Sudan University of Sciences and Technology

College of Engineering

Electrical Engineering

Dynamic Analysis of Three Phase Induction Motor

التحليل الديناميكي للمحرك الحثي ثلاثي الطور

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(Power &Machines)

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الآيــــــــــــــــــة

قال تعالى:

((سَبَّحَ لِلَّـــهِ مَا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ وَهُوَ الْعَزِيزُ الْحَكِيمُ))

سورة الحشر(1)

الإهـــــــــداء

نقدم هذا الجهد المتواضع وهو ثمرة اجتِهادنا إلي ينابيع

العطاء الذي ذرع في نفوسنا الطموح و المثابرة إلي

آباءنا الكرام....

والي منابع الحنان التي لا تنضب

أمهاتنا العزيزات....

إلي من يحملون في عيونهم ذكريات طفولتنا وشبابنا...

إخواننا و أخواتنا...

اصدقاءنا...

إلي كل محبي العلم و العرفة.

إلي زملائنا وزميلاتنا

إلي من ضاقت السطور عن ذكرهم فوسعتهم قلوبنا...

اليكم جميعاً نهدي هذا العمل المتواضع.

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ABSTRACT

Induction machines are considered 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.

مستخلص

تعتبر الماكينات الحثية أكثر الآلات الكهربية إستخداما ونجد ان معظم المستخدم منها هي المحركات الحثية . ويمثل بدء المحرك الحثي هو الخطوة الأكثر أهمية . وتستند النظرية في هذا المشروع على تمثيل المحرك الحقيقي من خلال مجموعة من المعادلات والقيم في الماتلاب بإستخدام ميزة النظام الفرعي وتمثيل المحرك الحقيقي باسلوب المحاكاة بحيث تكون جميع الآثار المادية متشابهة. يبدأ المحرك تحت أحمال مختلفة بطريقتين :البداية المباشرة والبداية الناعمة. ولكل طريقة تمت دراسة ومناقشة منحنيات التيار وعزم الدوران والسرعة والكفاءة ومعامل القدرة.

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LIST OF SYMBOLS

vR, vY, vB	Stator voltages V
vr, vy, vb	Rotor voltages V
iR, iY, iB	Stator currents A
ir, iy, ib	Rotor currents A
vA, vB, va, vb	Stator and rotor voltages on A,B axis V
vD, vQ, vd, vq	Stator and rotor voltages on D,Q axis V
iA, iB, ia, ib	Stator and rotor currents on A,B axis A
iD, iQ, id, iq	Stator and rotor currents on D,Q axis A
Rs	Stator resistance Ω
Rr	Rotor resistance Ω
Ls	Stator inductance H
Lr	Rotor inductance H
M	Stator to rotor mutual inductance
Ms	Stator to stator mutual inductance
Mr	Rotor to rotor mutual inductance
θ	Stator angle
ωr	Mechanical speed r.p.m
J	Moment of inertia kg.m^2
s	Slip
f	Frequency Hz
P	No. of poles
Rm	No load resistance Ω
Xm	No load inductance Ω
Xir	Rotor mutual inductance
Xis	Stator mutual inductance

T	Torque N.m
Tb	Breakdown Torque N.m
C1	Phase transformations
C2	Commutator transformations
Te	Electrical torque N.m
Tm	Mechanical torque N.m
Ns	Synchronous speed r.p.m
N	Rotor speed r.p.m
Er	Induced voltage of rotor V

CHAPTER ONE
INTRODUCTION

1.1 General Concept:

An electrical motor is such an electromechanical device which converts electrical energy into a mechanical energy. and classified induction motor to two types; squirrel cage motors and wound rotor motors, and The constructional of the induction motor consists essentially of two major parts:

Stator: of a three phase induction motor is made up of number of slots to construct a three phase winding circuit which is connected to a three phase AC source,

Rotor: of a three phase induction motor consist of cylindrical laminated core with parallel slots that can carry conductors. The conductors are heavy copper or aluminum bars which fits in each slots and they are short circuited by the end rings. The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed because this arrangement reduces magnetic humming noise and can avoid stalling of motor.

The induction motor is deferent from other motors in that rotor received the energy by induction not by directs connect. When the stator winding poly-phase Induction machine is excited by balanced poly-phase voltages a rotating magnetic field is produced in the air gap. The rotating field is traveling at synchronous speed. To examine the air gap flux and m.mfs waves, the space fundamental component of the resultant air gap flux wave than travels past the rotor at slip speed and induces slip-frequency e.mfs in the rotor circuits.

In case of three phase AC operation, most widely used motor is three phase induction motor as this type of motor does not require any starting device or we can say they are self starting induction motors.

To study the dynamic analysis of the three-phase inductive motor we study the transient state of starting the engine, which has a high starting current and to avoid the risk of high current used several methods.

1.2 Problem Statement:

Starting a motor from the standstill with the rated stator voltage applied can result in large starting current, typical as much as six to eight times the rated current of the motor. The starting current of a large induction motor could result in excessive voltage drop along the feeder that is disruptive or objectionable to other load in some feeder.

1.3 Objectives:

The objective of this project is to study transient performance three phase induction motor during starting by using (MATLAB/ Simulink) and discuss the effectives of starting current on torque and speed at various cases.

1.4 Methodology:

The method is applied to convert the three phase induction motor to two phases without loss or any affection in dynamic analysis by using phase transformation matrix C_1 and convert two phase rotating axes to stationary axis in reference frame by using commutator transformation matrix C_2

Then the new quantities ; voltages, current and impedance equations have been deduced and they have been used to find current and speed differential equations and then the program of (MATLAB- Simulink) has been used to solve these equation and to simulate the startup in order to Study and understand the dynamic analysis of three phase induction motor.

1.5 Project Layout:

This project is presented in five chapters. The scope of each chapter is explained as follows:

Chapter one: Gives an introduction including general concepts, problem statement, objectives and methodology.

Chapter two: The induction motor including construction, equivalent circuit, torque speed curve and power flow.

Chapter three: Presents the transient of three phase induction motor and Mathematical model of induction motor.

Chapter four: Contains results and discussions.

Chapter five: Present the conclusion and recommendations.

CHAPTER TWO

THREE PHASE INDUCTION MOTOR

2.1 Three Phase Induction Motor:

Three-phase asynchronous motors can be considered among the most reliable electrical machines: they carry Three-phase out their function for many years with reduced maintenance and adapt themselves to different performances according to the requirements of both production as well as service applications.

As already said, these motors find their application in the most different industrial sectors, such as food, chemical metallurgical industries, paper factories or water treatment and extractive systems. The applications concern the equipment with machine components running at fixed or variable speed such as for example lifting systems as lifts or good hoists, transporting systems as conveyors, ventilation and air conditioning installations without forgetting the commonest use with pumps and compressors

The three-phase induction motors are the most widely used electric motors in industry. They run at essentially constant speed from no-load to full-load.

However, the speed is frequency depended and consequently these motor are not easily adapted to speed control. We usually prefer DC motors when large speed variations are required. Nevertheless, the three phase induction motors are simple, rugged, low-priced, easy to maintain and can be manufactured with characteristics to suit most industrial requirements. In this chapter we will focus our attention on the general principles of three-phase induction motors.

Like any electric motors, a three-phase induction motor has a stator and a rotor. The stator carries a three-phase winding (called rotor winding). Only the stator winding is fed from three-phase supply.

The rotor winding derives its voltage and power from the externally energized stator winding through electromagnetic induction and hence the name. The induction motor may be considered to be a transformer with a rotating secondary and it can, therefore, be described as a “transformer type” AC. Machine in which electrical energy is converted into mechanical energy.

2.1.1 Advantages:

(1) It has simple and rugged construction.

(2) It is relatively cheap.

(3) It requires little maintenance.

(4) It has high efficiency and reasonably good power factor.

(5) It has self-starting torque.

2.1.2 Disadvantages:

(1) It is essentially a constant speed motor and its speed cannot be changed easily.

(2) Its starting torque is inferior to DC shunt motor.

2.2 Construction of 3-phase Induction Motor:

The 3-phase induction motor consists of two main parts:

2.2.1 Stator:

Stator, as its name indicates stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three phase supply is given to it. Stator is made up of number of stampings in which different slots are cut to receive 3-phase winding circuit which is connected to 3-phase AC supply. The three phase windings are arranged in such a manner in the slots that they produce a rotating magnetic field after AC supply is given to them. The windings are wound for a definite number of poles depending upon the speed requirement, as speed is inversely proportional to

The number of poles, given by the formula:

$$Ns = \frac{120 \times f}{p} \quad (2.1)$$

The stator of the three phase induction motor consists of three main parts:

(1) Stator Frame.

(2) Stator Core.

(3) Stator Winding or Field Winding.

2.2.2 Rotor:

The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft. Rotor consists of cylindrical laminated core with parallel slots that carry conductor bars. Conductors are heavy copper or aluminum bars which fits in each slots. These conductors are brazed to the short circuiting end rings. The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed for the following reason, they reduce magnetic hum or noise and they avoid stalling of motor. The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

(1) Squirrel cage rotor:

Applications: this motor is used in lathes, drilling machine, fan, blower printing machines etc.

(2) Wound rotor: is used where high starting torque is required i.e. in hoists, cranes, elevator etc.

As shown in figure.2.1 bellow:

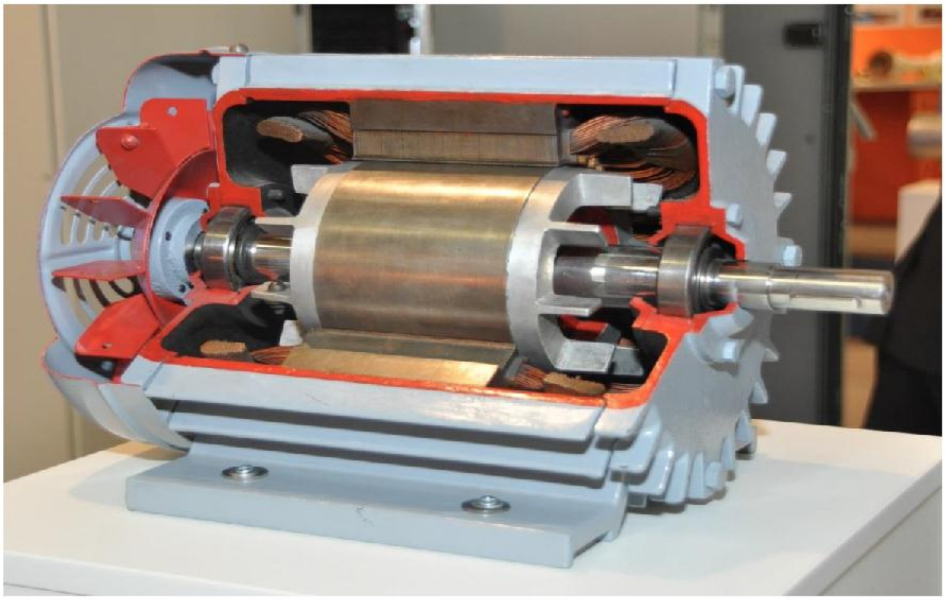

Figure 2.1: cutaway diagram of rotor induction motor.

2.2.3 Other Components of 3-phase Induction Motor:

(1) Shaft for transmitting the torque to the load. This shaft is made up of steel

(2) Bearings for supporting the rotating shaft.

(3) One of the problems with electrical motor is the production of heat during its rotation. In order for this problem we need fan for cooling.

(4) For receiving external electrical connection Terminal box is needed.

(5) There is a small distance between rotor and stator which usually varies from 0.4 mm to 4 mm. Such a distance is called air gap.

2.3 Equivalent Circuit of an Induction Motor:

The energy is transferred from primary winding to secondary winding entirely by induction; therefore induction motor is essentially a transformer, at stand still. The induction motor is actually a static transformer having its secondary winding short-circuited.

When the rotor operates at slip S, the frequency of rotor currents is, S times the frequency of the stator currents therefore the revolving field produced by the rotor currents revolves with respect to rotor itself at speed :

$$\frac{120\times sf}{P} = \frac{120\times f}{P} = Ns\times s \qquad (2.2)$$

Mechanical speed of the rotor:

$$N = Ns\ (1- s) \qquad (2.3)$$

The speed of the revolving field of the rotor with respect to stator or space is obtained by combining the rotational speed of rotor field with respect to rotor with mechanical speed of the rotor; hence speed of the rotor revolving field with respect to stationary stator or space:

$$Ns = sNs + Ns(1-s) \qquad (2.4)$$

Then:

$$s = \frac{Ns-N}{Ns} \qquad (2.5)$$

Hence from the point of view of stator, the induction motor still can be considered as static transformer, even when its rotor is rotating, and it’s possible to represent the performance of an induction motor by a transformer phasor diagram. Actually the rotor field does not exist alone but combine with the revolving field of stator to produce a resultant field, just as in the transformer, the resultant field is produced by the combination of primary & secondary ampere-turns. In the transformer the load on secondary is electrical and in an induction motor the load is mechanical.

The equivalent circuit for a 3-pahse induction motor is shown in the figure. 2.2:

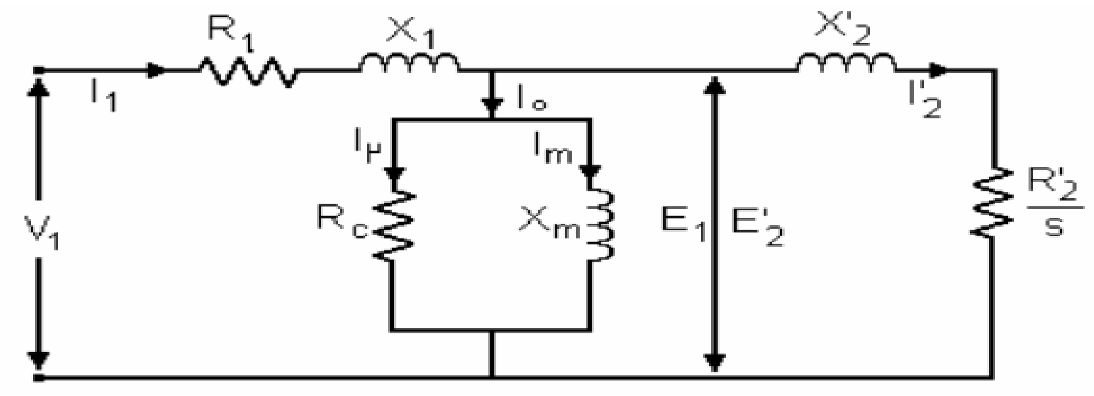

Figure 2.2: The exact equivalent circuit.

Where V is applied voltage per phase, R_1 and X_1 are stator resistance and leakage reactance per phase respectively, Rr and Xr are rotor resistance and stand still leakage reactance per phase respectively, K is the turn ratio of secondary to primary, Rm and Xm no load resistance.

The equivalent circuit can be simplified by transferring no load current Component to the supply terminals, as shown in figure 2.3:

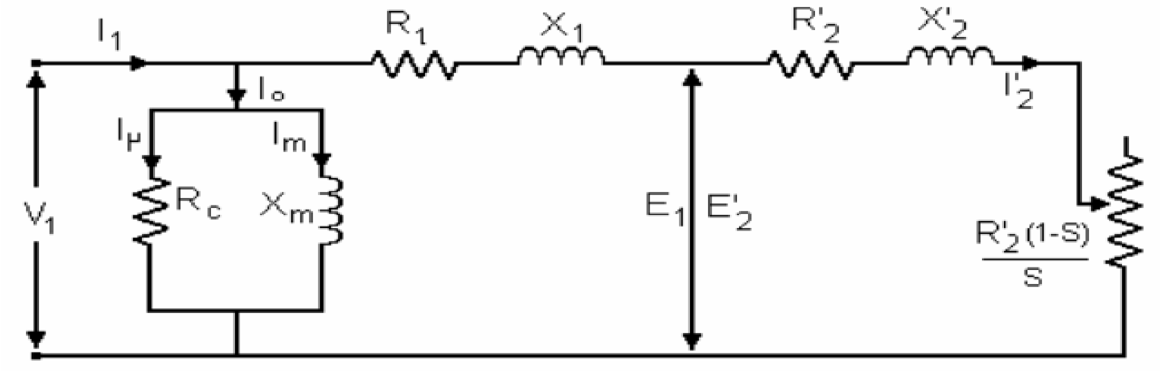

Figure 2.3: Approximate equivalent circuit.

2.4 Starting Torque:

The torque developed by the motor at the instant of starting is colled starting torque. In some cases, it is greater than the normal running torque, whereas in some other cases it is somewhat less. It occurs at (s=1).

Let:

$$K_1 = \frac{3}{2\pi Ns} \tag{2.6}$$

$$Z_2 = \sqrt{R_2^2 + X_2^2} \tag{2.7}$$

$$I_2 = \frac{E2}{\sqrt{R_2^2+X_2^2}} \tag{2.8}$$

$$\text{Cos } \emptyset_2 = \frac{R_2}{\sqrt{R_2^2+X_2^2}} \tag{2.9}$$

$$T_{ST} = K\, E_2\, I_2 \text{ Cos } \emptyset_2 \tag{2.10}$$

$$T_{ST} = \frac{K\, E22\, R_2}{R_2^2+X_2^2} \tag{2.11}$$

2.5 Torque and Speed Curves:

The torque and speed curves shown in figure 2.4 for a range of s=0 (Nr=Ns), to s=1(Nr=0), with R2 as the parameter.

Now :

$$E=E_r=sE \tag{2.12}$$

$$Z_r = \sqrt{R_2^2 + sX_2^2} \tag{2.12}$$

$$I_r = \frac{sE2}{Z2} = \frac{sE2}{\sqrt{R_2^2+X_2^2}} \tag{2.13}$$

$$\text{Cos } \emptyset_2 = \frac{R2}{\sqrt{R_2^2+sX_2^2}} \tag{2.14}$$

$$T = K_1 E_r I_r \cos(\emptyset 2) \tag{2.15}$$

$$K_1 = \frac{3}{2\pi Ns} \tag{2.16}$$

$$T = \frac{K1\ s\ E22\ R_2}{(R22)+(sX22)} \qquad (2.17)$$

It is clear that when s=0, T=0, hence the curve starts from point o. At normal speed, close to synchronism, the term (sX_2) is small and hence negligible Rr.

$$T \propto s/R_2 \qquad (2.18)$$

Or: T ∝ s (if R_2 is constant)

Hence for low values of slip, the slip/ torque curve is approximately straight line. As slip increases (increasing load in the motor) the torque also increases, and become maximum when:

$$s = \frac{R_2}{X\mathrm{ir}} \qquad (2.19)$$

This torque is known as (pull-out) or (breakdown) torque (Tb) or stalling torque. As the slip further increases (i.e. motor speed faults) with further increase in motor load, and then Rr becomes negligible as compared to (sXr). Therefore, for large values of slip

$$T_b \propto \frac{s}{(sX_{\mathrm{ir}}^2)} \propto \frac{1}{s} \qquad (2.20)$$

Hence, the torque/slip curve is a rectangular hyperbola. So, we see that beyond the point of maximum torque, any further increase in motor load results in decrease of torque developed by the motor. The result is that the motor slows down and eventually stops. The circuit-breakers will be tripped open if the circuit has been so protected. In fact, the stable operation of the motor lies between the values of (s=0) and that corresponding to maximum torque. It is seen that although maximum torque does not depend on R_2. Yet the exact location of Tmax is dependent on it. Greater the Rr, greater is the value of slip at which the maximum torque occurs, as shown in following figure 2.4.

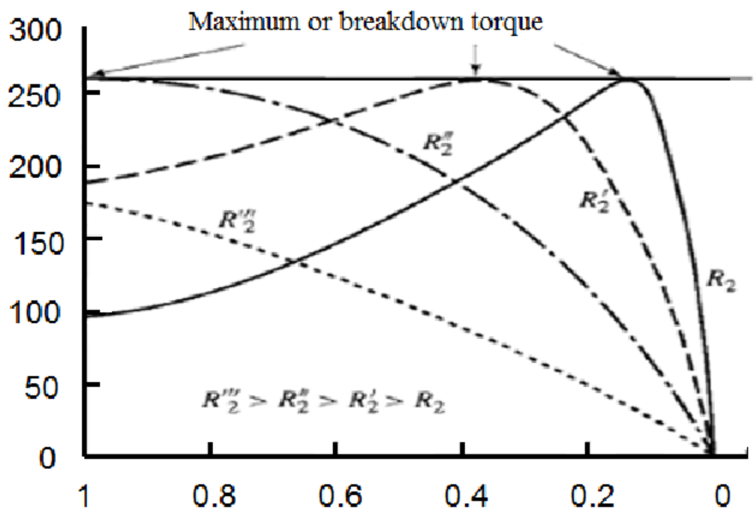

Figure 2.4: torque and speed curve.

2.6 Power Flow in a 3-phase Induction Motor:

From the equivalent circuit for induction motor we see that the total power input to the rotor (Pg) is the power flow diagram as shown in figure (2.5) bellow:

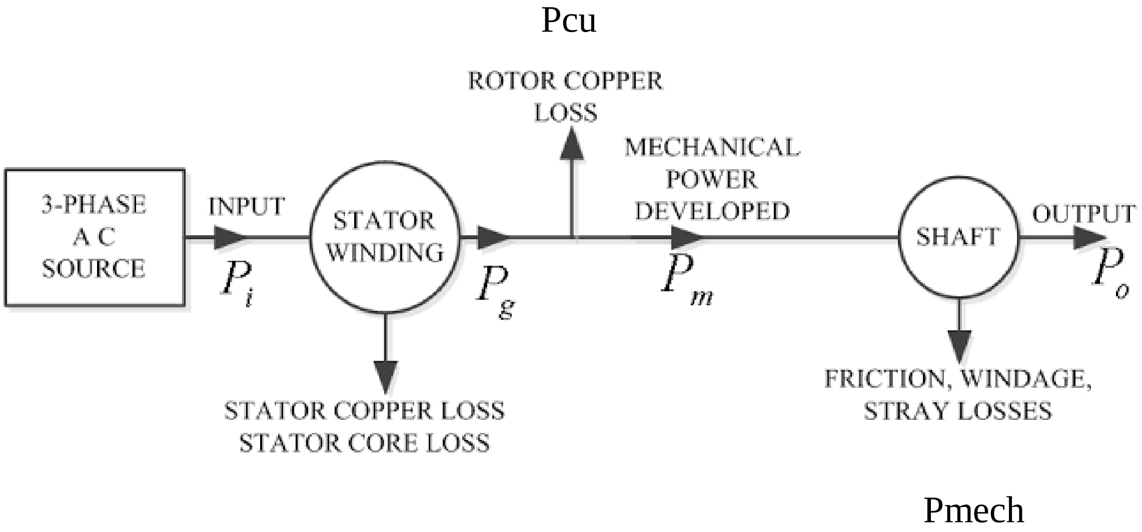

Figure 2.5: Power Flow diagram.

CHAPTER THREE

TRANSIENT STATE AND MATHEMATICAL MODEL

3.1 Transient states:

The steady-state stator and rotor currents and the travelling wave gap flux that exist induction machine running at fixed speed with constant unidirectional torque have to be established from the instant when the stator of the inert machine is switched on to the supply. Magnetic energy has to be supplied, as has the kinetic energy of the rotating systems and the various losses, as well as the energy absorbed by the load in raising it to the final steady-state condition. The energizing process is complicated by the reaction of cores to the rapid rise of flux density. The skin effect in conductors and the mechanical deformations of motor shaft and structure as quickly varying torques are developed. The difference between the actual and the steady-state conditions for given speed and load are bridged by transient currents and fluxes which appear instantaneously and there after decay exponentially at rates determined by the parameters and time constants of the several electric circuits and the instantaneous speed of the machine. The term switching is applied to transients arising as a result of the energizing of an inert machine.

Transients are also generated when one steady-state is changed to another, as when re-switching, if it is disconnected from the supply for a brief and then reconnected, transient currents and torques appear. These transients are some times of great severity, as when a motor is plugged or dynamically beaked, or subjected to supply-voltage interruptions especially where there are capacitor banks across the stator terminals, considerable torque and current transients may occur even when motor terminal connections are changed during run-up a star-delta switch. Very large induction machines when switched, re-switched or subject to the voltage fluctuation resulting from a power system fault, may react strongly on the system by drawing or supplying transient power.

3.2 Constant-linkage Theorem:

Physical appreciation of the transient condition is afforded by the theorem of the constant linkage. Which states that in a closed circuit of zero resistance, the algebraic sum of its magnetic linkages remains constant? No circuit (super conduction part) is devoid of resistance but the linkage nevertheless remains instantaneously constant immediately after a sudden change because it takes time for stored magnetic energy to be altered a process approximating to a time exponential vise or decay. When for example a3-phase voltage is suddenly applied to the stator terminals of an inert induction machine, phase fluxes begin to build up at rates proportional to the instantaneous voltages (which are inevitably, UN equal). The stationary rotor develops corresponding opposition currents that initially maintain the inert condition of zero linkage. If the rotor moves, these currents may be carried round, but rapidly decay. On disconnecting a running motor, the stator currents are quenched; but as the short-circuited motor maintains its linkage by unidirectional current a trapped or ‘frozen’ flux is carried round with the rotor. The trapped flux decays, but induces rotational emf, in the stator winding; the transient currents and torques that occur on re-switching depend on the stator emf so induced, and if these have phase-opposition to the supply voltages at the instant of reconnection. The transient currents may by severe and transient torque may have negative (-ve) peak.

3.3 Electromechanical Transient:

When the induction motor transfer from an operating condition to another there are many changes happened in the motor behavior. To study these changes there are some cases shown below:

3.4 Change of Load:

Reduced low-slip damping and transient synchronizing torques are also exhibited when a running motor is subjected to sudden change of load. During the rapid retardation following a large load application, the trapped rotor flux combines with the main synchronously rotating field to produce synchronizing torque which reverses cyclically as the speed drops and develops wide resultant fluctuations of motor torque, the peaks decaying as the rotor currents settle to the new condition.

3.5 Fluctuating Load:

If a load, such as a reciprocating compressor, imposes a slip and torque oscillation, cyclically generated rotor fluxes are trapped, of magnitude dependent on the load-oscillation frequency and the short-circuit time constant. They produce synchronizing torques, the elastic nature of which in combination with the load (or to one of its harmonics) the slip-swing may be augmented by resonance, causing a strong pulsation of the stator current wave form envelope.

3.6 Transformations from 3-phase to d-q axes:

In general, for any induction machine, the direct and quadrature axis coils do not correspond directly to those of the actual machine though they represent by their resultant m.m.f, the resultant m.m.f, of the windings they replace. It is not essential that the transformed winding axes are fixed with respect to the stator; they nay alternatively be aligned with moving references frame. If they so are chosen that they move at the same speed as the air-gap field itself.

3.7 Mathematical Model:

Figure (3.1) shows the three phases of an induction machine R, B, Y phases of stator and r, b, y phases of rotor:

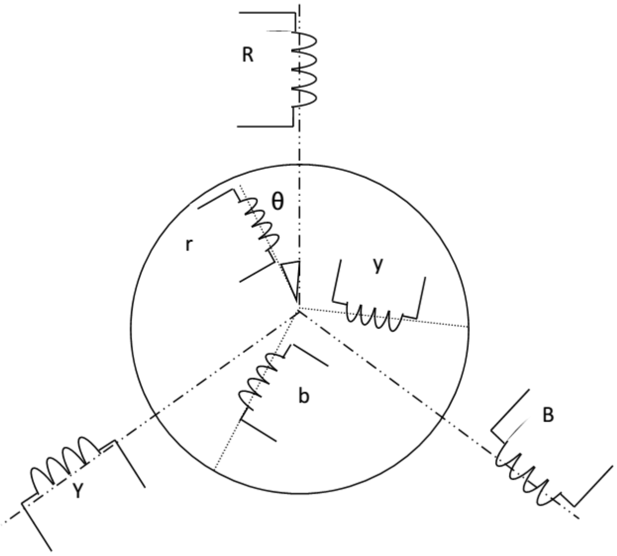

Figure 3.1: rotor and stator for 3-phase induction motor.

The equation can be:

$$\begin{bmatrix} vR \\ vY \\ vB \\ vr \\ vy \\ vb \end{bmatrix} = \begin{bmatrix} Rs+\rho Ls & \rho Ms & \rho Ms & M\cos\theta & M\cos\theta 2 & M\cos\theta 3 \\ \rho Ms & Rs+\rho Ls & \rho Ms & M\cos\theta 2 & M\cos\theta 3 & M\cos\theta \\ \rho Ms & \rho Ms & Rs+\rho Ls & M\cos\theta 3 & M\cos\theta & M\cos\theta 2 \\ M\cos\theta & M\cos\theta 2 & M\cos\theta 3 & Rr+\rho Lr & \rho Mr & \rho Mr \\ M\cos\theta 2 & M\cos\theta 3 & M\cos\theta & \rho Mr & Rr+\rho Lr & \rho Mr \\ M\cos\theta 3 & M\cos\theta & M\cos\theta 2 & \rho Mr & \rho Mr & Rr+\rho Lr \end{bmatrix} * \begin{bmatrix} iR \\ iY \\ iB \\ ir \\ iy \\ ib \end{bmatrix}$$

(3.1)

Where:

$\theta 2 = \theta - 2\pi/3$, $\theta 3 = \theta + 2\pi/3$

The system impedance matrix is:

$$[Z] = \begin{bmatrix} Zss & Zsr \\ Zrs & Zrr \end{bmatrix} \qquad (3.2)$$

Where:

$$\text{Zss}=\begin{bmatrix} Rs+\rho Ls & \rho Ms & \rho Ms \\ \rho Ms & Rs+\rho Ls & \rho Ms \\ \rho Ms & \rho Ms & Rs+\rho Ms \end{bmatrix} \quad (3.3)$$

$$\text{Zsr}=\begin{bmatrix} M\cos\theta & M\cos\theta 2 & M\cos\theta 3 \\ M\cos\theta 2 & M\cos\theta 3 & M\cos\theta \\ M\cos\theta 3 & M\cos\theta & M\cos\theta 2 \end{bmatrix} \quad (3.4)$$

$$\text{Zrs}=\begin{bmatrix} M\cos\theta & M\cos\theta 2 & M\cos\theta \\ M\cos\theta 2 & M\cos\theta 3 & M\cos\theta 3 \\ M\cos\theta 3 & M\cos\theta & M\cos\theta 2 \end{bmatrix} \quad (3.5)$$

$$\text{Zrr}=\begin{bmatrix} Rr+\rho Lr & \rho Mr & \rho Mr \\ \rho Mr & Rr+\rho Lr & \rho Mr \\ \rho Mr & \rho Mr & Rr+\rho Lr \end{bmatrix} \quad (3.6)$$

The transformation of the three-phase induction machine to two-phase machine is done by using the phase transformation matrix C1 as follows*:*

$$[V']=\begin{vmatrix} C1t & 0 \\ 0 & C1t \end{vmatrix} [V']=\begin{vmatrix} Vm\cos\omega rt \\ Vm\sin\omega rt \\ 0 \\ 0 \end{vmatrix} \quad (3.7)$$

$$[I']=\begin{vmatrix} C1t & 0 \\ 0 & C1t \end{vmatrix} \quad (3.8)$$

$$[Z']=\begin{vmatrix} C1t & 0 \\ 0 & C1t \end{vmatrix} [Z']\begin{vmatrix} C1 & 0 \\ 0 & C1 \end{vmatrix} \quad (3.9)$$

Then the new voltage equation is written as follws:

$$\begin{bmatrix} v0 \\ vA \\ vB \\ v0 \\ va \\ vb \end{bmatrix} =$$

$$\begin{bmatrix} Rs+\rho Ls0 & 0 & 0 & \rho M3\cos\theta 3 & 0 & 0 \\ 0 & Rs+\rho Ls & 0 & 0 & \rho M\cos\theta & \rho M\sin\theta \\ 0 & 0 & Rs+\rho Ls & 0 & \rho M\sin\theta & -\rho M\cos\theta \\ \rho M3\cos\theta 3 & 0 & 0 & Rr+\rho Lr0 & 0 & 0 \\ 0 & \rho M\cos\theta & \rho M\sin\theta & 0 & Rr+\rho Lr & 0 \\ 0 & \rho M\sin\theta & -\rho M\cos\theta & 0 & 0 & Rr+\rho Lr \end{bmatrix} * \begin{bmatrix} i0 \\ iA \\ iB \\ i0 \\ ia \\ ib \end{bmatrix} \tag{3.10}$$

Under normal conditions, the zero components can be ignored and then the impedance will be:

$$\begin{bmatrix} vA \\ vB \\ va \\ vb \end{bmatrix} = \begin{bmatrix} Rs+\rho Ls & 0 & \rho M\cos\theta & \rho M\sin\theta \\ 0 & Rs+\rho Ls & \rho M\sin\theta & -\rho M\cos\theta \\ \rho M\cos\theta & \rho M\sin\theta & Rr+\rho Lr & 0 \\ \rho M\sin\theta & -\rho M\cos\theta & 0 & Rr+\rho Lr \end{bmatrix} * \begin{bmatrix} iA \\ iB \\ ia \\ ib \end{bmatrix} \tag{3.11}$$

Applying the commutator transformation C2 on voltage current and impedance matrixes:

$$[V''] = \begin{vmatrix} U & 0 \\ 0 & C2t \end{vmatrix} \quad [V'] = \begin{vmatrix} Vm\cos\omega rt \\ Vm\sin\omega rt \\ 0 \\ 0 \end{vmatrix} \tag{3.12}$$

$$[I''] = \begin{vmatrix} U & 0 \\ 0 & C2t \end{vmatrix} [I'] \tag{3.13}$$

$$[Z''] = \begin{vmatrix} U & 0 \\ 0 & C2t \end{vmatrix} [Z'] \begin{vmatrix} C1 & 0 \\ 0 & C1 \end{vmatrix} = \begin{vmatrix} Z'ss & Z'srC2 \\ C2tZ'rs & C2tZ'rrC2 \end{vmatrix} \tag{3.14}$$

$$[V''] = [Z''][I''] \tag{3.15}$$

$$\begin{bmatrix} vD \\ vQ \\ vd \\ vq \end{bmatrix} = \begin{bmatrix} Rs+\rho Ls & 0 & \rho M & 0 \\ 0 & Rs+\rho Ls & 0 & \rho M \\ \rho M & \omega rM & Rr+\rho Lr & \omega rLr \\ -\omega rM & \rho M & -\omega rLr & Rr+\rho Lr \end{bmatrix} \begin{bmatrix} iD \\ iQ \\ id \\ iq \end{bmatrix} \tag{3.16}$$

From equation (3.16) we found:

$$vD = iD(Rs+\rho Ls)+\rho Mid \tag{3.17}$$

$$vQ = iQ(Rs+\rho Ls)+\rho Miq \tag{3.18}$$

$$vd = \rho MiD+\omega rMiQ+id(Rr+Lr)+\omega rLriq \tag{3.19}$$

$$vq = -\omega rMiD+\rho MiQ-\omega rLrid+iq(Rr+\rho Lr) \tag{3.20}$$

$$\rho[I] = [L]^{-1}([V]-[R][I]-\omega r[G][I] \tag{3.21}$$

Where :

$$[L] = \begin{bmatrix} Ls & 0 & 0 & M \\ 0 & Ls & M & 0 \\ 0 & M & Lr & 0 \\ M & 0 & 0 & Lr \end{bmatrix} \tag{3.22}$$

$$[L]^{-1} = \frac{1}{Lr*Ls-M*M} \begin{bmatrix} Lr & 0 & M & 0 \\ 0 & Lr & 0 & M \\ M & 0 & Ls & 0 \\ 0 & M & 0 & Ls \end{bmatrix} \tag{3.23}$$

$$[R]=\begin{bmatrix} Rs & 0 & 0 & 0 \\ 0 & Rs & 0 & 0 \\ 0 & 0 & Rr & 0 \\ 0 & 0 & 0 & Rr \end{bmatrix} \tag{3.24}$$

$$[G]=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & M & 0 & Lr \\ -M & 0 & -Lr & 0 \end{bmatrix} \tag{3.25}$$

$$[R][I]=\begin{bmatrix} Rs & 0 & 0 & 0 \\ 0 & Rs & 0 & 0 \\ 0 & 0 & Rr & 0 \\ 0 & 0 & 0 & Rr \end{bmatrix} * \begin{bmatrix} iD \\ iQ \\ iq \\ id \end{bmatrix} = \begin{bmatrix} RsiD \\ RsiQ \\ Rriq \\ Rrid \end{bmatrix} \tag{3.26}$$

$$\omega r[G][I]=\omega r\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -M & 0 & 0 & -Lr \\ 0 & M & Lr & 0 \end{bmatrix} * \begin{bmatrix} iD \\ iQ \\ iq \\ id \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -\omega r(MiD-Lrid) \\ \omega r(MiQ-Lriq) \end{bmatrix} \tag{3.27}$$

$$V-[R][I]-\omega r[G][I]=\begin{bmatrix} vD-Rsid \\ vQ-RsiD \\ vq-Rriq+\omega r(MiD+Lrid) \\ vD-Rrid-\omega r(MiQ+Lriq) \end{bmatrix} \tag{3.28}$$

When:

$$\omega r=\frac{d\theta}{dt} \tag{3.29}$$

$$\rho=\frac{d}{dt} \tag{3.30}$$

$$\frac{d}{dt}\begin{bmatrix} iD \\ iQ \\ iq \\ id \end{bmatrix} = \begin{bmatrix} Ls & 0 & 0 & M \\ 0 & Ls & M & 0 \\ 0 & M & Lr & 0 \\ M & 0 & 0 & Lr \end{bmatrix}^{-1} \begin{bmatrix} vD - RsiD \\ vQ - RsiD \\ vq - Rriq + \omega r(MiD + LriD) \\ vD - Rrid - \omega r(MiQ + Lriq) \end{bmatrix} \tag{3.31}$$

$$[Te] = [It][G][I] \tag{3.32}$$

$$[Te] = [iD \quad iQ \quad id \quad iq] * \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & M & 0 & Lr \\ -M & 0 & -Lr & 0 \end{bmatrix} * \begin{bmatrix} iD \\ iQ \\ id \\ iQ \end{bmatrix} = MidiQ - MiqiD \tag{3.33}$$

$$Te - Tm = J\,\frac{d\omega r}{dt} \tag{3.34}$$

$$\frac{d\omega r}{dt} = \frac{Te - Tm}{J} \tag{3.35}$$

CHAPTER FOUR

SIMULATION AND RESULTS

4.1 The induction motor model:

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

The motor equations on the coordinates system (d− q) are set as:

Currents equations:

$$\frac{d(iD)}{dt} = \frac{1}{Ls} v_D - \frac{Rs}{Ls} i_D - \frac{M}{Ls}\frac{d(id)}{dt} \tag{4.1}$$

$$\frac{d(iQ)}{dt} = \frac{1}{Ls} v_Q - \frac{Rs}{Ls} i_Q - \frac{M}{Ls}\frac{d(iq)}{dt} \tag{4.2}$$

$$\frac{d(id)}{dt} = - \frac{Rr}{Lr} i_d - \frac{M}{Lr}\frac{d(iD)}{dt} - \omega_r i_q - \omega_r\frac{M}{Lr} i_Q \tag{4.3}$$

$$\frac{d(iq)}{dt} = - \frac{Rr}{Lr} i_d - \frac{M}{Lr}\frac{d(iD)}{dt} + \omega_r i_d + \omega_r\frac{M}{Lr} i_D \tag{4.4}$$

Torque and Speed equations:

$$Te = \frac{3}{2} PM(i_Q i_d - i_D i_q) \tag{4.5}$$

$$\frac{d\omega r}{dt} = \frac{(Te - Tm)}{J} \tag{4.6}$$

The input and output power equations:

$$P_s(t) = P_D + P_Q = \frac{3}{2}(v_D i_D + v_Q i_Q) \tag{4.7}$$

$$Q_s(t) = Q_D + Q_Q = \frac{3}{2}(v_Q i_D + v_D i_Q) \tag{4.8}$$

$$S(t)=\sqrt{Ps^2+Qs^2} \qquad (4.9)$$

$$P_{out}=Te\omega_r= Te\frac{N}{p} \qquad (4.10)$$

$$\square=\frac{Puot(t)}{Pin(t)} \qquad (4.11)$$

$$\cos\Phi1=\frac{Pin}{S(t)} \qquad (4.12)$$

The following data for a 18.5kw, 220volt, 50Hz induction motor parameters

Table 4.1: Parameters of the induction motor:

Motor rating			TB	IB	r1	x1	xm	r1'	x1'	J
Kw	Volt	r.p.m	N.m	amp	Ohm	Ohm	Ohm	Ohm	Ohm	$Kg.m^2$
18.5	220	1500	125	52	0.159	0.05	26.13	0.16	0.051	0.234

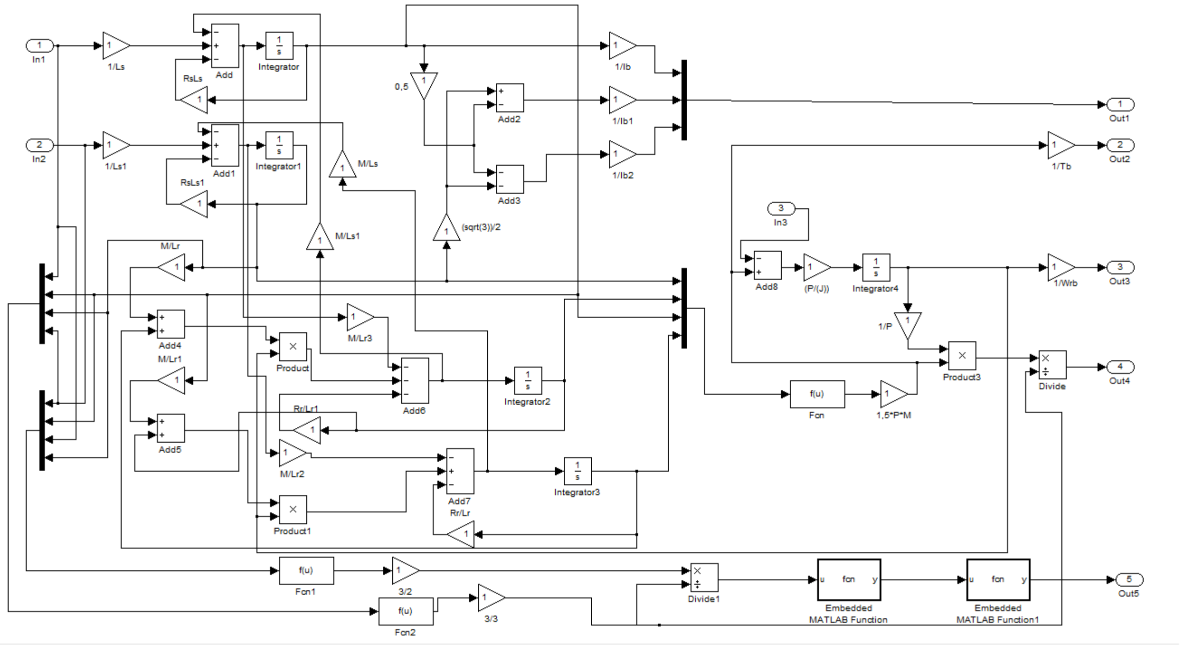

Figure 4.1: Block diagram(1) for the induction motor model in MATLAB as a subsystem.

4.2 Cases study:

There are two methods were applied:

4.2.1 Direct starting method:

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

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). The (subsystem) icon is dragged into the opened model and then double-clicked.

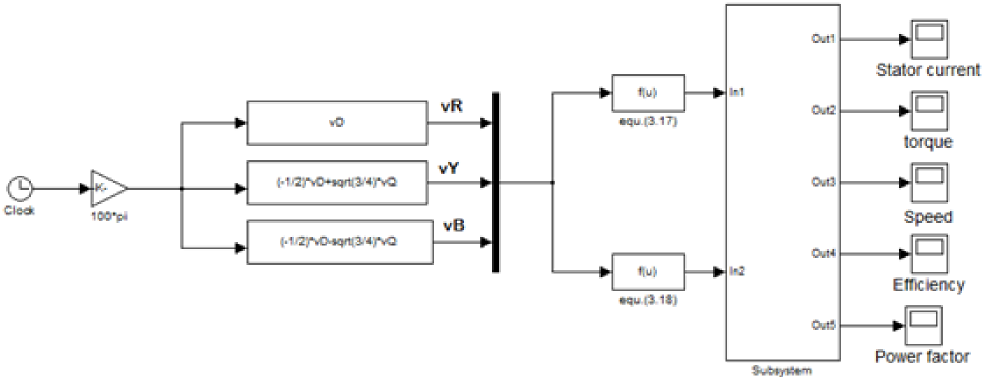

Figure 4.2: Block diagram(2) for the induction motor model in MATLAB as a subsystem.

Case1: Direct starting curves in the No-load case:

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

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 stationary. Stationary is reached when the speed curve reaches a certain value and gets steady. For example, in figure (4.2) the speed reaches stationary at about (0.4 sec).

Table 4.2: Direct starting of nominal load test result:

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

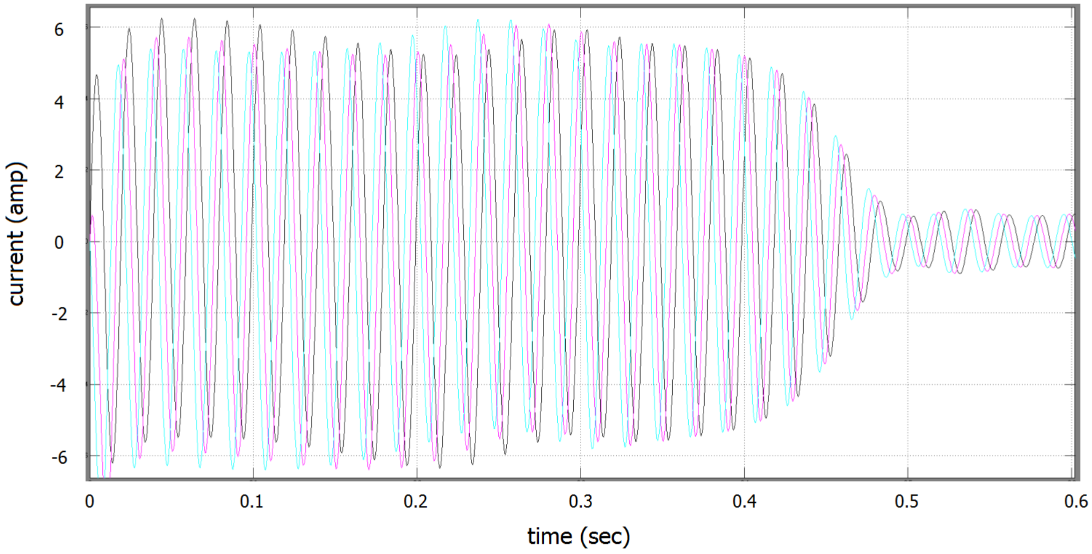

Figure (4.3): Starting currents curves in the Direct starting No-load.

Figure (4.3) shows the relationship between currents and time, so we observe a value of starting currents arrive to 6.3 pu for 0.4 second.

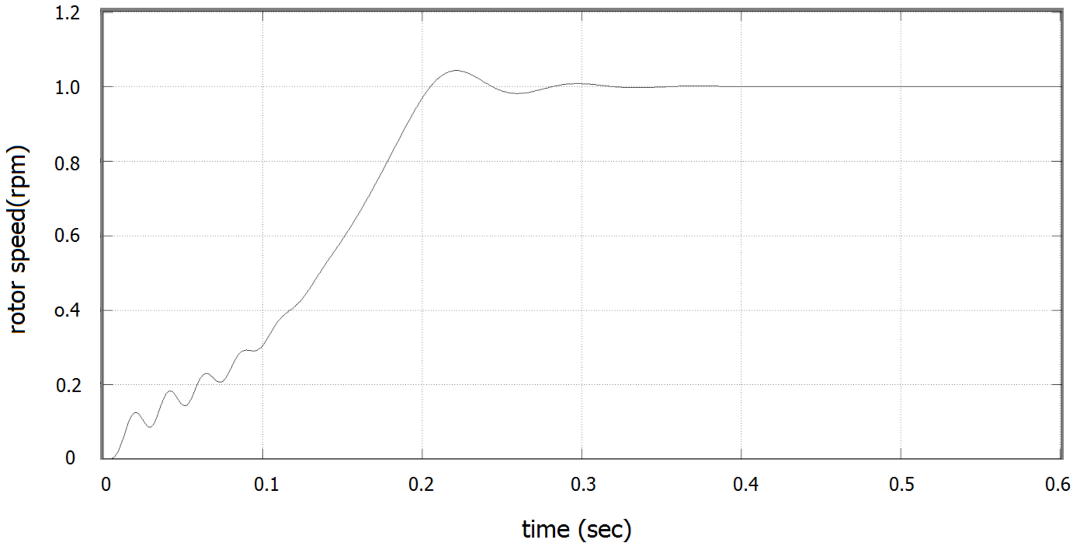

Figure (4.4): Speed curve in the Direct starting No-load.

Figure (4.4) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1.05 pu and it stables at 1 pu at 0.4 second.

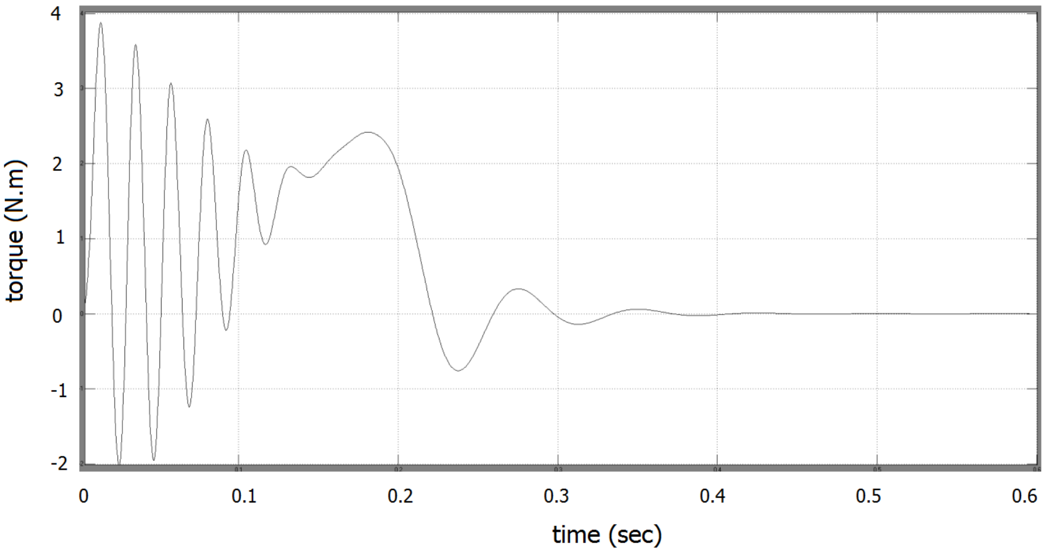

Figure (4.5): Starting torque curve in the Direct starting No-load.

Figure (4.5) shows the relationship between torque and time, so we observe a value of starting torque arrive to 3.8 pu and it decrease to arrive 0 pu at 0.4 second.

Case2: 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.

Table 4.3: Direct starting of 75% load test result:

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

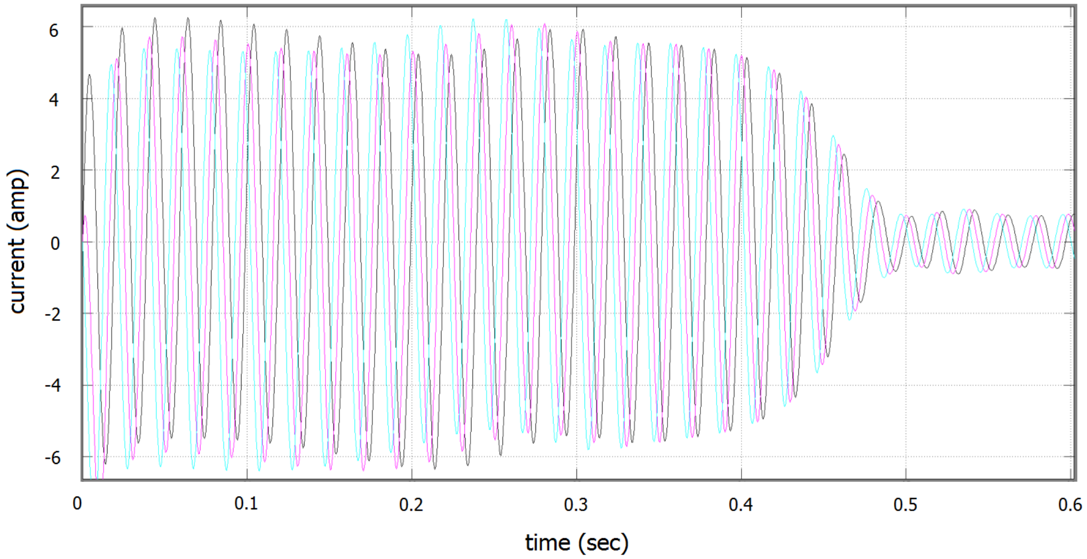

Figure (4.6): Starting currents curves in the Direct starting 75% of the load.

Figure (4.6) shows the relationship between currents and time, so we observe a value of starting currents arrive to 6.1 pu for 0.6 second.

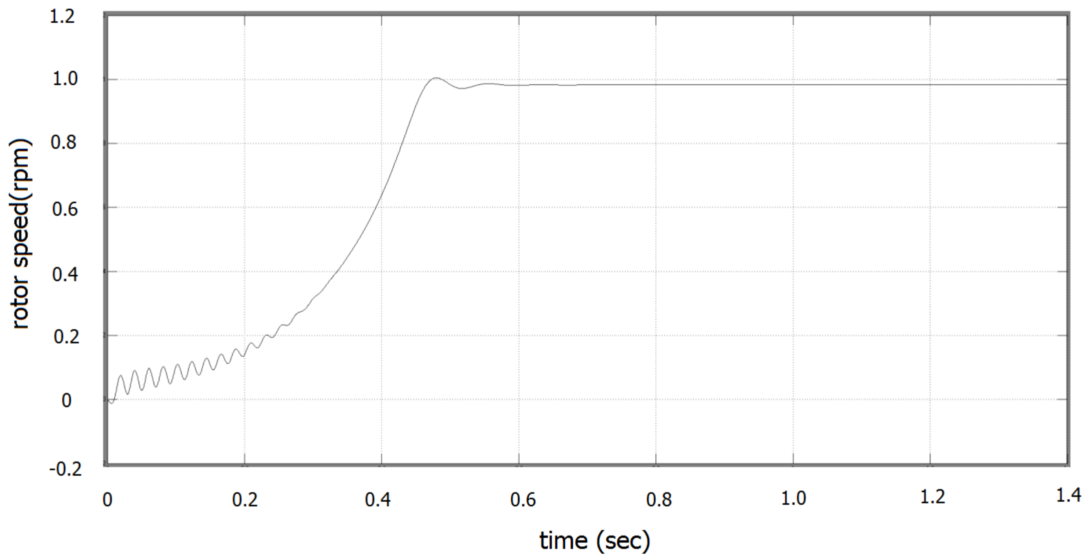

Figure (4.7): Speed curve in the Direct starting 75% of the load.

Figure (4.7) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1 pu and it stables at 0.98 pu at 0.6 second.

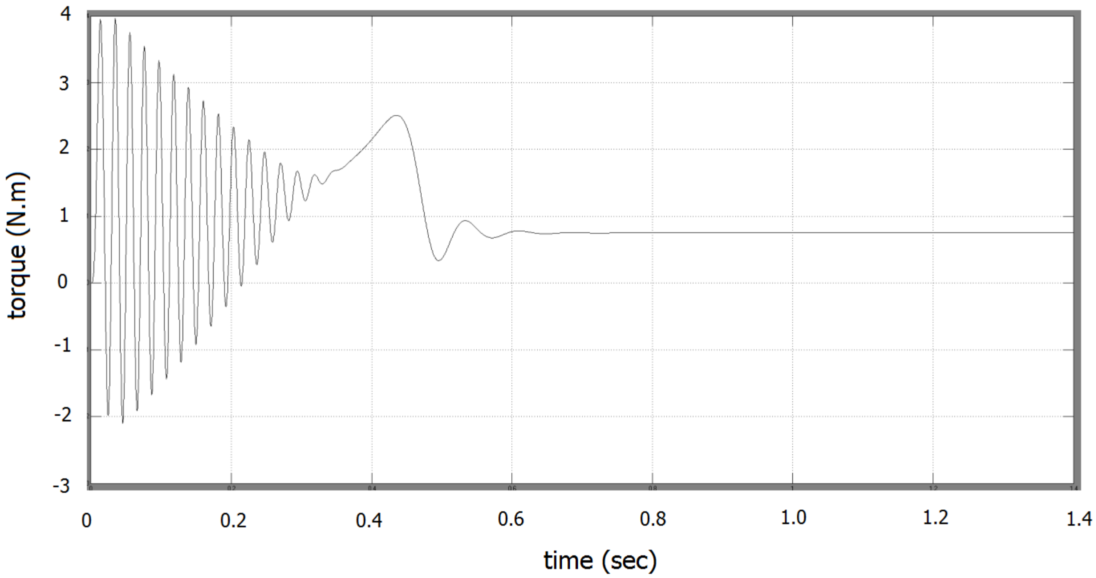

Figure (4.8): Starting torque curve in the Direct starting 75% of the load.

Figure (4.8) shows the relationship between torque and time, so we observe a value of starting torque arrive to 3.95 pu and it decrease to arrive 0 pu at 0.6 second.

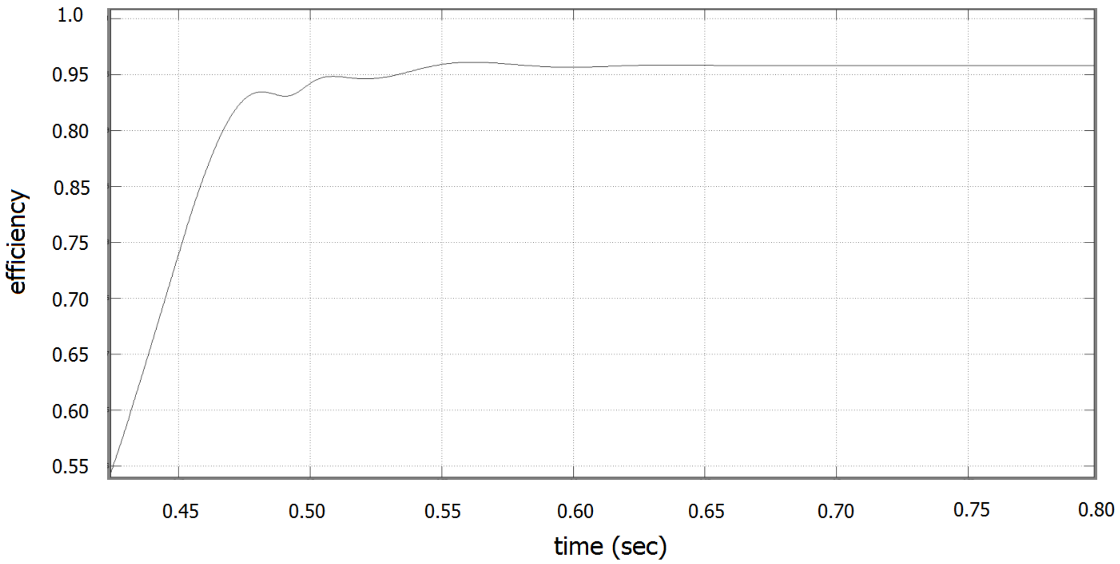

Figure (4.9): Efficiency curve in the Direct starting 75% of the load.

Figure (4.9) shows the relationship between efficiency and time, so we observe the efficiency increase from 0.54 at 0.40 second to 0.96 at 0.65 second.

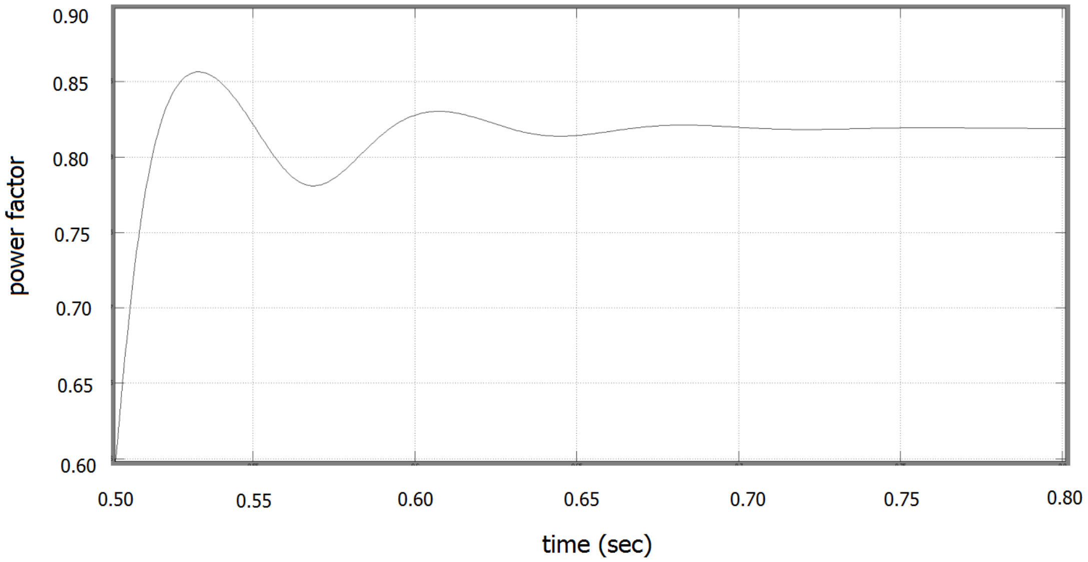

Figure (4.10): Power factor curve in the Direct starting 75% of the load.

Figure (4.10) shows the relationship between power factor and time, so we observe the power factor is increase from 0.60 at 0.50 second to arrive the maximum value of it at 0.86 at 0.53 second and it stable at 0.82 at 0.75 second.

Case3: 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.

Table 4.4: Direct starting of nominal load test result:

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

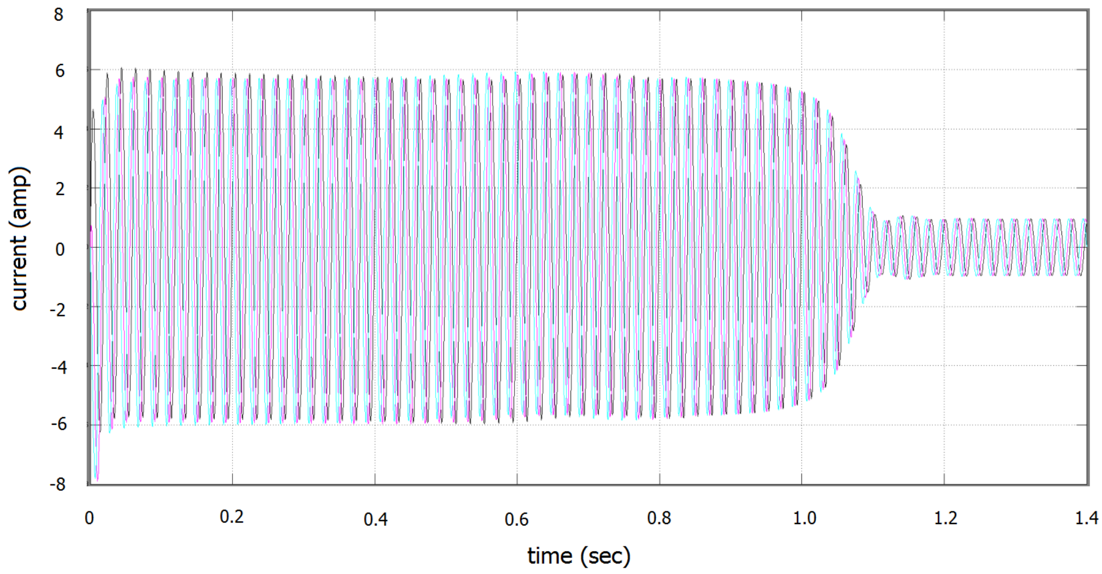

Figure (4.11): Starting currents curves in the Direct starting nominal load.

Figure (4.11) shows the relationship between currents and time, so we observe a value of starting currents arrive to 6 pu for 1.2 second.

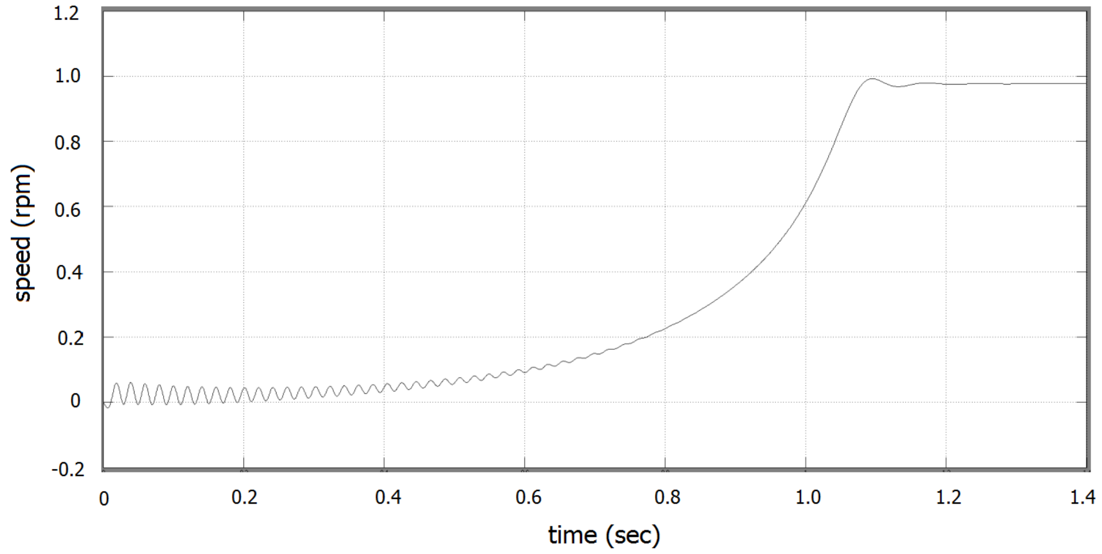

Figure (4.12): Speed curve in the Direct starting nominal load.

Figure (4.12) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1 pu and it stables at 0.98 pu at 1.2 second.

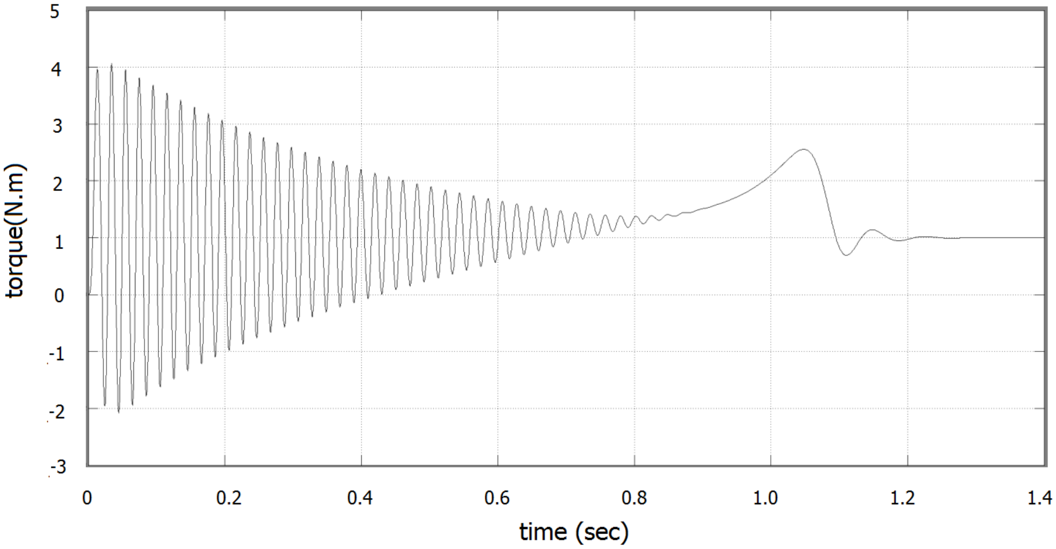

Figure (4.13): Starting torque curve in the Direct starting nominal load.

Figure (4.13) shows the relationship between torque and time, so we observe a value of starting torque arrive to 4.1 pu and it decrease to arrive 0 pu at 1.2 second.

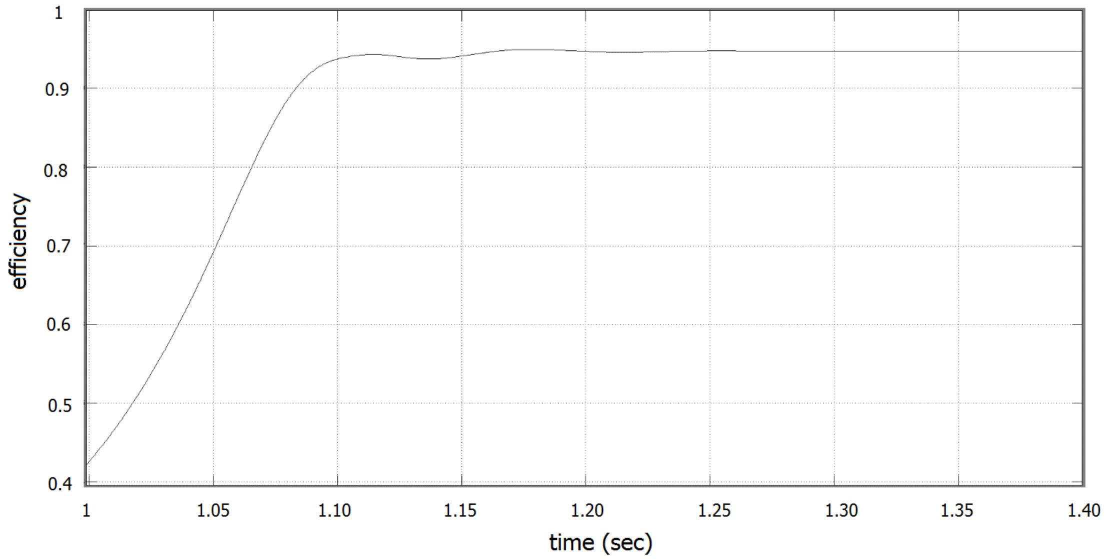

Figure (4.14): Efficiency curve in the Direct starting nominal load.

Figure (4.14) shows the relationship between efficiency and time, so we observe the efficiency increase from 0.42 at 1 second to 0.95 at 1.2 second.

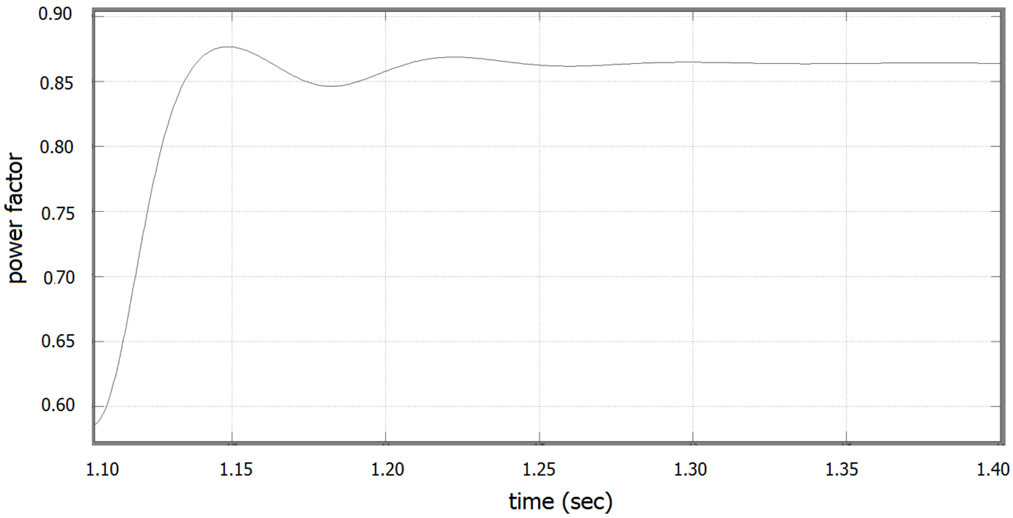

Figure (4.15): Power factor curve in the Direct starting nominal load

Figure (4.15) shows the relationship between power factor and time, so we observe the power factor is increase from 0.57 at 1.1 second to arrive the maximum value of it at 0.87 at 1.14 second and it stable at 0.86 at 1.2 second.

4.2.2 Soft starting 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.

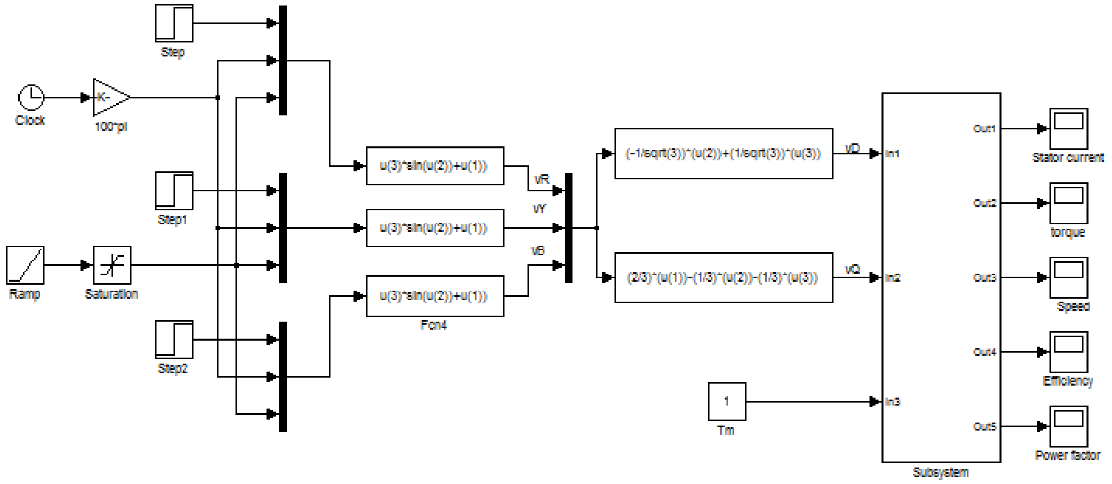

Figure 4.16: Block diagram(3) for the induction motor model of Soft starting**.**

Case1: Soft starting curves in the nominal load case:

The starting voltage is set to 200V using the Ramp icon shown in figure (4.):

Table 4.5: Soft starting of nominal load test result:

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

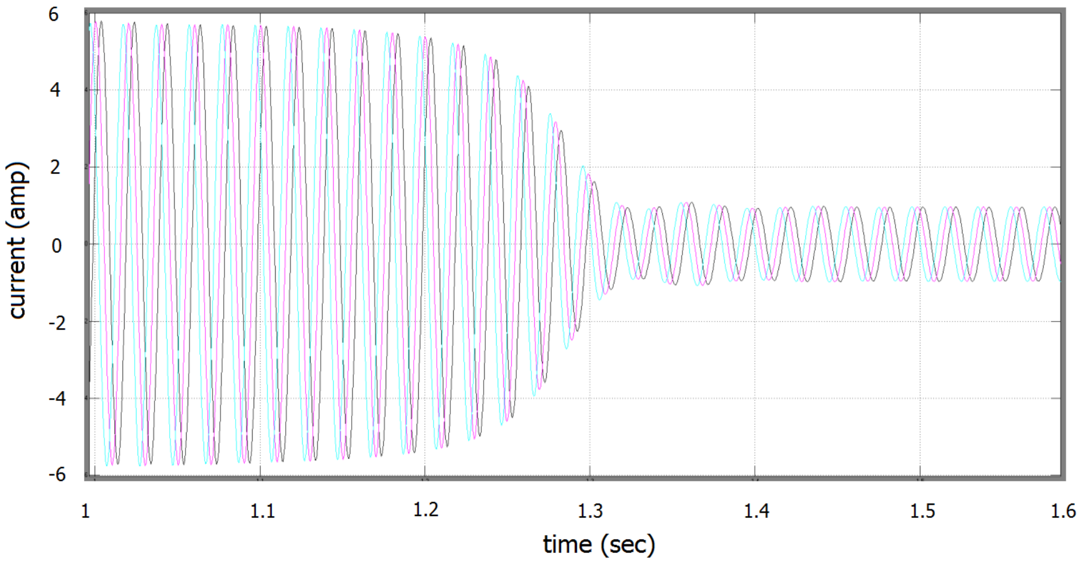

Figure (4.17): Starting currents curves in the Soft starting nominal load.

Figure (4.17) shows the relationship between currents and time, so we observe a value of starting currents arrive to 5.9 pu for 1.45 second.

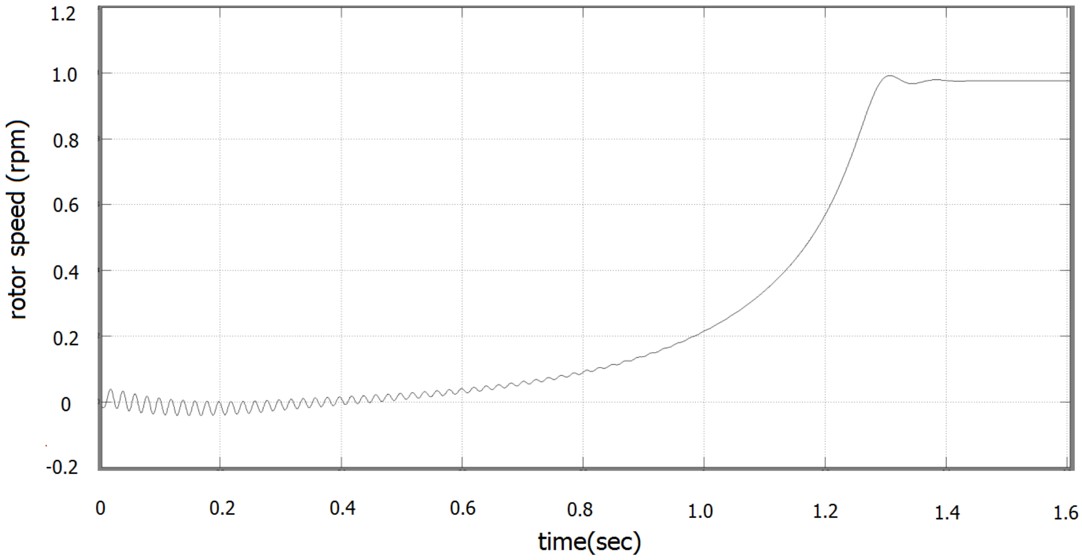

Figure (4.18): Speed curve in the Soft starting nominal load.

Figure (4.18) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1 pu and it stables at 0.98 pu at 1.45 second.

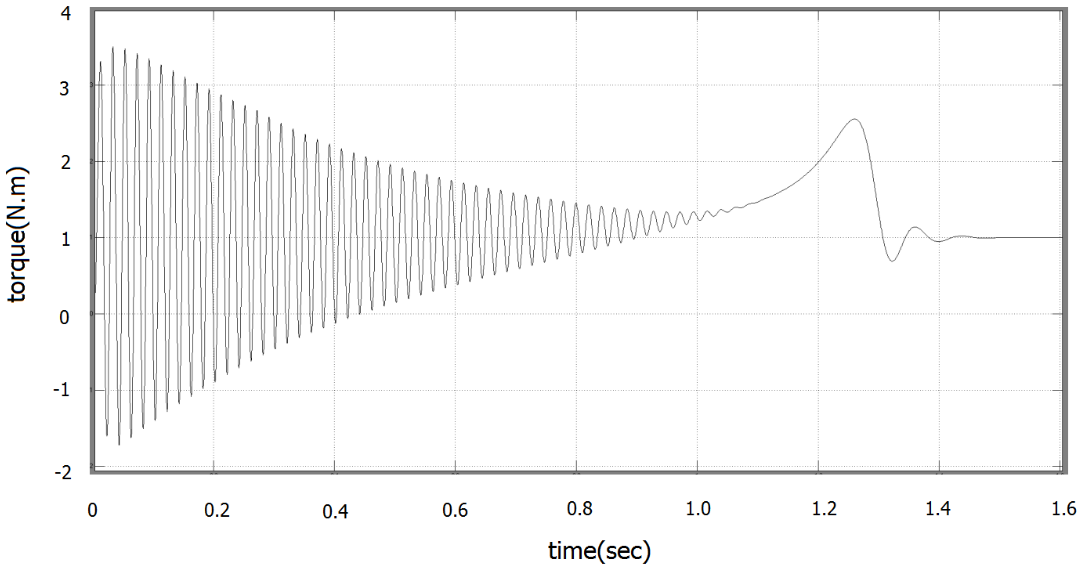

Figure (4.19): Starting torque curve in the Soft starting nominal load.

Figure (4.19) shows the relationship between torque and time, so we observe a value of starting torque arrive to 3.45 pu and it decrease to arrive 0 pu at 1.45 second.

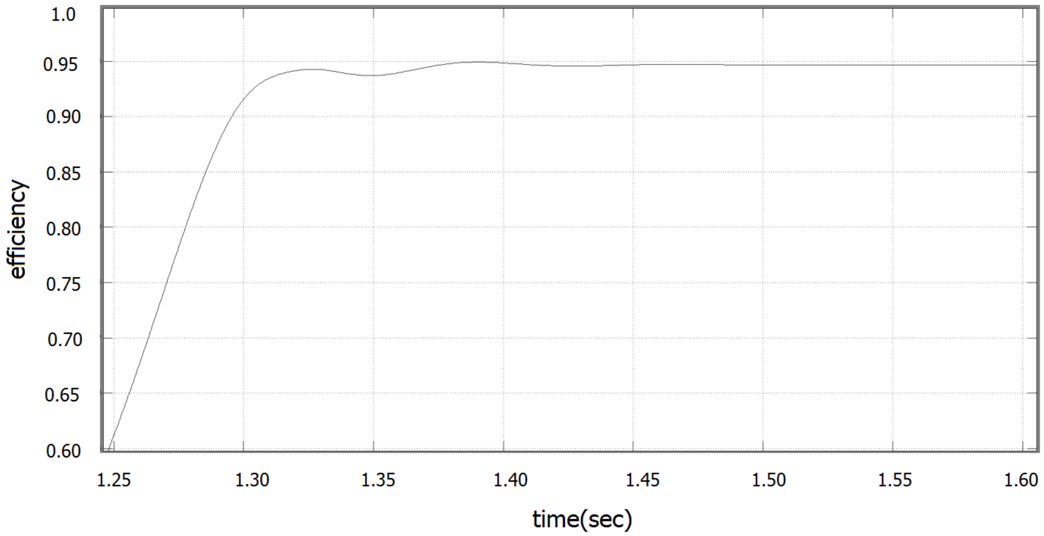

Figure (4.20): Efficiency curve in the Soft starting nominal load.

Figure (4.20) shows the relationship between efficiency and time, so we observe the efficiency increase from 0.6 at 1.25 second to 0.95 at 1.45 second.

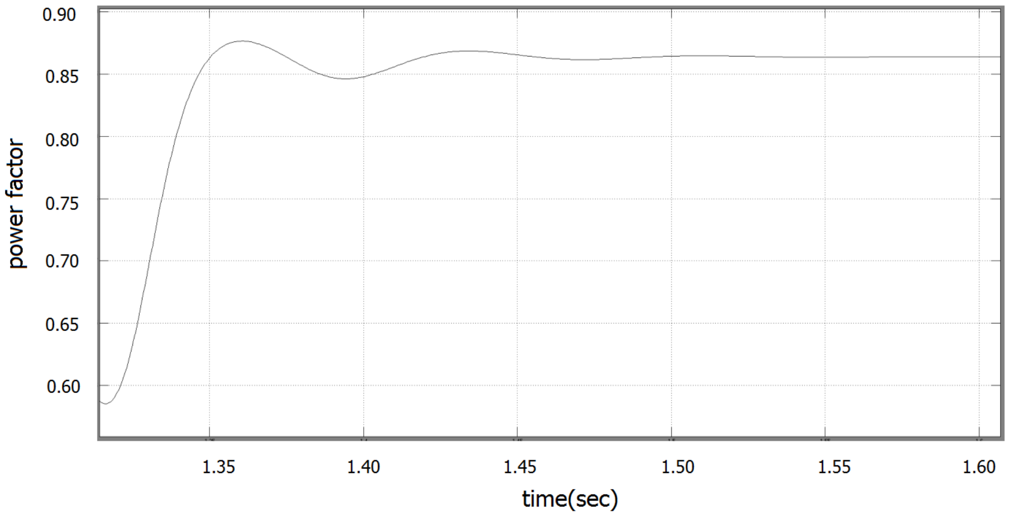

Figure 4.21: Power factor curve in the Soft starting nominal load.

Figure (4.21) shows the relationship between power factor and time, so we observe the power factor is increase from 0.57 at 1.3 second to arrive the maximum value of it at 0.87 at 1.36 second and it stable at 0.86 at 1.45 second.

Case2: Soft starting curves in the 75% of nominal load case:

The starting voltage is set to 170V using the Ramp icon shown in figure (ii) in appendix.

Table 4.6: Soft starting of 75% load test result:

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

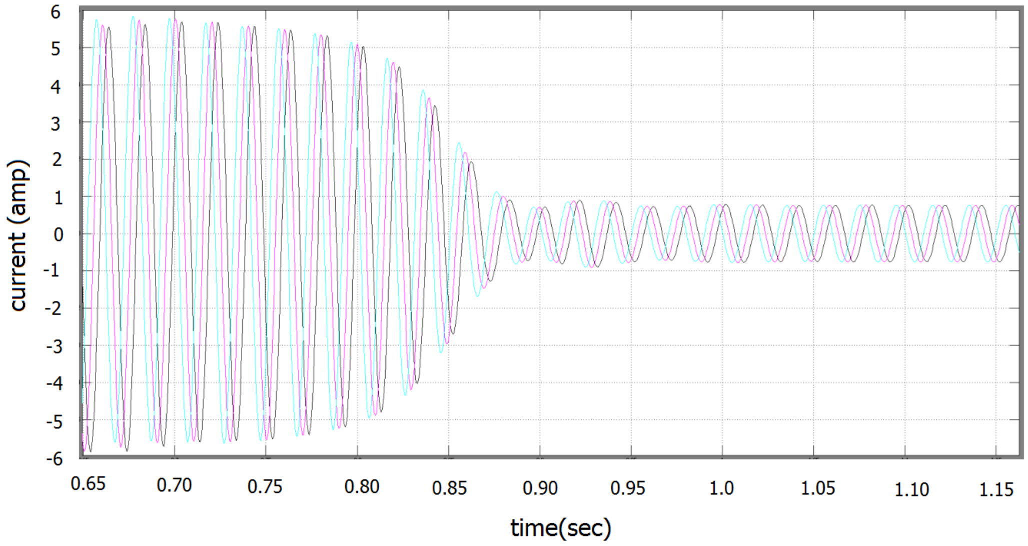

Figure (4.22): Starting currents curves in the Soft starting 75% of the load.

Figure (4.22) shows the relationship between currents and time, so we observe a value of starting currents arrive to 5.8 pu for 1.15 second.

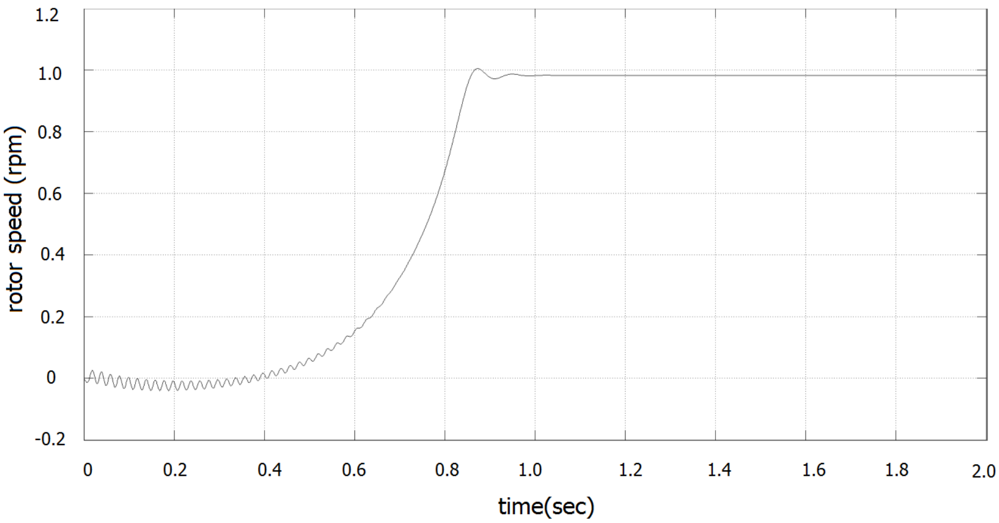

Figure (4.23): Speed curve in the Soft starting 75% of the load.

Figure (4.23) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1 pu and it stables at 0.98 pu at 1.15 second.

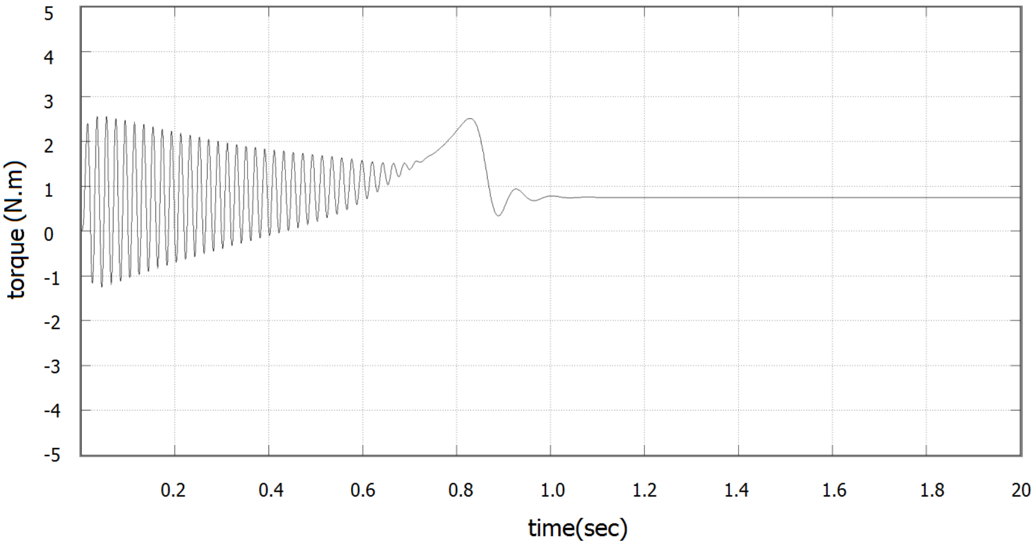

Figure (4.24): Starting torque curve in the Soft starting 75% of the load.

Figure (4.24) shows the relationship between torque and time, so we observe a value of starting torque arrive to 2.6 pu and it decrease to arrive 0 pu at 1.15 second.

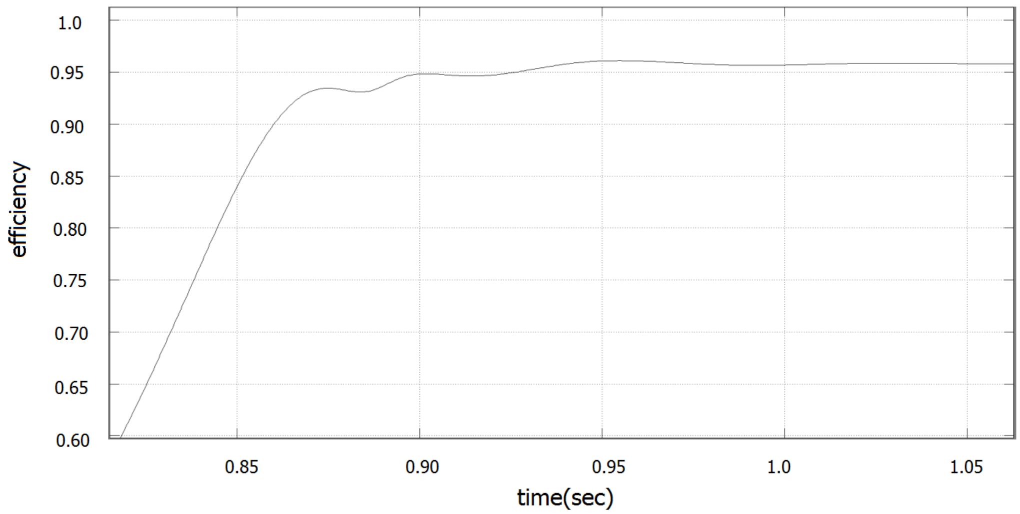

Figure (4.25): Efficiency curve in the Soft starting 75% of the load.

Figure (4.25) shows the relationship between efficiency and time, so we observe the efficiency increase from 0.6 at 0.81 second to 0.96 at 1.15 second.

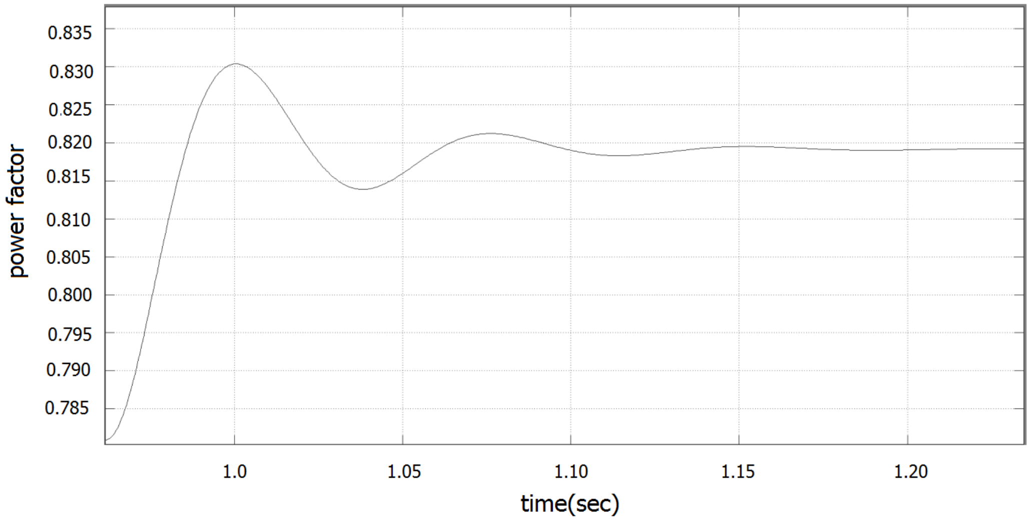

Figure (4.26): Power factor curves in the Soft starting 75% of the load.

Figure (4.26) shows the relationship between power factor and time, so we observe the power factor is increase from 0.78 at 0.95 second to arrive the maximum value of it at 0.83 at 1.36 second and it stable at 0.82 at 1.15 second.

Case3: Soft starting curves in the 50% of nominal load case:

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

Table 4.7: Soft starting of 50% load test result:

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

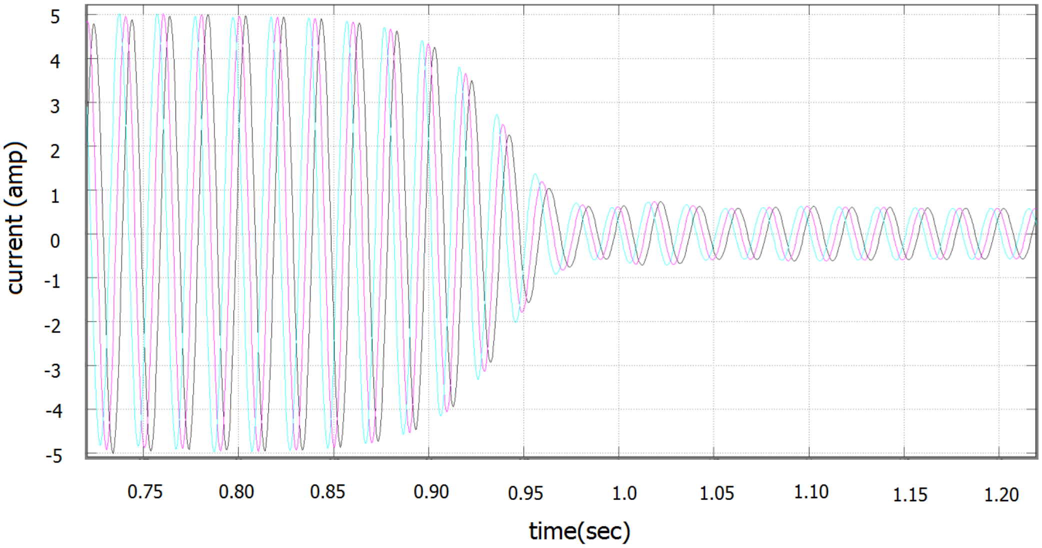

Figure (4.27): Starting currents curves in the Soft starting 50% of the load.

Figure (4.27) shows the relationship between currents and time, so we observe a value of starting currents arrive to 5 pu for 1.22 second.

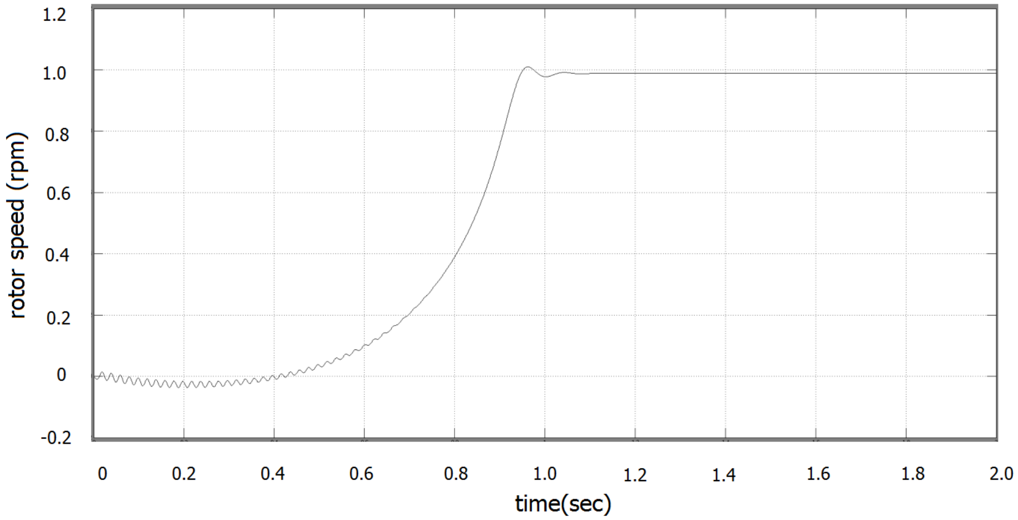

Figure (4.28): Speed curve in the Soft starting 50% of the load.

Figure (4.28) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1 pu and it stables at 0.98 pu at 1.22 second.

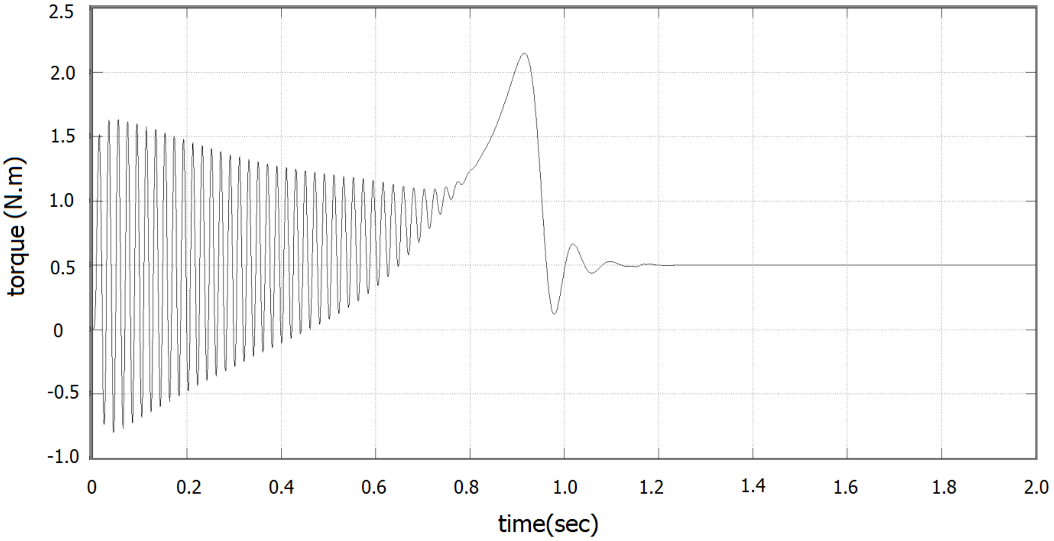

Figure (4.29): Starting torque curve in the Soft starting 50% of the load.

Figure (4.29) shows the relationship between torque and time, so we observe a value of starting torque arrive to 1.6 pu and it decrease to arrive 0.5 pu at 1.22 second.

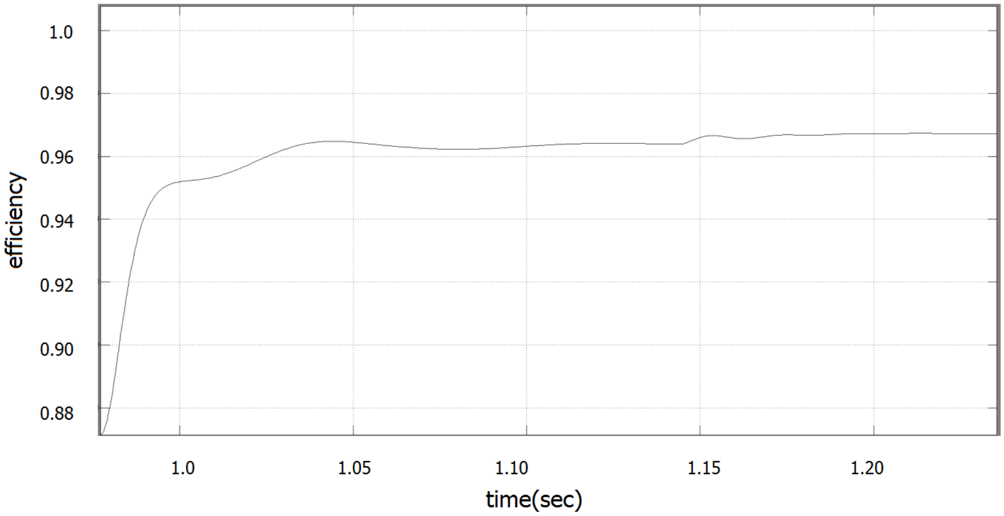

Figure (4.30): Efficiency curve in the Soft starting 50% of the load.

Figure (4.30) shows the relationship between efficiency and time, so we observe the efficiency increase from 0.85 at 0.97 second to 0.97 at 1.22 second.

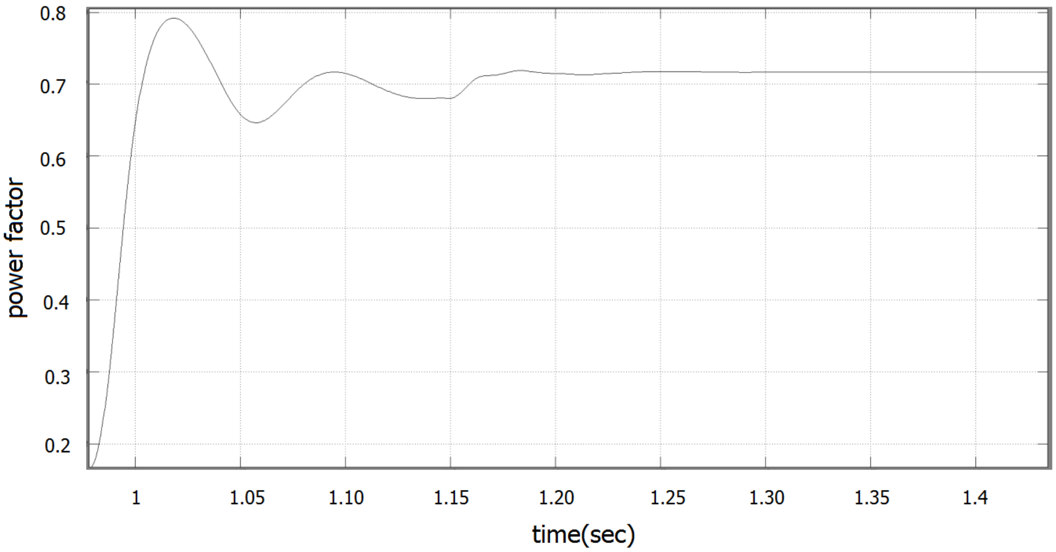

Figure (4.31): Power factor curve in the Soft starting 50% of the load.

Figure (4.31) shows the relationship between power factor and time, so we observe the power factor is increase from 0.18 at 0.97 second to arrive the maximum value of it at 0.79 at 1.02 second and it stable at 0.72 at 1.22 second.

Case4: Soft starting curves in the 25% of nominal load case:

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

Table 4.8: Soft starting of 25% load test result:

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

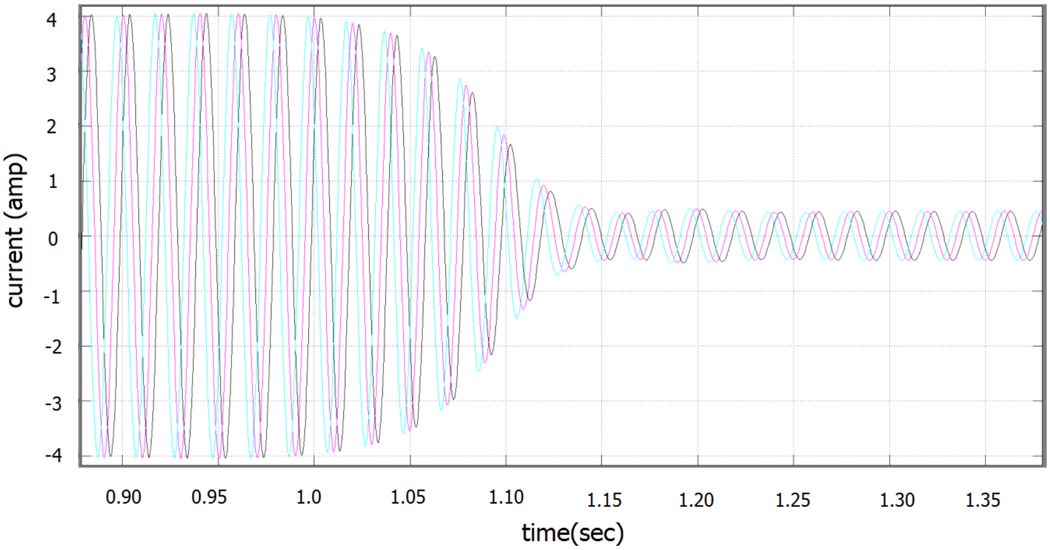

Figure (4.32): Starting currents curves in the Soft starting 25% of the load.

Figure (4.32) shows the relationship between currents and time, so we observe a value of starting currents arrive to 4 pu for 1.3 second.

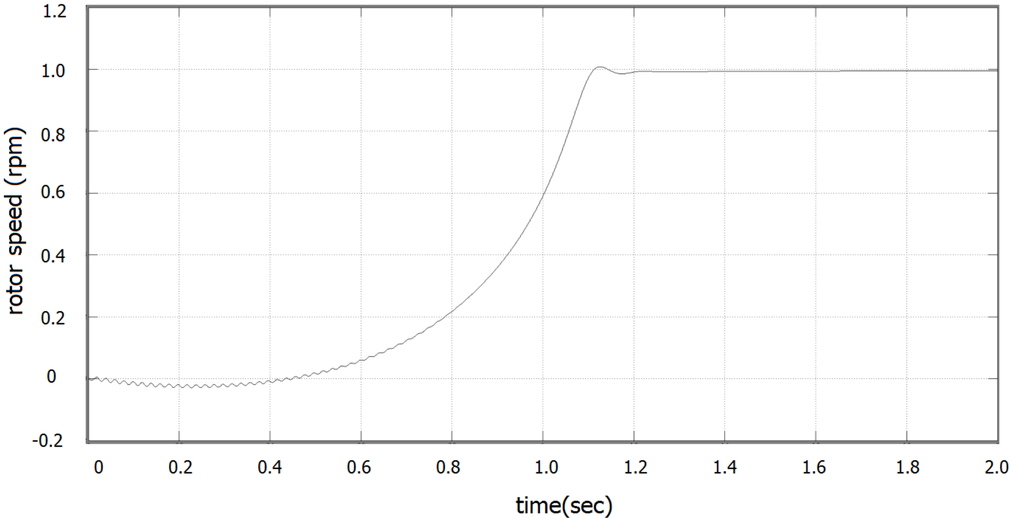

Figure (4.33): Speed curve in the Soft starting 25% of the load.

Figure (4.33) shows the relationship between speed and time, so we observe the value of speed is increase from 0 to 1 pu and it stables at 0.98 pu at 1.3 second.

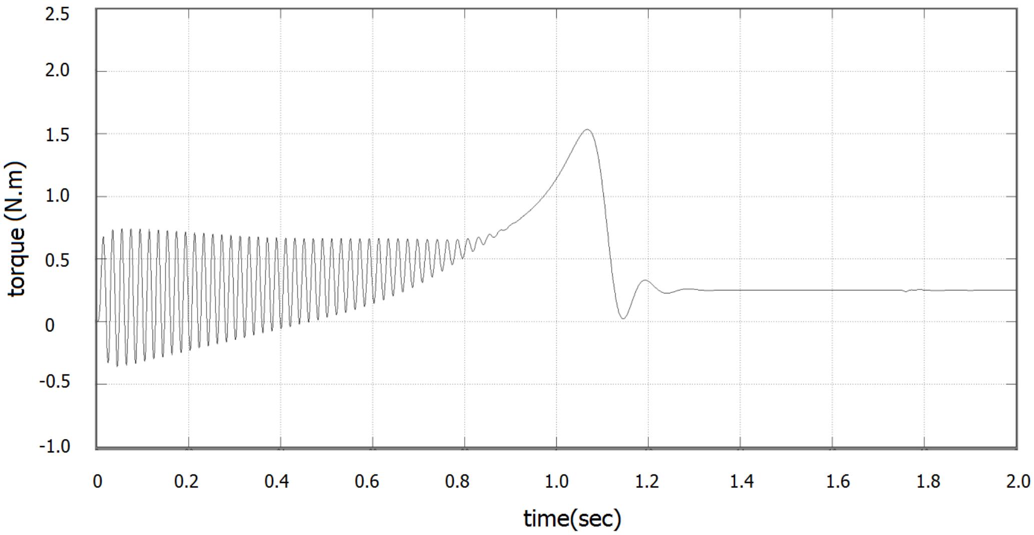

Figure (4.34): Starting torque curve in the Soft starting 25% of the load.

Figure (4.34) shows the relationship between torque and time, so we observe a value of starting torque arrive to 0.75 pu and it decrease to arrive 0.25 pu at 1.3 second.

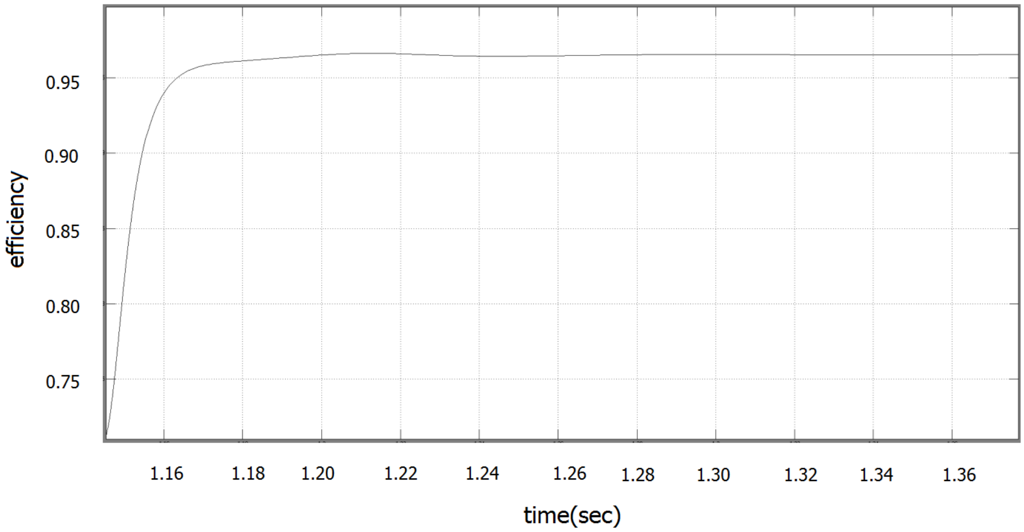

Figure (4.35): Efficiency curve in the Soft starting 25% of the load.

Figure (4.35) shows the relationship between efficiency and time, so we observe the efficiency increase from 0.70 at 1.14 second to 0.97 at 1.3 second.

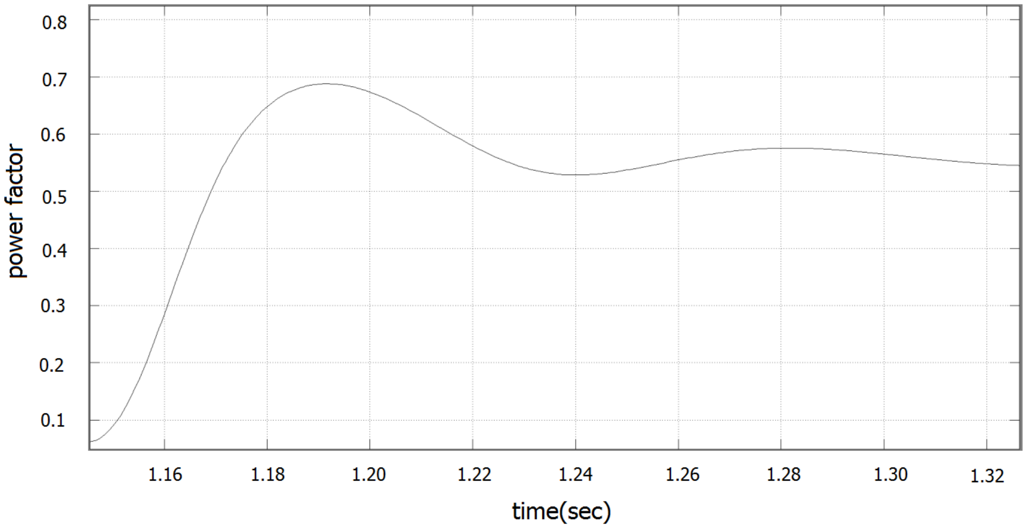

Figure (4.36): Power factor curve in the Soft starting 25% of the load.

Figure (4.36) shows the relationship between power factor and time, so we observe the power factor is increase from 0.06 at 1.14 second to arrive the maximum value of it at 0.68 at 1.19 second and it stable at 0.55 at 1.3 second.

-Direct starting results:

Table (4.9) 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 stationary.

Table (4.9): Comparison of direct starting results:

T load (%)	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

- Soft starting results:

Table (4.10) shows that when increasing the load torque the starting current increases along with the starting torque, whereas the stationary time is changing but not in a certain pattern.

Table (4.10): Comparison of soft starting results:

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

- Discussion:

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 stationary. 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.

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.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion:

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 three phase 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.

Based on this analysis we found the efficiency and 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 transient state.

5.2 Recommendations:

Study transient state of a three phase induction motor during faulty(short circuit), restudy the dynamic performance of three phase induction motor in case of one phase failure, and we advise to apply SIMULINK on other electrical machine.

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