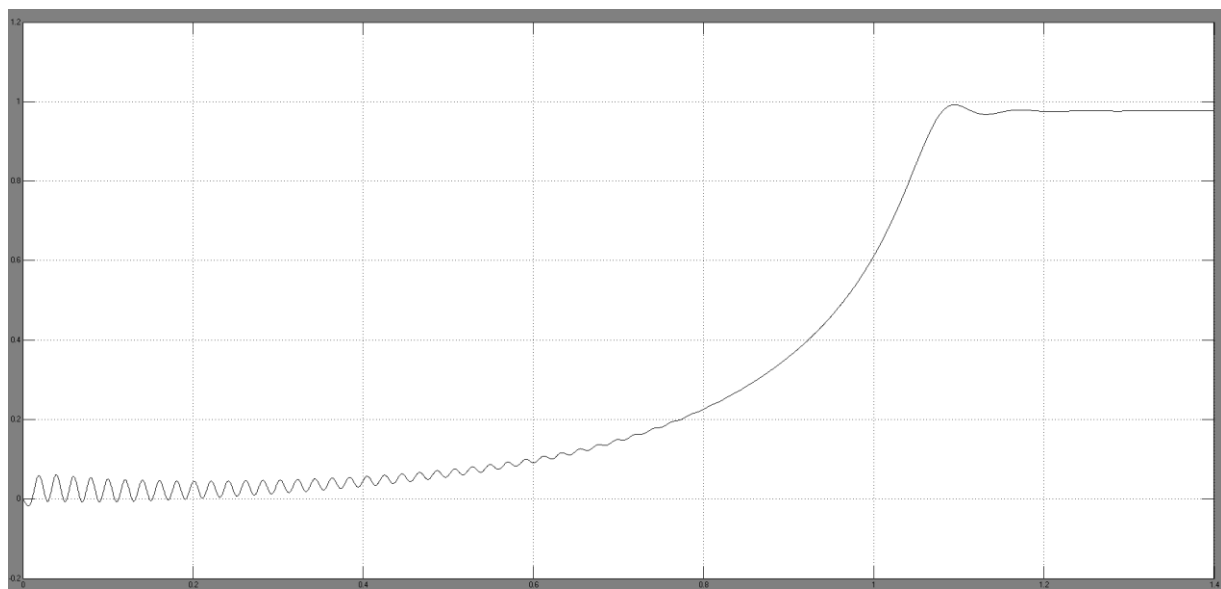
In this case the load torque value will be set to (125 Nm), which is the nominal value.

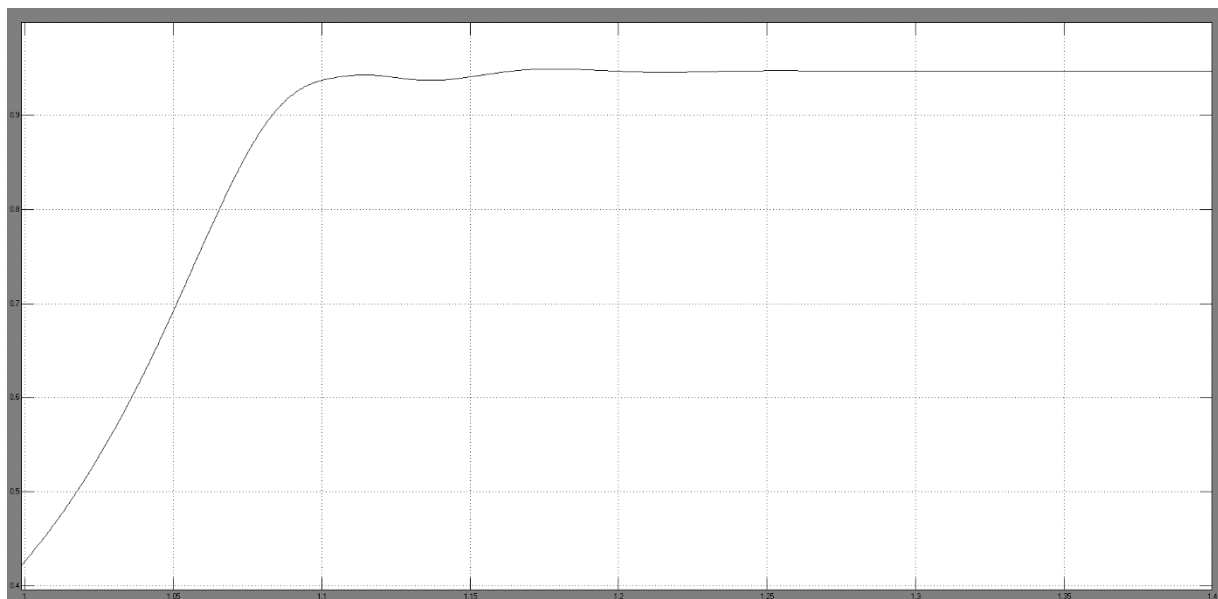Figure(4.11) Starting currents curves in the nominal load case

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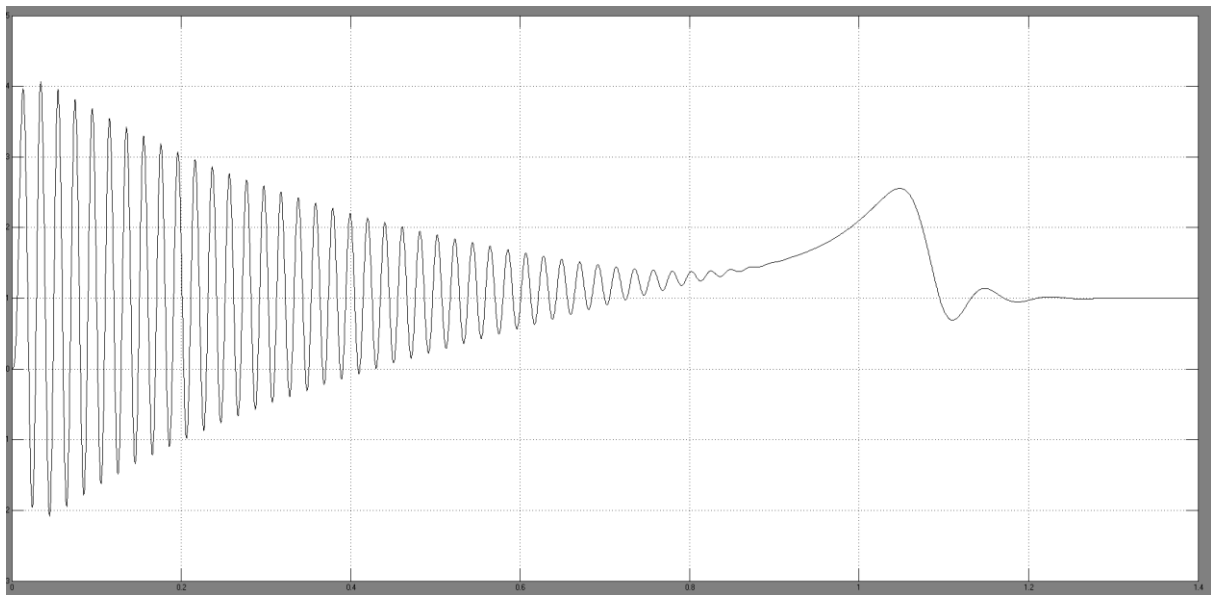
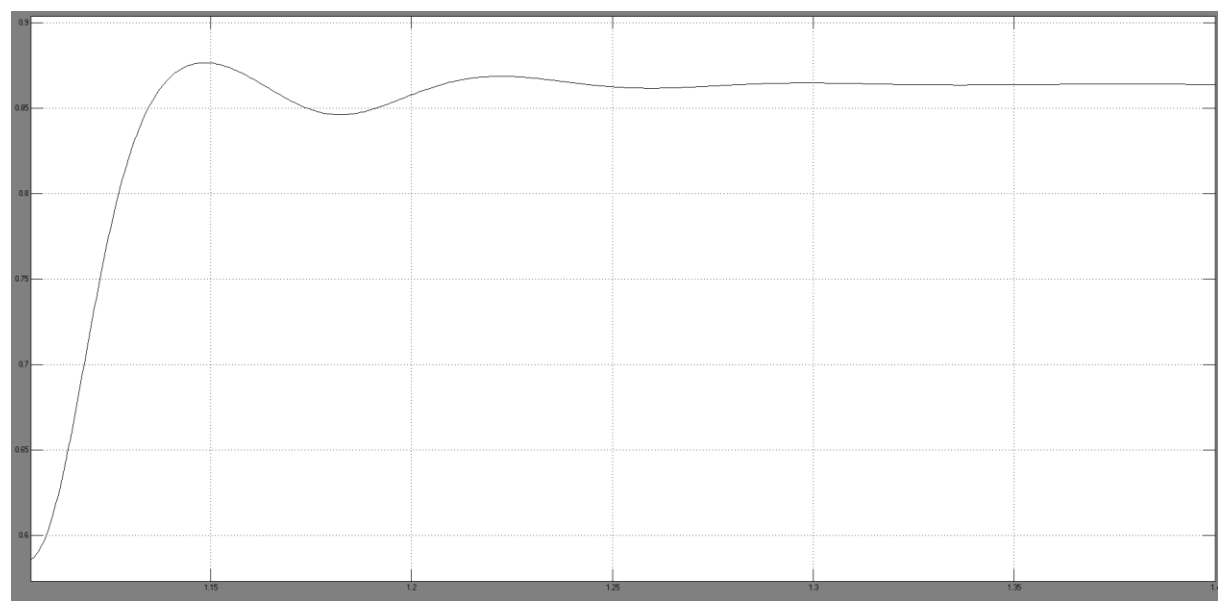Figure(4.12) Starting torque curve in the nominal load case

Figure(4.13) Speed curve in the nominal load case

Figure(4.14) Efficiency curve in the nominal load case

Figure(4.15) Power factor curve in the nominal load case

Nnominal load test reaults table:

Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
6	4.1	1.2	95	86

Table (4.3)

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Chapter 5: Soft staring method:

This method is implemented by gradually increasing the voltage applied on the induction motor, starting from a certain value up to the nominal voltage of the motor. The process of increasing the voltage gradually is performed by a three phase thyristor ac voltage regulator.

The regulator consists of six thyristors -two for each phase- that are connected to the motor as shown in figure (5.1). The voltage of the motor can be adjusted by modifying the pulses triggering angles, which are applied on the thyristors gates [1, p 456].

The certain voltage value applied on the motor is experimentally found. It is the least value the motor could start at.
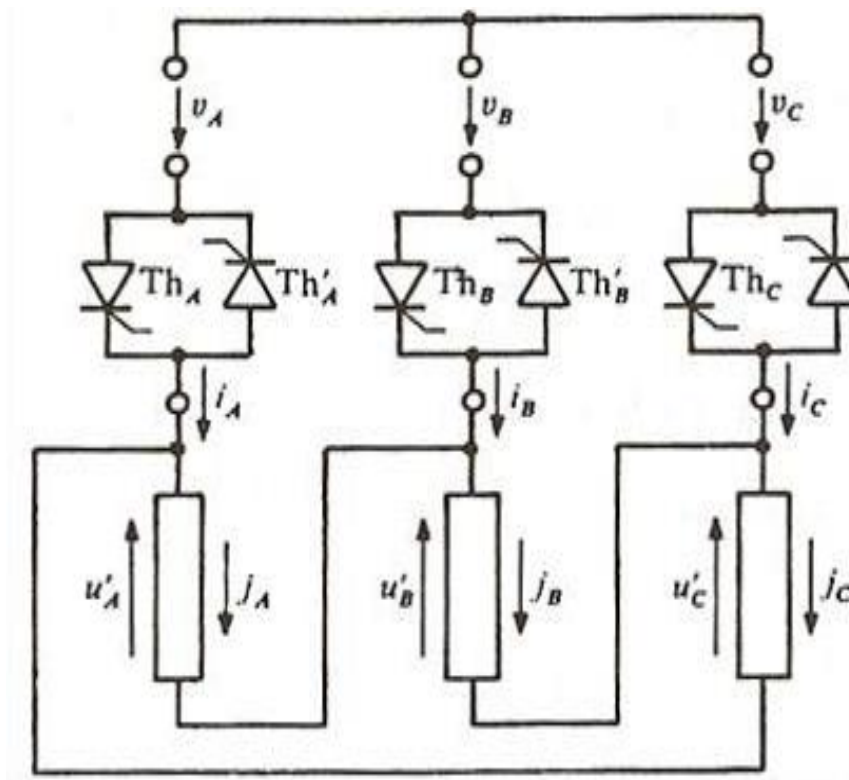

Figure (5.1) the induction motor connected to the thyristor regulator

On the other hand, the implementation of the soft start method has been done using the following model:
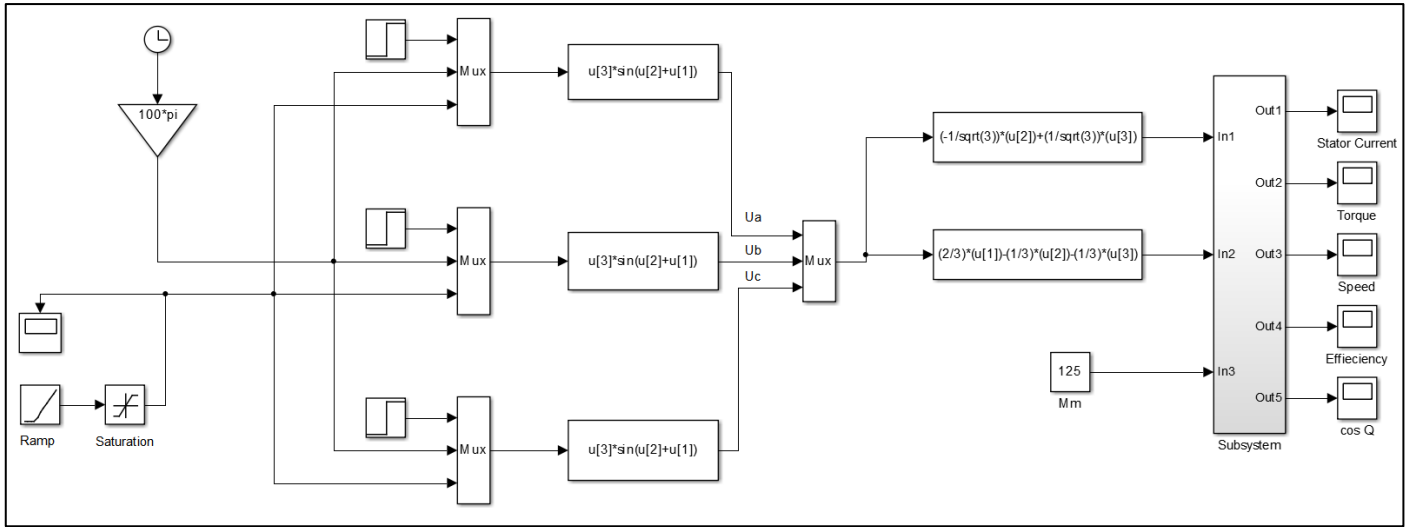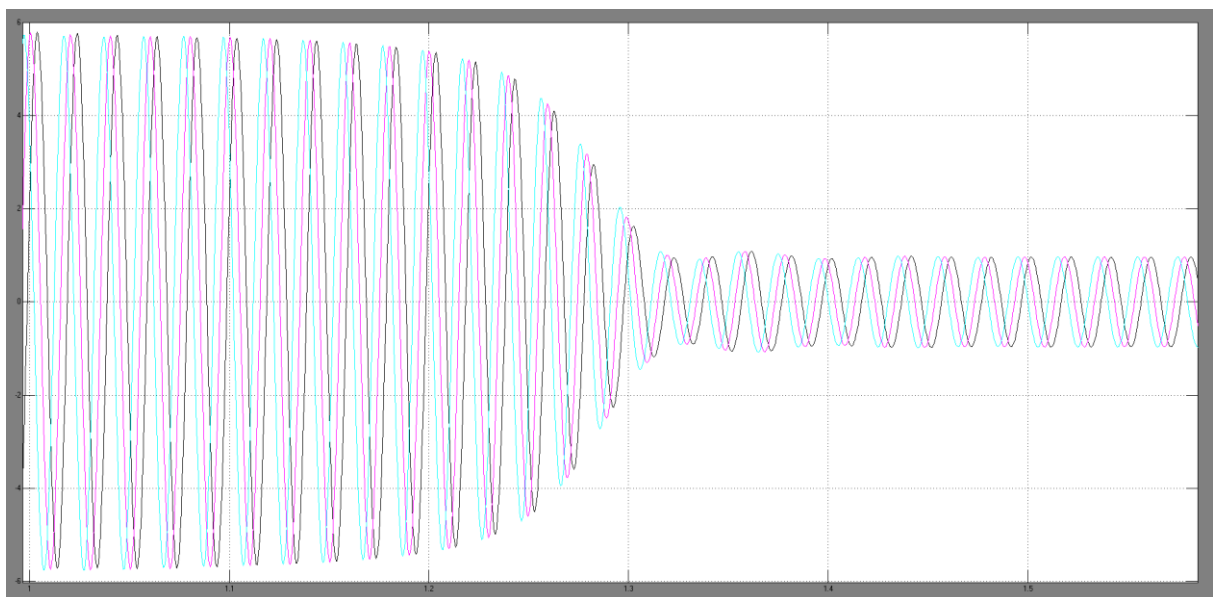

Figure (5.2) Block diagram for the induction motor model in the Soft starting case

Note: The constant (Mm) in figure (5.2) represents the load torque (T_m), which could vary between zero (no-load case) and the nominal load torque (125 Nm) as mentioned before.

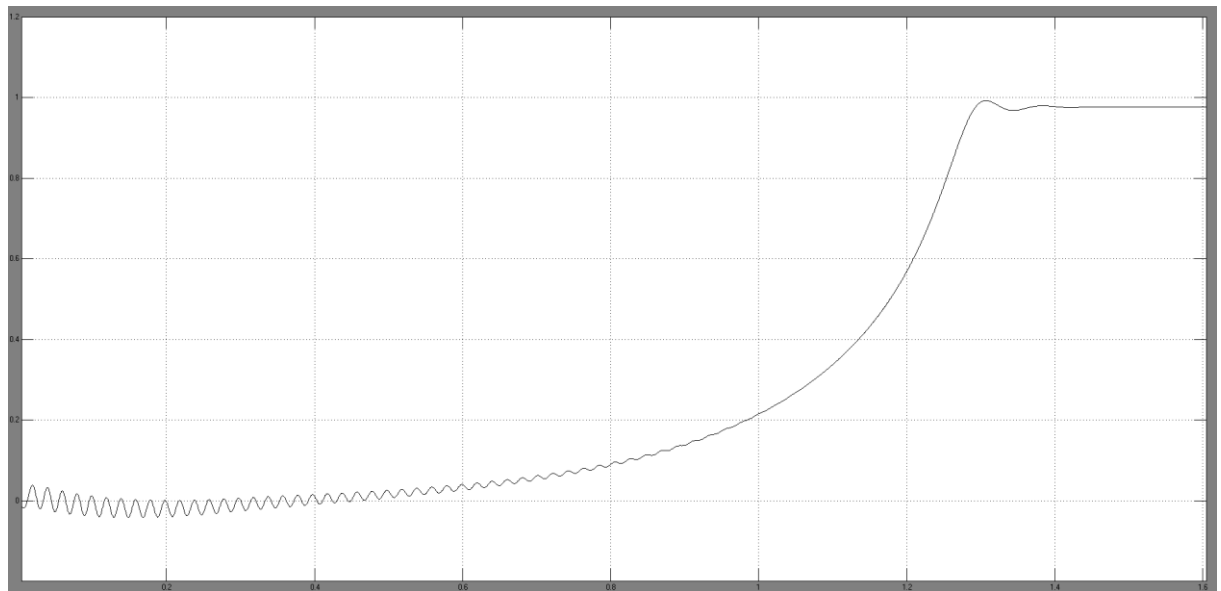## 1. Soft starting curves in the nominal load case:

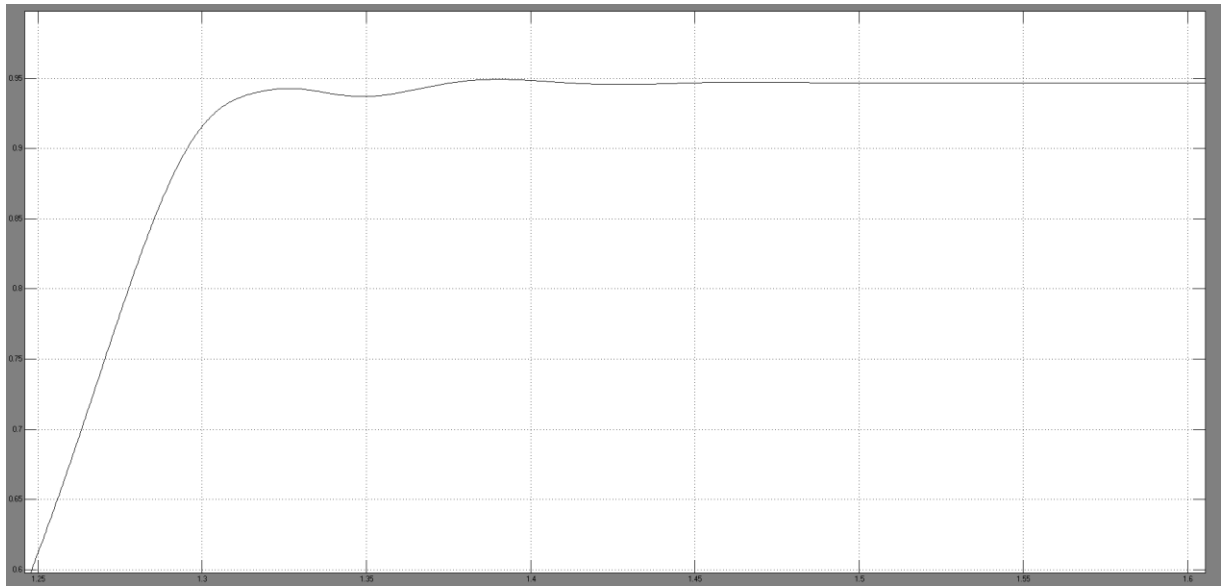The starting voltage is set to 200V using the Ramp icon shown in figure (5.2)

Figure(5.3) Starting currents curves in the Soft starting nominal load case
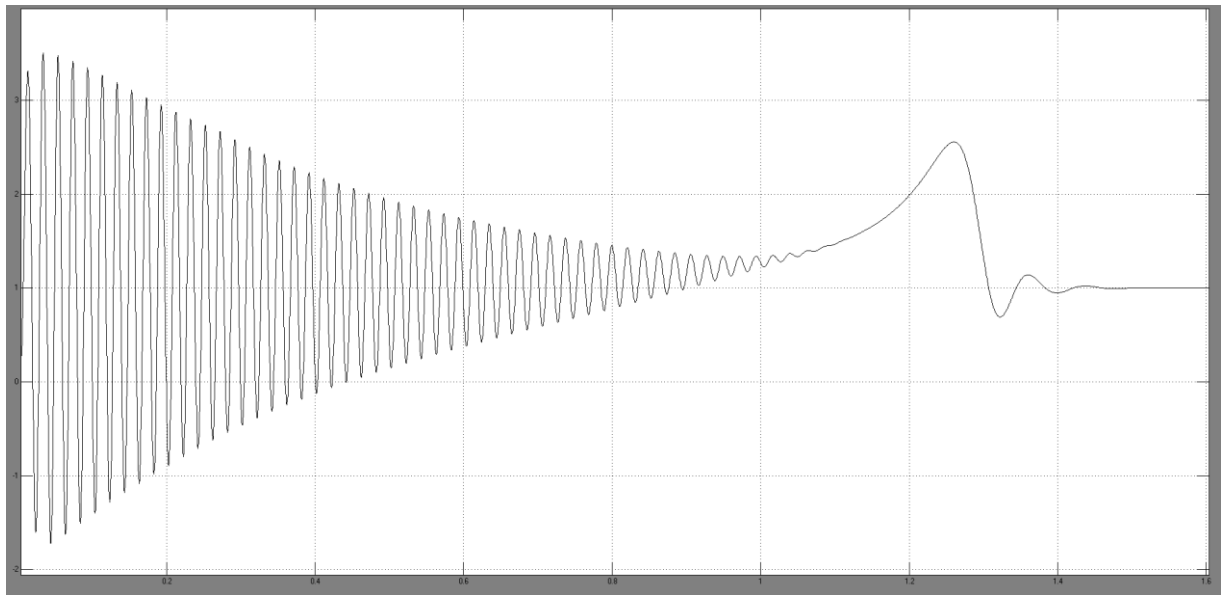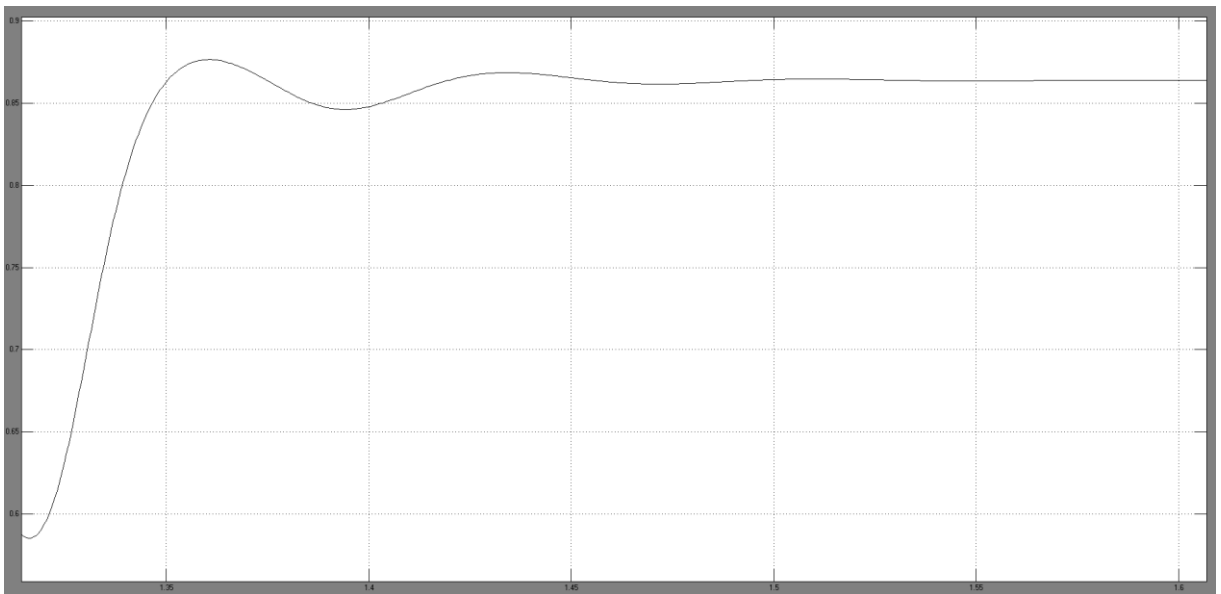
Figure(5.4) Torque curve in the Soft starting nominal load case

Figure(5.5) Speed curve in the Soft starting nominal load case

Figure(5.6) Efficiency curve in the Soft starting nominal load case

Figure(5.7) Power factor curve in the Soft starting nominal load case
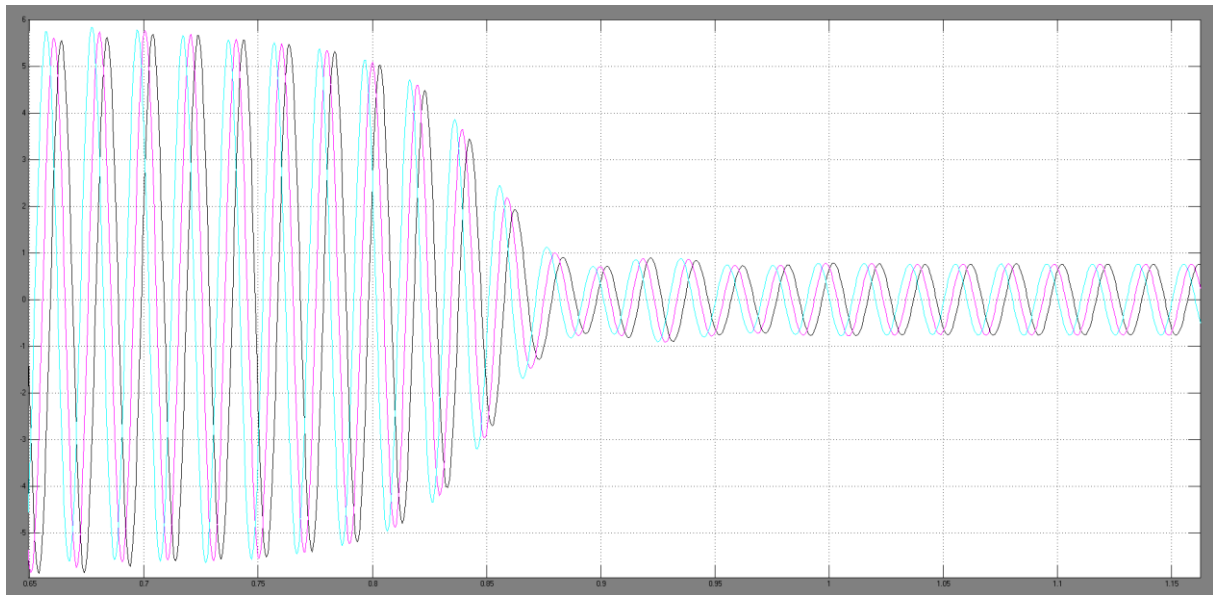
Soft starting nominal load test reaults table:

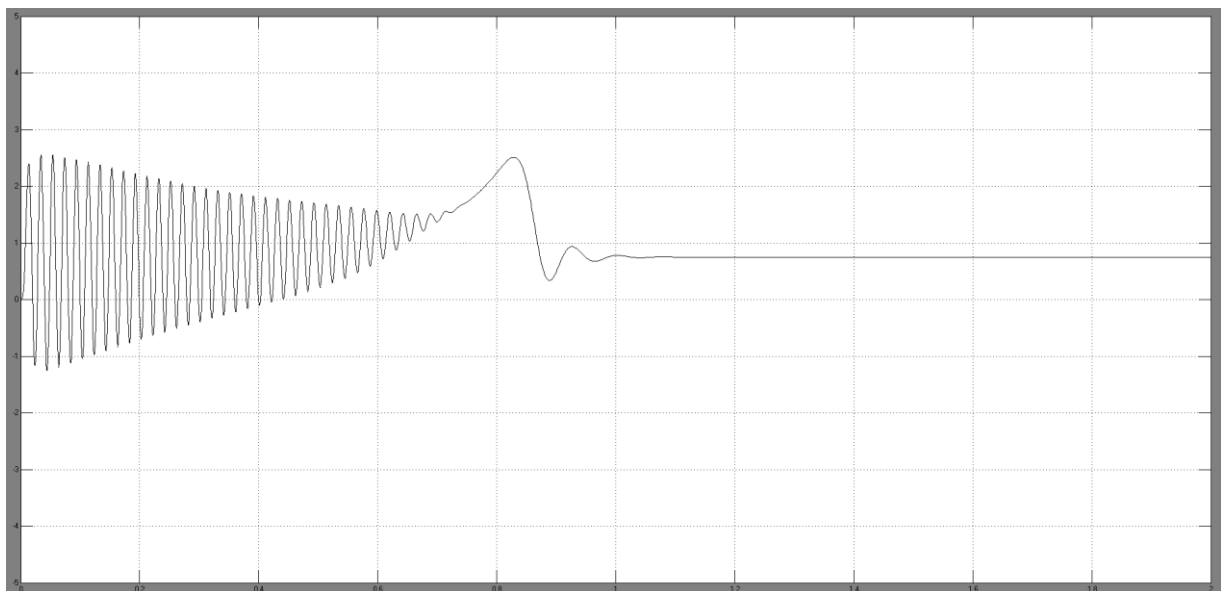| Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
5.9	3.45	1.45	95	86

Table (5.1)

2. Soft starting curves in the 75% of nominal load case:
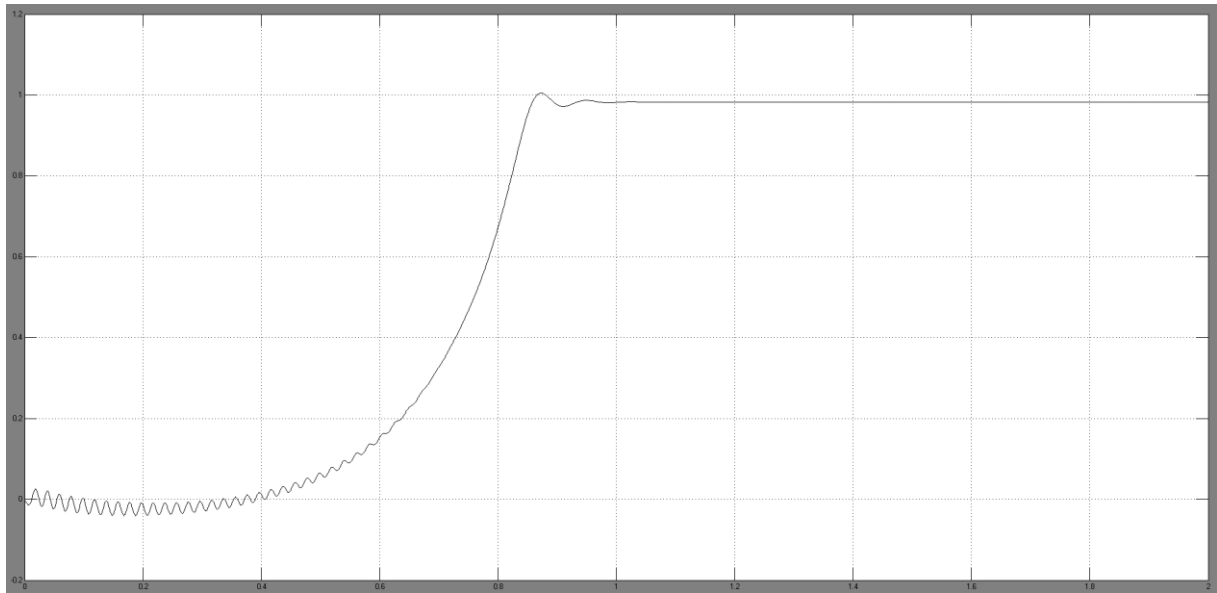
The starting voltage is set to 170V using the Ramp icon shown in figure (5.2)
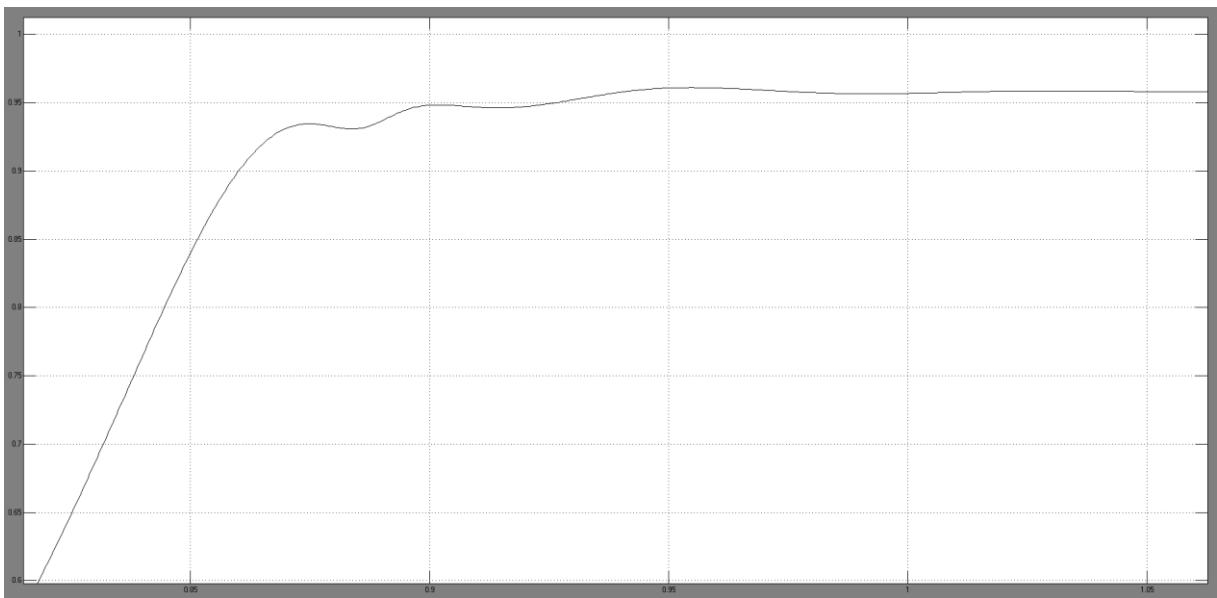

Figure(5.8) Starting currents curves in the Soft starting 75% nominal load case

Figure(5.9) Torque curve in the Soft starting 75% nominal load case

Figure(5.10) Speed curve in the Soft starting 75% nominal load case

Figure(5.11) Efficiency curve in the Soft starting 75% nominal load case

Figure(5.12) Power factor curve in the Soft starting 75% nominal load case

Soft starting 75% nominal load test reaults table:

Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
5.8	2.6	1.15	96	82

Table(5.2)

3. Soft starting curves in the 50% of nominal load case:

The starting voltage is set to 135V using the Ramp icon shown in figure (5.2)

Figure(5.13) Currents curves in the Soft starting 50% nominal load case
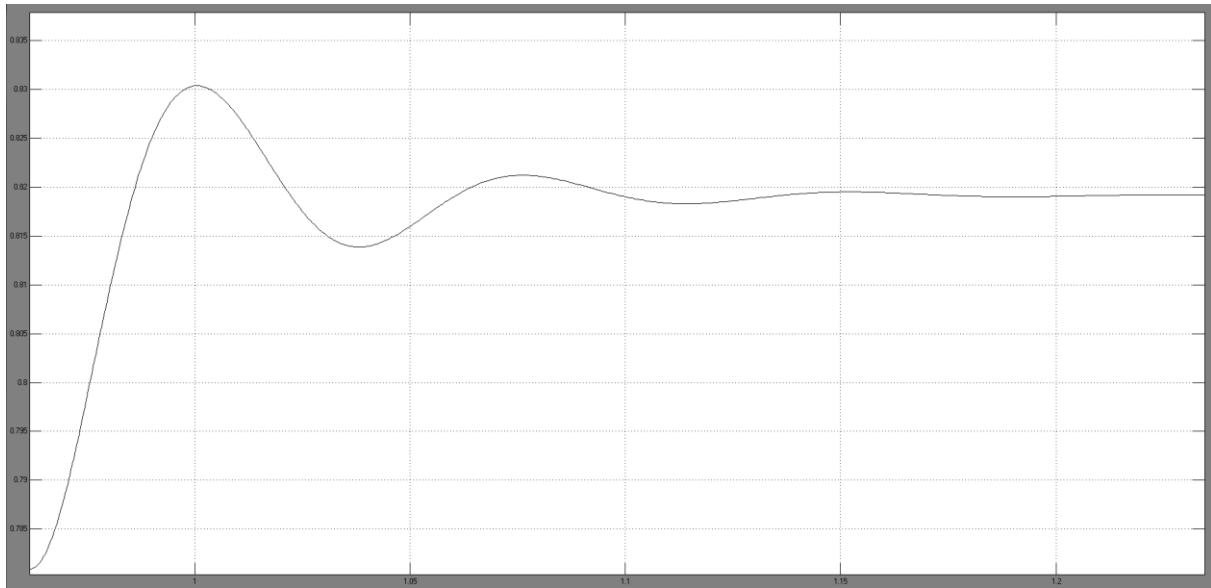
31

Figure(5.14) Torque curve in the Soft starting 50% nominal load case

Figure(5.15) Speed curve in the Soft starting 50% nominal load case

Figure(5.16) Efficiency curve in the Soft starting 50% nominal load case

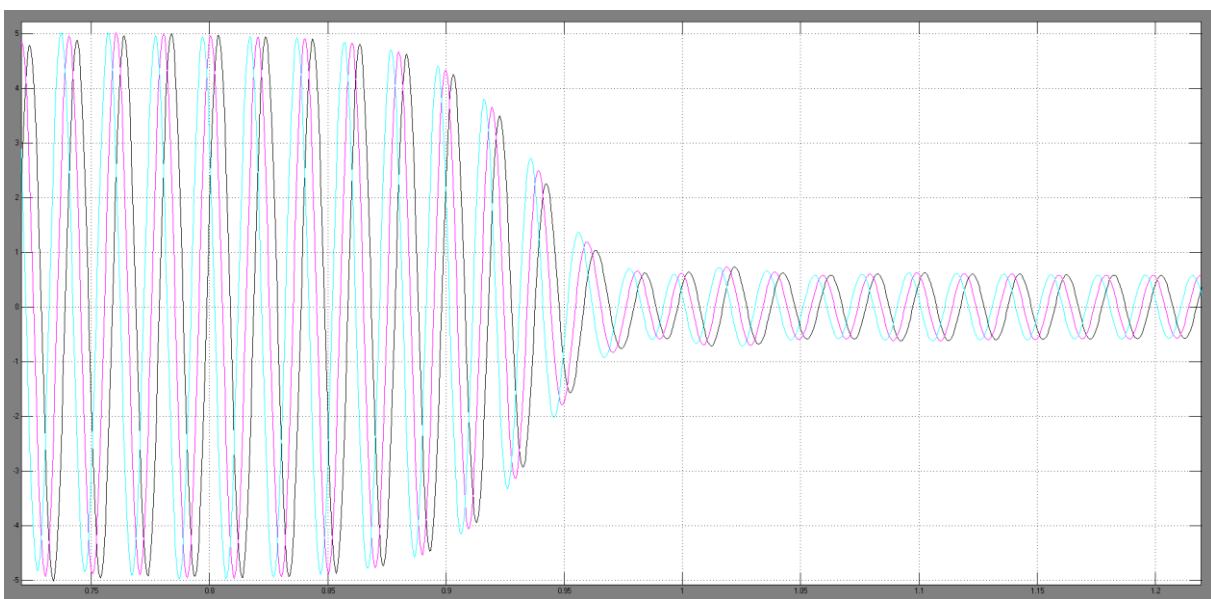Figure(5.17) Power factor curve in the Soft starting 50% nominal load case

Soft starting 50% nominal load test reaults table:

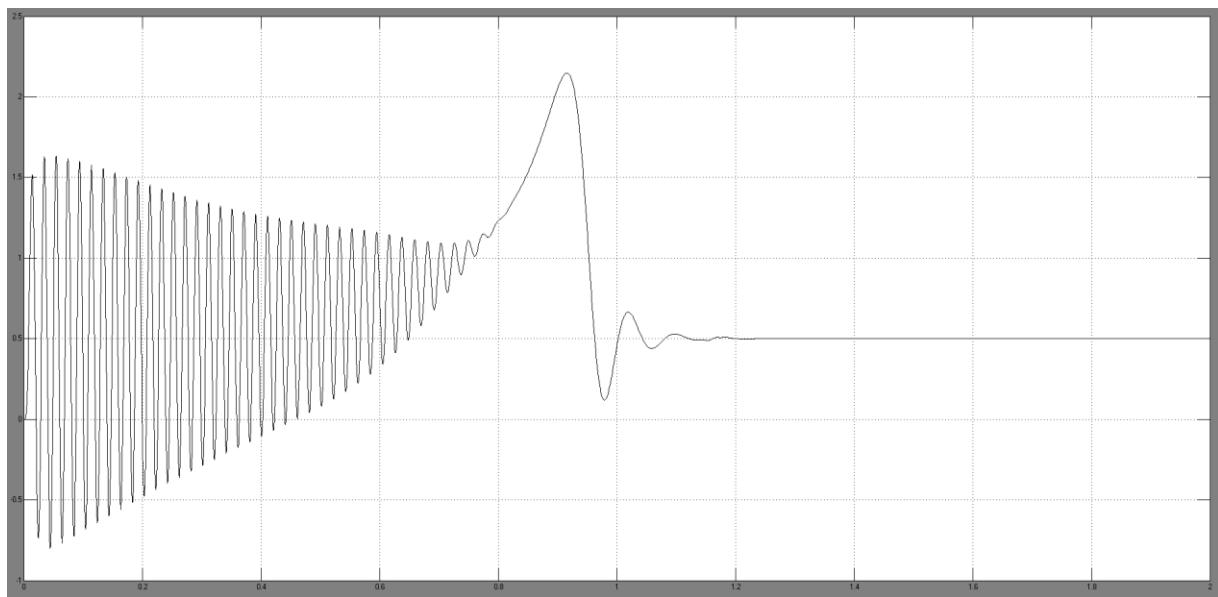| Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
5	1.6	1.22	97	72

Table(5.3)

33

4. Soft starting curves in the 25% of nominal load case:

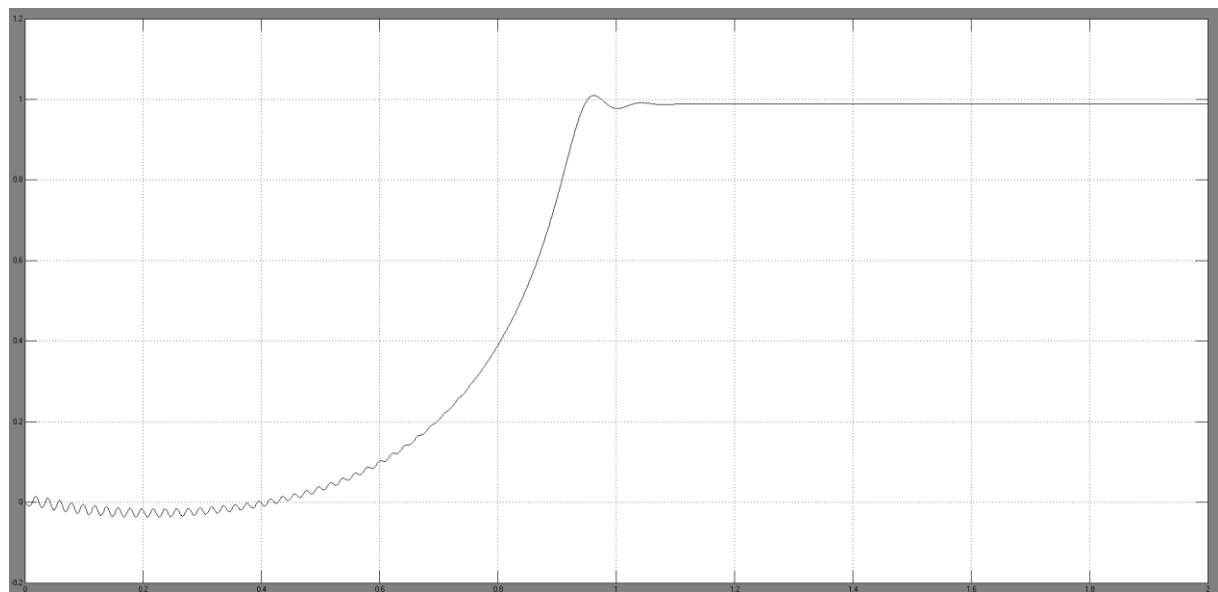The starting voltage is set to 90V using the Ramp icon shown in figure (5.2)

Figure(5.18) Currents curves in the Soft starting 25% nominal load case
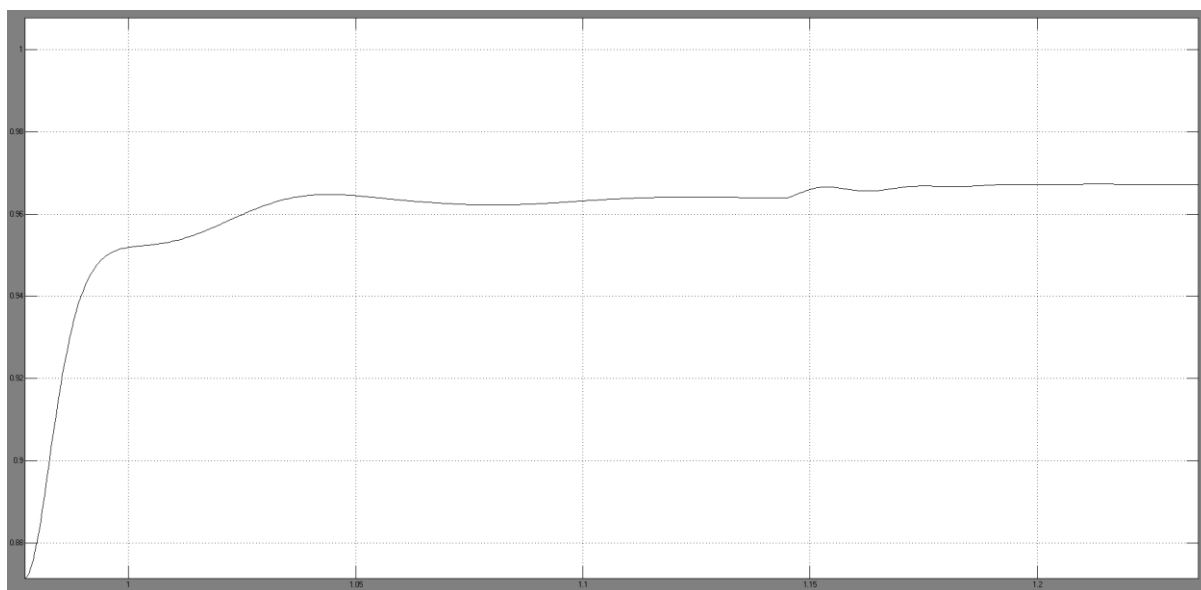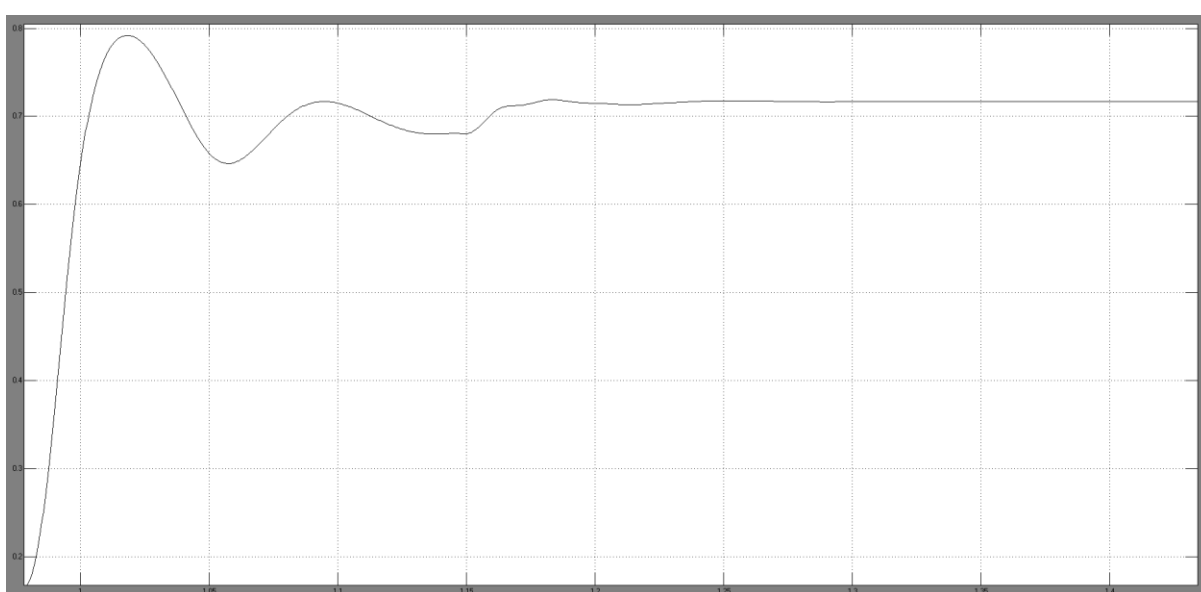

Figure(5.19) Torque curve in the Soft starting 25% nominal load case
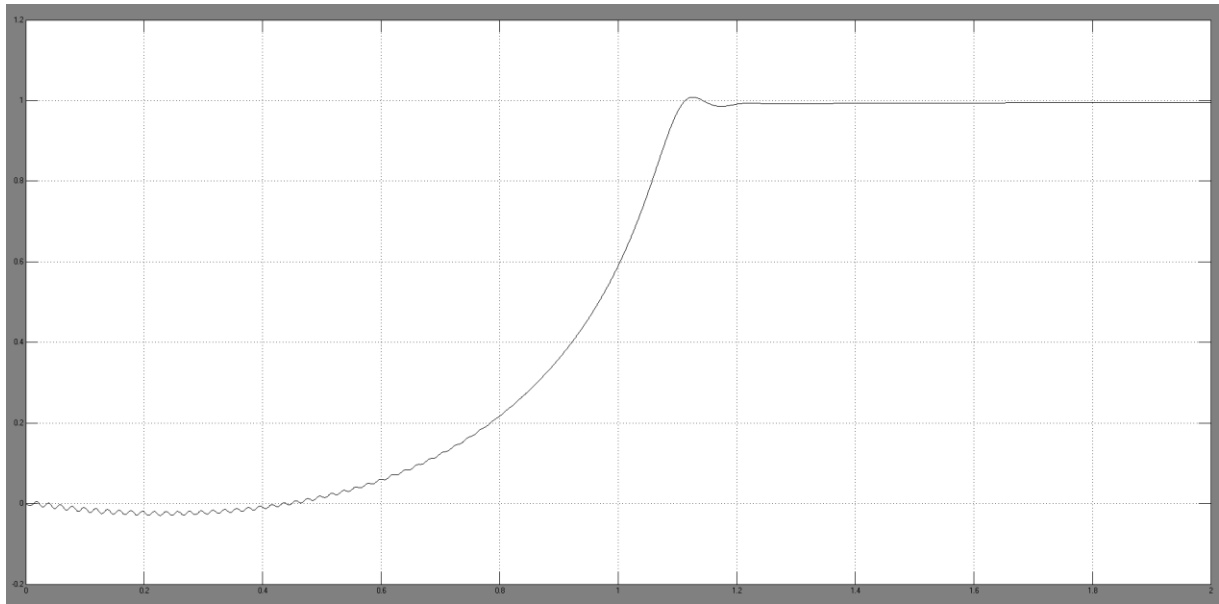
Figure(5.20) Speed curve in the Soft starting 25% nominal load case
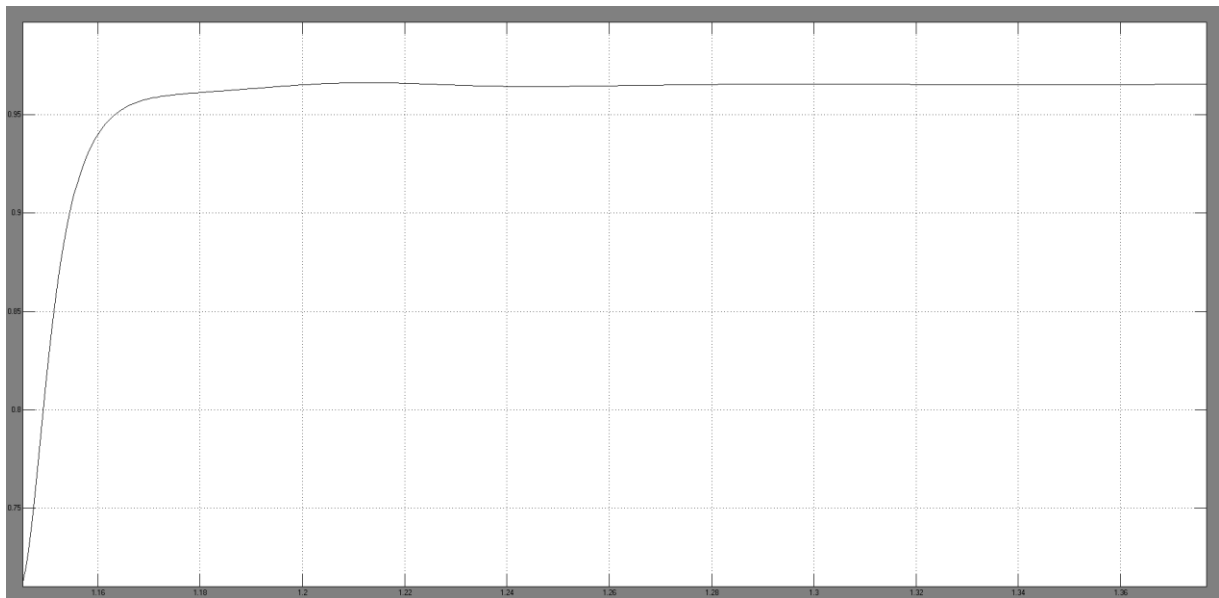
Figure(5.21) Efficiency curve in the Soft starting 25% nominal load case
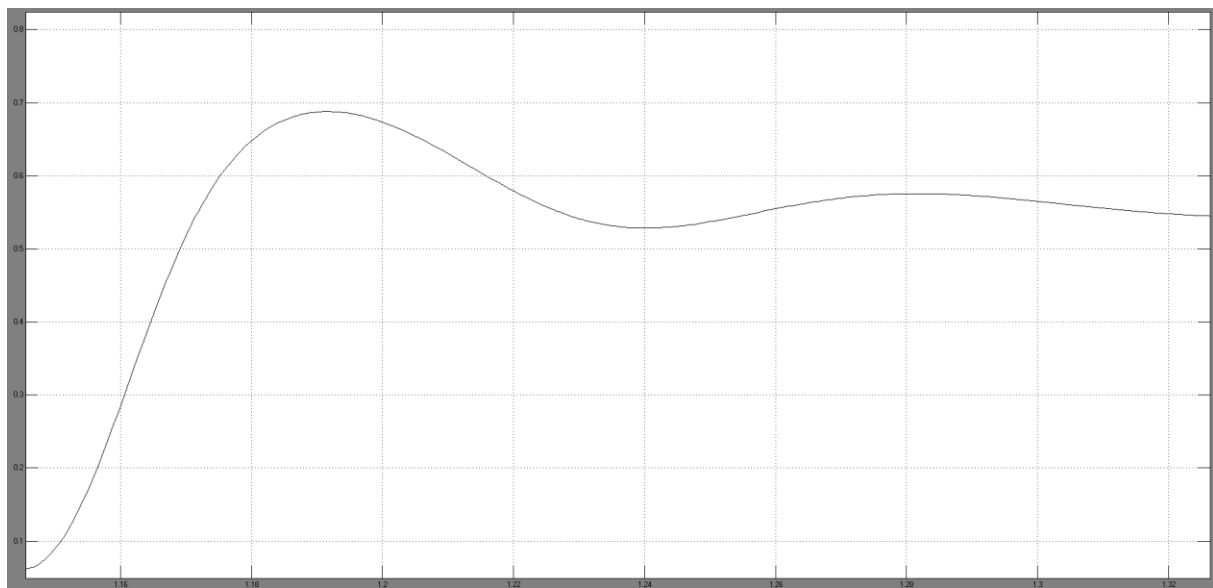
Figure(5.22) Power factor curve in the Soft starting 25% nominal load case
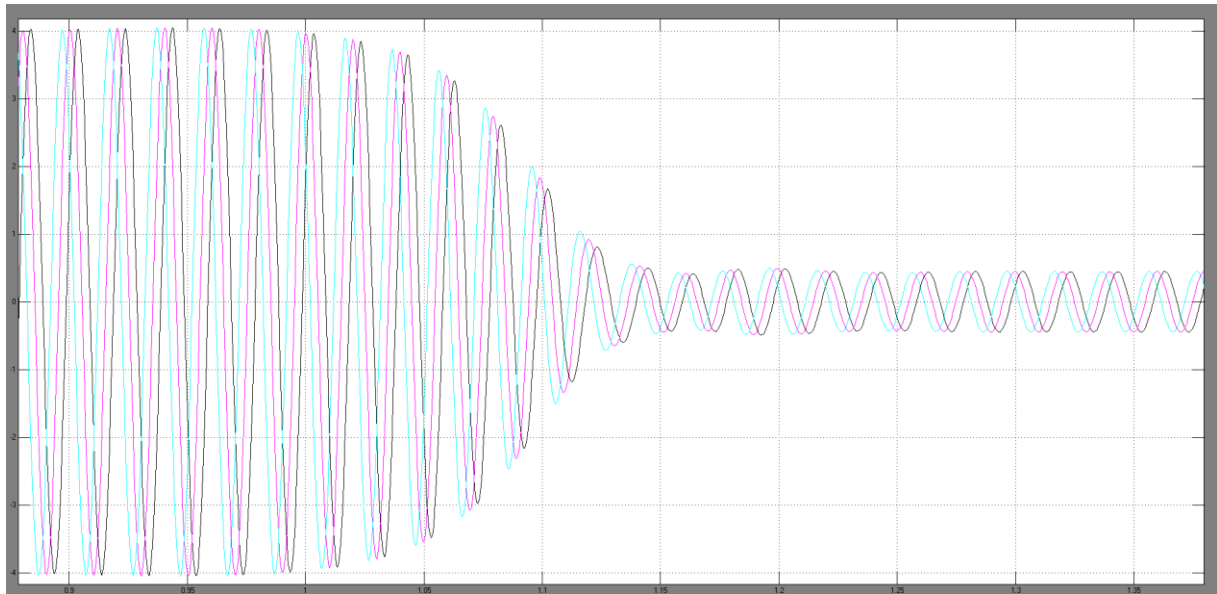
Soft starting 25% nominal load test reaults table:

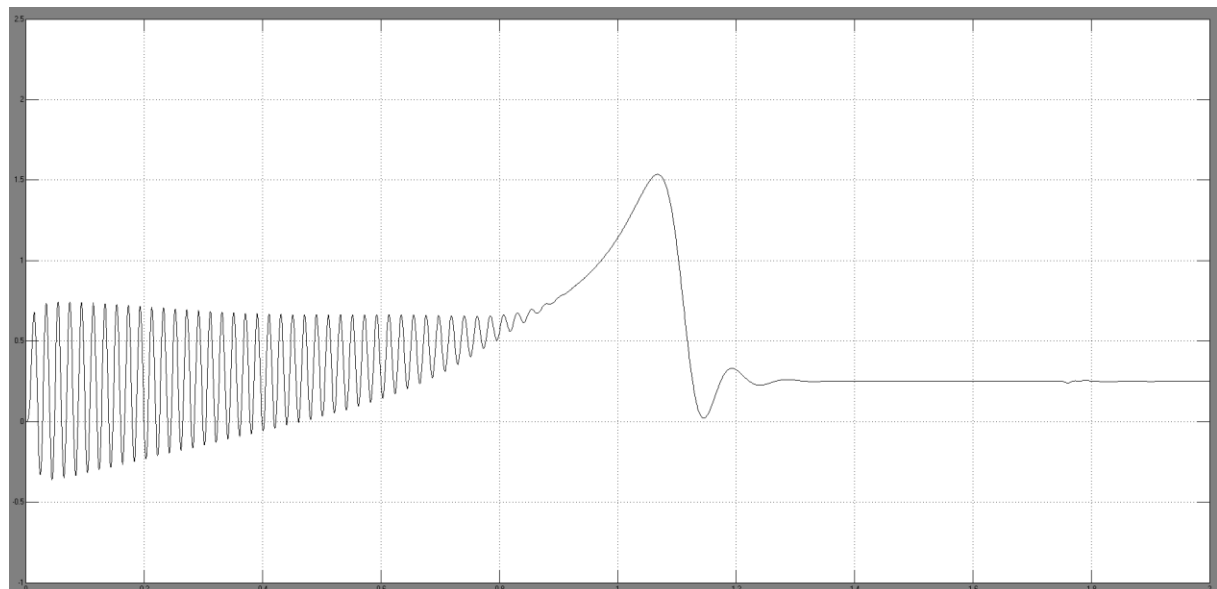| Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
4	0.75	1.3	97	55

Table (5.4)

Chapter 6: conclusions and discussion

In this chapter the results of the Direct and Soft starting methods are highlighted and discussed according to the previous simulations in chapters 4 and 5.

- Direct starting results:

Table 6.1 shows that when increasing the load torque the starting current decreases, while the starting torque increases along with the transient state, which leads to delaying the stationarity.

Tload (%)	Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
0	6.3	3.8	0.4	-	-
75	6.1	3.95	0.6	96	82
100	6	4.1	1.2	95	86

Table (6.1)

- Soft starting results:

Table 6.2 shows that when increasing the load torque the starting current increases along with the starting torque, whereas the stationarity time is changing but not in a certain pattern.

Tload (%)	Ist (pu)	Tst (pu)	Transient (s)	Efficiency (%)	Power factor (%)
25	4	0.75	1.3	97	55
50	5	1.6	1.22	97	72
75	5.8	2.6	1.15	96	82
100	5.9	3.45	1.45	95	86

Table (6.2)

- General discussion and clarification:

The efficiency and the power factor are almost the same in both of the Direct and Soft starting methods. However, they have no effect on the starting process, because they are taken after the transient state.

The transient state, on the other hand, has a rather significant effect on the starting process; since it determines the time the motor needs to reach stationarity. The Direct starting method has a short transient, whereas the Soft starting method has a quite large one.

The starting torque of the Direct starting method is large and consistent at all torque loads, whereas it is fluctuating between small values and large ones in the Soft starting method.

Last but not least, the starting current is decreasing when increasing the load in the Direct starting method, which is contrary to the increasing one in the Soft starting one.

Conclusions:

The previous results showed that the Direct starting method requires a large starting current which causes a disturbance to voltages on the supply lines. In other words, the large starting current produces a severe voltage drop which affects the operation of other equipment. Other than that, it is a quite good method because it provides a large starting torque in a short transient state, without the need of external equipment to help starting the motor. The previous features make the Direct starting method the most common one to start a 3ph induction motor.

The Soft starting method requires a reasonable starting current to generate a small starting torque at a long transient state, not to mention the need of external thyristor voltage regulator which means extra costs. On the other hand, it provides a smooth startup without any jerks along with a controlled flawless acceleration. These features give the Soft starting method a reliable accuracy with less current needed at the expense of stationarity delay and external equipment charges.

References:

[1] H. Boghos and A. Al Jazi, *Asynchronous Machines.* Damascus, Syria: DU, 2007.

[2] C. Ong*, Dynamic Simulation of Electric Machinery*. West Lafayette, Indiana: Upper Saddle River, N.J. : Prentice Hall PTR, 1998

[3] Krause, P. C., *'Simulation of symmetrical induction machinery'*, IEEE T rans. Power Apparatus Systems, Vol. PAS-84, No. 11, (1965)

[4] P. Stekl, *3-Phase AC Indudction Vector Control Drive with Single Shunt Current Sensing*. Czech Republic: Freescale Czech Systems Laboratories, 2007

[5] N. Mohan, *Advanced electric drives analysis control and modeling using matlab / simulink.* Hoboken, New Jersey: John Wiley & Sons,Inc, 2014.

[6] http://publications.lib.chalmers.se/records/fulltext/64463/64463.pdf

Appendix 1

Notes:

The simulations are not run by the m-file but are run by the Simulink models. However, the process goes by these steps:

1. The m-file is opened and run, which stores the values at Matlab datasheet to be used when needed in the Model.

2. Then the model is opened and run as well, and the parameters which are not defined in the model are taken as values from the datasheet.

3. The main system in figure 3.2 has three inputs and five outputs, while the subsystem has only two inputs and five outputs. The main system inputs are the three phase voltages implemented as equations. The objective is to represent these voltages on Alpha Beta coordinates system as two voltages, using simple conversion equations.

4. The subsystem -on the other hand - represents the equations found on pages (10, 11) as blocks, to process and preview them as outputs. For instance, the current i_α^s can be easily substituted by a simple integration and 3 gains (1/Ls, Rs/Ls, M/Ls), and then its value could be taken from the current curves since each current has a unique color. The same method is used on all the blocks to produce the outputs, which can be previewed by double clicking on the wanted icon in the main system.

5. If the reader would like to run the tests again he should make the changes (in the starting voltage for example) in the model instead of the code since there is no code. This could be more difficult than the standard way, but it is easier when making the simulations for the first time.

6. Regarding the current equations found on page 10, they are slightly different from the ones found in reference number [5] since it has introduced the equations according to (qd) coordinates. Note that in order to use [5] equations the axis (Alpha) should be considered as the axis (d) and the axis (Beta) as (q). For instance, i_α^s corresponds to i_d^s and i_β^s corresponds to i_q^s and so on.

Matlab simulation code

```
%DATA OF A THREE PHASE INDUCTION MOTOR
%Pn=18.5 kw;
M=0.0489; %H the constant of exchanged induction
Rr=0.16; %ohm the rotor resistance
Ls=0.05; %H the stator inductance
Lr=0.051; %H the rotor inductance
Rs=0.159; %ohm the stator resistance
P=2; % the number of pairs of poles
J=0.234%K.GM^2 % moment of inertia
Wrb=314; % 2πf
Tb=125; % the nominal torque
Ib=52; % the nominal current
Tfactor1=((3/2)*M*P);
Tfactor2=(p/(J))
```

Glossary of Symbols

i_α^s : The stator current represented on the axis alpha.

i_β^s : The stator current represented on the axis beta.

i_α^r : The rotor current represented on the axis alpha.

i_β^r : The rotor current represented on the axis beta.

u_α^s : The stator voltage represented on the axis alpha.

u_β^s : The stator voltage represented on the axis beta.

u_α^r : The rotor voltage represented on the axis alpha.

u_β^r : The rotor voltage represented on the axis beta.

$M = L_m$: the constant of mutual induction.
R_r: the rotor resistance.
R_s: the stator resistance.
L_s: the stator inductance.
L_r: the rotor inductance.
p: the number of pairs of poles.
J: the moment of inertia.
$W_{rb} = W_r$: the angular velocity.
T_b: the nominal torque.
T_m: the load torque.
I_b: the nominal current.
n_b: the motor speed.
η : the efficiency.
$p_2(t)$: the mechanical power (output of the motor).
$p_1(t)$: the electrical power (input of the motor).
$Cos\varphi_1$: the power factor.
T_{em}: the electromagnetic torque.
P_n: real power in kw.

p_α^s : The stator real power represented on the axis alpha.

p_β^s : The stator real power represented on the axis beta.

q: reactive power.

q_α^s : The stator reactive power represented on the axis alpha.

q_β^s : The stator reactive power represented on the axis beta.

s: apparent power.

Ω_r :the mechanical angular speed.

Appendix 2: Motor modelling

In reference [1], which is written in Arabic and with an origin in a Russian scientific tradition, a 3-phase induction motor model is given as described by equations 18-32 in this thesis, based on the (α, β) coordinates system.

References [2], [5] and [6] confirm the model. In [6], Appendix A, it is described how the (α, β) coordinates system is a special case of the (d, q) coordinates system. Reference [5] presents a mathematical model on page 45 which reduces to the same as the one given by equations (18) - (21) if certain requirements are used:

1. One chooses $\omega_d = 0$, i.e. if one chooses a coordinate system which is attached to the stator. This is described in [6], Appendix A.

2. One uses Ls = Lm + Lls (see [5], Eq 2.15 and p. 32) where Lm is the mutual inductance indicated as M in reference [1]. Lls is the leakage inductance.

3. One uses the constant $k = \sqrt{\frac{3}{2}}$. In reference [5], p. 32, this is justified as modeling correctly in the (d, q) coordinates system so that the mmf is represented correctly.

In that case, variables in [5, p. 45] can be replaced by the variables used in [1]:

$$k\,i_\alpha^s = i_{sd} \qquad k\,i_\alpha^r = i_{rd} \qquad k\,u_\alpha^s = v_{sd} \qquad k\,u_\alpha^r = v_{rd}$$

$$k\,i_\beta^s = i_{sq} \qquad k\,i_\beta^r = i_{rq} \qquad k\,u_\beta^s = v_{sq} \qquad k\,u_\beta^r = v_{rq}$$

With this the equations (22), (30), (31) and (32) agree with the corresponding equations in [5]. Equation (23) agrees with the corresponding equation in [5]