Addis Ababa University

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School of Electrical and Computer Engineering

Multi-Phase Induction Motor For Electric Vehicle

A Thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Electrical and Computer Engineering (Control Engineering)

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Abstract

This thesis is presents a multiphase induction motor for electric vehicle, designing of m-phase machine at which constant current and power condition by varying number of phase that increases from single phase to m-phase unto the minimum value of slot size ends. So these paper presents have two major section to fit full operational characteristic m-phase induction for electric vehicle those section are includes designing of induction motor that evaluate the minimum value of slot size and m-phase induction motor modelling for proper control ; then model is based on generalized d-q model of n phase induction motor drive. Multi -phase induction motor (more than three phases) drives possess several advantages over conventional three-phase drives, such as reduced the number of battery needed for supply, reducing the accident due to the sudden condition crashing of car, minimizing of the load on car in cases of minimizing the number battery supply, lower torque pulsation, higher torque density, fault tolerance, stability, high efficiency and lower current ripple. In this paper, a generalize d–*q* axis model is developed in Matlab/Simulink for an m-phase induction motor. The simulation results are presented for 3,5,9 and 12 phase induction motor under constant current and power conditions by varying phase and analyzing the phase voltage .

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Chapter 1

1. Introduction

At 1960 there is a problem on convectional three phase machine in case of low frequency, torque ripples due to the six step operation inverters, so in order to overcome this problem developing multiphase machine is the one way of solution lowest frequency torque ripple harmonic in the n phase machine is caused by time harmonics in the supply of the order 2n+1.

Multiphase motor drives have attracted, [1].However, during the next 20 years limited attention. [2] The pace started accelerating during the 1990s, but it was not until the beginning of this century that the multiphase motor drives have become a focus of a substantial worldwide attention within the drives research community. This has predominantly resulted from developments in three very specific application areas, namely electric ship propulsion, traction (including electric and hybrid electric vehicles) and the concept of 'more-electric' aircraft.

The major problem arises convectional motor is their speed control as it is complicated in industrial drive applications. However, with the advent of cheap and fast switching power electronics devices not only the control of induction machine became easier and flexible but also the number of phases of machine became a design parameter [3]

Due to the importance of induction motors, new strategies and configurations of design are being sought that are capable of improving efficiency. Another problem was the need to increase the efficiency and reduce the energy consumption. The use of a common magnetic structure shared by two sets of stator windings is not new but dated back to 1930, where in an attempt to increase the power capability of a large synchronous generator, the stator winding has to be doubled. From that time to date, research activities in this area, has receive much attention.

One of the advantages of a multiphase motor drive over a three-phase motor drive is the improved reliability. The reliability and overall performance of multiphase machine is investigated and the result showed that multiphase machine has a lot of benefits compared to the conventional machine Multiphase machines are perceived to offer many advantages such as improved magnetomotive force (MMF) waveforms, reduced line voltages and increased efficiencies. The consequential benefits of these are reduced torque pulsations, lower losses, reduced acoustic noise and reduced power ratings of supply converters.

Due to the development of the power electronics the control induction machine become easier. So modeling of multiphase induction machine is preferable than conventional three phase machine in case of above mention, For the long period of time DC machine dominant but now a time because of the development of power electronics IM is selected, when the machine is not directly fed from standard power sources, there is no need for specified number of phases. Higher numbers of phases are more advantageous. Multiphase machine has several advantages over the conventional three phase motor such as reduced torque pulsation, reduced per phase rotor harmonic current, high reliability and high fault tolerance

[4] for the first time in 1969 have presented the preliminary investigation on inverter fed five phase induction motor and suggested that the amplitude of the torque pulsation can be reduced by increasing the number of phases.(these too look for inverter development) Derivation of the voltage equations in phase variables and the transformation to the d–q–o reference frame of a multi-phase machine with unsymmetrical phase displacement has been reported by [5],

1.2 Problem Statement

Conventional three phase induction machines are needs high voltage supply ,but high voltage source is not recommended for electric vehicle for different reason,

- If we use high voltage (conventional three phase induction motor)
    - ✓ it needs much energy used
    - ✓ it needs many number of DC- battery source
    - ✓ high mechanical load on car ,in case of using many DC-battery
    - ✓ easy to kills the passengers in case of shocking during sudden accident occur

in order to overcome the above problem designing of multiphase induction motor at which constant phase current and power ,by increasing the number phase ; consequently, source voltage is decreasing with the same size machine design of the conventional three phase ….. therefore selecting of multiphase induction machine preferable for those solving problem coming due to high voltage and minimizing the load battery on the car, also designing & modelling of multi-phase induction machines are many advantageous in addition to the objective of this thesis, those advantageous are:- reduced current/phase without increasing voltage/phase, lower torque pulsation, higher torque density, fault tolerance, stability, high efficiency and lower current so these thesis is to solving the problem coming due to high voltage and much number of battery use by selecting the appropriate phase of induction motor for electric vehicle at same current and power rates at low voltage, with the same physical size of motor of conventional three phase induction motor ,consequently decreasing the voltage needs for n-phase induction machine supply that case for minimizing the number battery source that loaded on the vehicle as increasing the number phase motor until it's optimality of slots size respect to the size motor as phase increases

1.3 Objectives

1.3.1 General Objective:

The thesis work is aimed at:

- Selection of induction motor with number of phases for electric vehicle application and modeling for proper control.

1.3.2 Specific Objectives:

- Selecting number of phases with respect to the performance parameter of electric vehicle.
- Physical quantities of limitation of multi-phase induction machine
- Modeling design control.

1.4 Methodology

The work to be carried out in this thesis design and modelling of multi-phase induction motor , at the condition of constant phase-current and power and also the operational characteristics of induction machine modelled for electric vehicle application . In order to achieve the design and modelling validate the model results, the following steps are followed:

- ✓ Carry out a review of available machine technologies in the market suitable for application designing of induction machine for electric vehicle.
- ✓ Carry out a design review and analysis of an existing induction machine, to determine whether the performance can be improved for the given space limitation, also carry out a fault tolerant review of the Protean machine.
- ✓ Design modification, design producer and mathematical calculation to fit the final limitation of minimum slot site ; where the phase machine increase at constant current and power, to improve the whereas the voltage per phase decreases needed for supply to induction machine for the same machine radius; this was achieved by carrying out an electromagnetic evaluation, stator and rotor design for each parameter needed

- ✓ Modelling induction motor and analyzing result of multiphase induction motor proper for electric vehicle to validate the model results; the modelled multi-phase induction motor that full fill the characteristics of induction machine property involved exploring a method to improve fill factor and full scale testing at various operating conditions

1.5 Literature Review

In this chapter an up-to-date survey of the current state of multiphase induction motor design for electric vehicle (EV) is presented. The requirements the EV poses on multi-phase motor design and modelling for proper control the different motor design with different concepts used in the drive train are considered. The aim of this thesis is designing of multiphase induction motor for electric vehicle at constant power and current phase as increasing the number of phase until the minimum slot size, so depending our survey multiphase induction motor was designed but it had not considering the high supply voltage influence on passenger when the time of sudden accident and load battery on the vehicle minimization ; therefore ,this paper s overcoming this problem , by considering the input power and current makes constant by varying the number phases. As result of increasing the number phases the voltage will be decreases at the condition of current and power.

1.5.1 Background

1.5.1.1 Brief Constructional Details of Induction Motor

A multi- phase induction motor have two major parts, the stator and the rotor. The construction of each one is basically a laminated core provided with slots which house windings. When one of the windings is exited with AC voltage, a rotating field is set up. This field produces an emf (Electromotive Force) in the other winding by transformer action which in turn circulates current in the later if it is short circuited. The currents flowing in the second winding interact with the field produced by the first winding there by producing a torque which is responsible for the rotation of the rotor.

Basically a three phase Induction motor consists of stator and rotor. The Induction motor is invented by Great scientist Nikol Tesla.

A set of insulated electrical windings are placed inside the slots of the laminated magnetic path in stator. The cross-sectional area of these windings must be large enough for the power rating of the motor. For a 3-phase motor, 3 sets of windings are required, one for each phase and also the same as m-phase motor, sets m- sets of winding is required.

As with the stator, the rotor consists of a set of slotted steel laminations pressed together in the form of a cylindrical magnetic path and the electrical circuit. There are two types of motor rotors: The wound rotor and Squirrel cage rotor. Because of the ease of winding, Squirrel cage induction motor is designed. [6]

1.5.1.2 Actual Design of Prototype M- Phase Induction Motor

To begin with, m-phase symmetrical induction machine, such that the spatial displacement between any two consecutive stator phases equals $\alpha = 2\pi/m$, is considered. Stator winding is treated as m–phase and it is assumed that the windings are sinusoidally distributed, so that all higher spatial harmonics of the magneto-motive force can be neglected. The phase number m can be either odd or even.

When the number of phases is six, i.e. m = 6, there are two, three phase windings. The two, three phase windings are displaced by 60^0 in symmetrical design but there is a problem of magnetic circulating currents.

So asymmetrical design is implemented in which two, three phase windings are displaced by 30^0, which eliminates (6n + 1) order harmonics, where n = 1,3,5…. [7]

A six phase machine can be easily constructed by splitting the 60^0 phase belt into two portions each spanning 30^0.The winding distribution factor increases from 0.965 for three phase to 1.0 for six phase for split phase belt connection.[8] A true six phase that retains the same winding pitch and distribution factor is shown in the table1 below.

Table 1:- A true m- phase that retains the same winding pitch and distribution factor

PHASE BELT ANGLE DEGREES (β)	120	60	60	40	30
NUMBER OF PHASE BELT PER POLE(q)	1.5	3	3	4.5	6
NUMBER OF STATOR TERMINALS (MINIMUM)	3	3	6	9	6
CONNECTION NAME	THREE PHASE	SEMI SIX PHASE	SIX PHASE	NINE PHASE	SIX PHASE
SCHEMATIC DIAGRAM OF STAR CONNECTION & VOLTAGE PHASOR DIAG—RAM (MESH CONNECTION MAY BE USED ALSO)					

1.5.2 Electric vehicles, past and present

The electric motor came into existence before the internal combustion engine, which means electric vehicles were around before ICE vehicles, however they started to decline during the oil boom when cheap gasoline was readily available [9]. ‘’The first battery powered electric vehicle was built in 1834 by Thomas Davenport, in 1838 Robert Davidson built the first battery powered locomotive and in the late 1800s and early 1900s electric vehicles started being manufactured in volumes ‘’, however, in these research can’t considering the voltage supply respect to the influence on passenger in the car and also the researcher was not includes the number of battery so these paper can solve those problems. Designing multiphase induction motor can overcome what the last researcher weakness were done [9].

The prevailing challenge faced by the EV has always been the battery, as the drive range of the EV is limited by its capacity. However there has been tremendous improvement in the motor design and electronic controllers since the start of the electric vehicle in the 1800s. As electric vehicles couldn’t compete with the ICE vehicles due to a limited drive range, they had to be employed more in low speed vehicles (LSVs) or neighborhood electric vehicles (NEVs) for use within inner cities, battery-powered for klifts and golf carts [9] etc.

In the last decade more focus has been put into the research and development of electric vehicles, since the drive for a cleaner source of energy as a means of propulsion was revived. The challenges most researchers face since reinitiating the design and manufacture of electric vehicles have been on improving the drive range and speed of the electric vehicle.

The 21st century has seen a huge development in electric vehicle manufacture, as improvement in power electronics and advancement of lithium-ion batteries came to play a major role in the development of electric vehicles. Most vehicle manufacturers have come up with electric vehicles: some of these vehicles are already in production and distributed for consumer use,

so this thesis is improving three main problems that occur for the last researcher 1) they are not considering the effect of the high supply voltage on passenger during the sudden accident occurrence 2) also they are not considering the number of batter respect the phase voltage ,however as we use high voltage that needed many number battery supply so these disadvantages respect to cost in those are by decreasing the number of battery needed for supply voltage by 70% it decrease by considering of current and power input are constant. making increasing the number phase up to the minimum slot size depending up on the motor capacity rate whilst others are still concept vehicles for the future.

CHAPTER 2

2.1 DESIGN OF MULTI PHASE INDUCTION MACHINES

The aim of this section is order to get at which the minimum slots ends ,by using the mathematical equation relation between the various physical and electrical parameters of the electrical machine by using Output equation of Induction motor by making the constant current and power with varying the number phases at these condition the voltage will be decreases then in order to fit the objective of the thesis as number phases increase the voltage decrease at that time the number of battery will decrease then we select the appropriate phase the minimum slot size ends so in order to full fill this objective the following step(1-29) must staffing the characteristics of induction machine property. Then after modelling the m-phase induction motor depending up on the designed machine parameters. M-phase induction machine is used in industrial applications from small workshops to large industries. These motors are employed in applications such as centrifugal pumps, conveyers, compressors crushers, electric vehicle, Air plane, ship propulsation and drilling machines etc. [10]

Induction motor design starts from stator design. Stator design depends upon number stator slots. so this paper focus at constant current and power as phase increases and the voltage is decreases ,however its limited on size of slots ,so in order to full fill this criteria, designing induction machine physical dimension at constant current and power within increase of phase and decrease of voltage to satisfy customer(for electric vehicle) specification ,The standard specification for the design of an induction motor are materials (lamination thickness, conductor diameter), performance indexes (efficiency, power factor, starting torque, starting current, breakdown torque), temperature by insulation class, frame sizes, shaft height, cooling types, service classes, protection classes, etc. are specified in national (or international) standards (NEMA, IEEE, IEC, EU, etc.) to facilitate the induction motor for various applications. so the machine design detail depend up on; (i)The main dimensions of the stator, (ii)Details of stator windings, (iii)Design details of rotor and (iv)its windings and Performance characteristics. In order to get the above design details IM for electric vehicle specifications Rated output power, rated voltage, number of phases, speed, frequency, connection of stator winding, type of rotor winding, working conditions, shaft extension details etc.’’

2.1.1 Design Procedures for Induction Motors

The major steps to fit the objective at which constant current and power designing of an IM may be divided into 5 areas: electrical, dielectric, magnetic, thermal and mechanical [11],

1) Electrical design*:* To supply the IM, the supply voltage, frequency, and number of phases are specified. From this data and the minimum power factor and a target efficiency, the phase connection (star or delta), winding type, number of poles, slot numbers and winding factors are calculated. Current densities are imposed.

2) Magnetic design: Based on output coefficients, power, speed, number of poles, type of cooling, and the rotor diameter is calculated. Then, based on a specific current loading (in A/m) and air gap flux density, the stack length is determined. Fixing the flux densities in various parts of the magnetic circuit with given current densities and slot mmfs, the slot sizing, core height, and external stator diameter *Do* are all calculated. Choosing *Do*, which is standardized, the stack length is modified until the initial current density in the slot is secured. It is evident that sizing the stator and rotor core may be done many ways based on various criteria.

3)Insulation design: Insulation material and its thickness, be it slot/core insulation, conductor insulation, end connection insulation, or terminal leads insulation depends on machine voltage insulation class and the environment in which the motor operates. [12] There are low voltage 400V/50Hz, 230V/60Hz, 460V/60Hz 690V/60Hz or less or high voltage machines (2.3kV/60Hz, 4kV/50Hz, 6kV/50Hz). When PWM converter fed IMs are used, care must be exercised in reducing the voltage stress on the first 20% of phase coils or to enforce their insulation or to use random wound coils.

4) Thermal design*:* Extracting the heat caused by losses from the IM is imperative to keep the windings, core, and frame temperatures within safe limits. Depending on application or power level, various types of cooling are used. Air cooling is predominant but stator water cooling in the stator of high speed induction motors (above 10,000 rpm) is frequently used. Calculating the loss and temperature distribution and the cooling system represents the thermal design.

5)Mechanical design*:* should be robust and Mechanical design refers to critical rotating speed, noise, and vibration modes, mechanical stress in the shaft, and its deformation displacement, bearings design, inertia calculation, and forces on the winding end coils during most severe current transients.

The art of successful design lies not only in resolving the conflict for space between iron, copper, insulation and coolant but also in optimization of cost of manufacturing, and operating and maintenance charges. The factors, apart from the above, that requires consideration are

1) Limitation in design (saturation, current density, insulation, temperature rise etc.,)
2) Customer's needs
3) National and international standards
4) Convenience in production line and transportation e. Maintenance and repairs
5) Environmental conditions etc.

i) Limitations in design: The materials used for the machine and others such as cooling. The limitations stem from saturation of iron, current density in conductors, temperature, insulation, mechanical properties, efficiency, power factor etc.

ii) Saturation: Higher flux density reduces the volume of iron but drives the iron to operate beyond knee of the magnetization curve or in the region of saturation. Saturation of iron poses a limitation on account of increased core loss and excessive excitation required to establish a desired value of flux. It also introduces harmonics.

iii) Current density: Higher current density reduces the volume of copper but increases the losses and temperature.

iv) Temperature: poses a limitation on account of possible damage to insulation and other materials.

v) Insulation (which is both mechanically and electrically weak): poses a limitation on account of breakdown by excessive voltage gradient, mechanical forces or heat.

vi) Mechanical strength of the materials poses a limitation particularly in case of large and high speed machines.

vii) High efficiency and high power factor poses a limitation on account of higher capital cost.

2.1.2 Choice of Specific Electrical and Magnetic loadings Specific magnetic loading

To choice of specific Electrical and magnetic loading depending up on performance of IM machine designed for electric vehicle at balanced overall design, therefore the following factor considered to choice the Electric and magnetic loading for specific design.

(i) ***Iron loss***: A high value of flux density in the air gap leads to higher value of flux in the iron parts of the machine which results in increased iron losses and reduced efficiency.

(ii) ***Voltage*****:** When the machine is designed for higher voltage space occupied by the insulation becomes more thus making the teeth smaller and hence *higher flux density in teeth and core*.

(iii) ***Transient short circuit current***: A high value of gap density results in decrease in leakage reactance and hence increased value of armature current under short circuit conditions.

(iv)***Stability:*** The maximum power output of a machine under steady state condition is indirectly proportional to synchronous reactance. If higher value of flux density is used it leads to smaller number of turns per phase in armature winding. This results in reduced value of leakage reactance and hence increased value of power and hence increased steady state stability.

(v) ***Parallel operation:*** The satisfactory parallel operation of synchronous generators depends on the synchronizing power. Higher the synchronizing power higher will be the ability of the machine to operate in synchronism. The synchronizing power is inversely proportional to the synchronous reactance and hence the machines designed with higher value air gap flux density will have better ability to operate in parallel with other machines.

2.1.2.1 Specific Electric Loading:

Following are the some of the factors which influence the choice of specific electric loadings.

1. ***Copper loss*****:** Higher the value of *q larger will be* the number of armature of conductors which results in *higher copper loss*. This will result in higher temperature rise and reduction in efficiency.

2. ***Voltage*****:** A *higher value of q* can be used for *low voltage* machines since the space required for the insulation will be smaller.

3. ***Synchronous reactance***: High value of q leads to higher value of leakage reactance and armature reaction and hence higher value of synchronous reactance. Such machines will have *poor voltage regulation*, lower value of current under short circuit condition and low value of steady state stability limit and small value of synchronizing power.
4. ***Stray load losses*****:** With increase of q stray load losses will increase.

2.2 Output equation For Multi-Phase Induction motor

The mathematical equation relation between the various physical and electrical parameters of the electrical machine by using Output equation of Induction motor the equation must include the such that :-Main dimensions , Length of air gap-,Rules for selecting rotor for IM machines , Design of rotor bars & slots ,Design of end rings ,Magnetic leakage calculations Leakage reactance of poly-phase machines, Magnetizing current ,Short circuit current ,Circle diagram ,Operating characteristics.

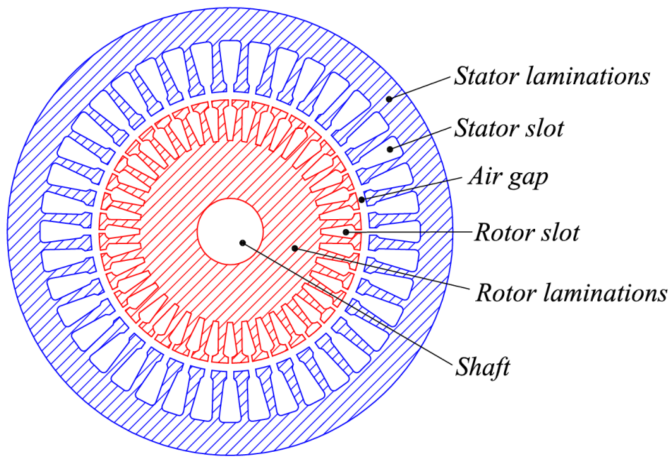


Figure 2.1 :- Stator and rotor laminations of an induction motor

In an induction **motor** the output equation can be obtained as follows

Consider an 'm' phase machine, with usual notations

Out put Q in KW=Input power *efficiency

Input power to motor= $m*V_{ph}*I_{ph}*\mathbf{cos}\,\phi*10^{-3}$ KW; where m=1, 2, 3 (2.1)

$V_{ph}=E_{ph}=4.44*f*\phi*T_{ph}*kw = 2.22f*\Phi*Z_{ph}*Kw$ (2.2)

If speed expressed in terms of rps $f=P*N_S/120=P*n_s/2$

Output = $3 * 2.22 * P*ns/2 * \Phi*Z_{ph}*Kw* I_{ph}* \eta* \cos\Phi * 10_{-3}$ KW

Output = $1.11 * P*\Phi * m*I_{ph} Z_{ph} * ns *Kw* \eta *\cos\Phi * 10^{-3}$KW

$P*\Phi = Bav*\pi*D*L$, and $m*I_{ph} *Z_{ph}/ (\pi*D) = q$

Output to motor = $1.11 * Bav*\pi*D*L*\pi*D*q* ns*Kw*\eta* \cos\Phi*10^{-3}$ KW

$Q = (1.11*\pi^2 Bav *q* Kw* \eta* \cos\Phi *10^{-3}) D^2*L* n_s$ KW

$Q = (11*Bav*q*Kw *\eta* \cos\Phi*10^{-3}) *D^{2*}L* ns$ KW (2.3)

Therefore Output $Q = Co*D^{2*}L* ns$ kW

where ; $\mathbf{Co = (11*Bav*q*Kw*\eta* \cos\Phi *10^{-3})}$

V_{ph} = phase voltage ; I_{ph} = phase current ;Z_{ph} = no of conductors/phase ;T_{ph} = no of turns/phase ;N_s = Synchronous speed in rpm ;n_s = synchronous speed in rps ;p = no of poles, ;q = Specific electric loading ;Φ = air gap flux/pole; Bav = Average flux density ;kw = winding factor ;η = efficiency ;cosΦ= power factor ;D = Diameter of the stator, ;L = Gross core length ;Co = Output coefficient

2.1.3 Main dimensions of Induction motor

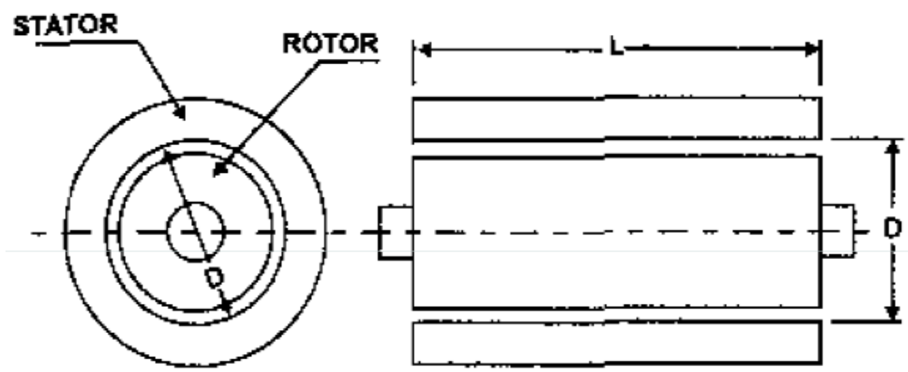


Figure 2.2:- shows the details of main dimensions of the of an induction motor.

2.1.4 Steps of Choosing of Specific loadings and other equation for Electric Machine

Step 1 choosing of Specific Magnetic loading or Air gap flux density

Choice of specific magnetic loading depend up on the interval of flux density and Iron losses ~~largely~~ depend upon air gap flux density, however, it have a Limitations in case of maximum and minimum values ,therefore around teeth the value of flux density is less than 1.8 Tesla and the flux density around core is between 1.3-1.5 Tesla .using high value of B_{av} it have some advantages are; Size of the machine reduced ,Cost of the machine decreases ,Overload capacity increases but at 50 Hz machine, the flux density 0.35 – 0.6 Tesla

Step 2:-choice of Specific Electric loading

To selecting specific electric loading for appropriate design making high value of q its own advantages to reduced size and reduced coast, but using high value q it also disadvantages it needs Higher amount of copper, More copper losses, temperature rise and Lower overload capacity Normal range 10000 ac/m – 450000 ac/m.

Step 3:-Choice of power factor and efficiency

Choice of power factor and efficiency under full load conditions will increase with increase in Rating of the machine. Percentage magnetizing current and losses will be lower for a larger Machine than that of a smaller machine. Further the power factor and efficiency will be higher for a high speed machine than the same rated low speed machine because of better cooling conditions.

Step 4:-Separation of D and L & calculation of the main Dimension

The output equation gives the relation between D^2L product and output of the machine. To separate D and L for this product a relation has to be assumed or established. Following are the various design considerations based on which a suitable ratio between gross length and pole pitch can be assumed.

a) To obtain minimum overall cost 1.5 to 2.0
b) To obtain good efficiency 1.4 to 1.6
c) To obtain good overall design 1.0 to 1.1
d) To obtain good power factor 1.0 to 1.3

As power factor plays a very important role the performance of induction motors it is advisable to design an induction motor for best power factor unless specified. Hence to obtain the best power factor the following relation will be usually assumed for separation of D and L.

Pole pitch/ Core length = 0.18/pole pitch or

$(\pi D/P) / L = 0.18/ (\pi D/P)$ i.e. $D = 0.135P\sqrt{L}$;where D and L are in meter. Using above relation D and L can be separated from D^2L product. However they obtained values of D and L has to satisfy the condition imposed on the value of peripheral speed.

Step 5:-selecting of Peripheral Speed

For the normal design of induction motors the calculated diameter of the motor should be such that the peripheral speed must be below 30 m/s. In case of specially designed rotor the peripheral speed can be 60 m/s.

$$v = \pi * Dn \tag{2.5}$$

(Peripheral Speed is an important factor in design. The peripheral speed refers to the speed on the periphery or the circumference of the rotor. The peripheral speed is given by the product of the circumference and the speed)

Step 6:-Design of Stator

Designing of Stator for induction motor one of the crucial point that is necessary in our design ; consists of stator core and stator slots. Stator slots: in general two types of stator slots are employed in induction motors viz, open clots and semi closed slots. Operating performance of the induction motors depends upon the shape of the slots and hence it is important to select suitable slot for the stator slots.

(i) ***Open slots:*** In this type of slots the *slot opening will be equal to that of the width of the slots* as shown in Fig 10. In such type of slots assembly and repair of winding are easy. However such slots will lead to higher air gap contraction factor and hence poor power factor. Hence these types of slots are rarely used in 3-ϕ induction motors.

(ii) ***Semiclosed slots***: In such type of slots, *slot opening is much smaller than the width of the slot* as shown in Fig and Fig 1. Hence in this type of slots assembly of windings is more difficult and takes more time compared to open slots and hence it is costlier. However the air gap characteristics are better compared to open type slots.

(iii) ***Tapered slots:*** In this type of slots also, *opening will be much smaller than the slot width*. However, the slot width will be varying from top of the slot to bottom of the slot with minimum width at the bottom as shown in Fig.

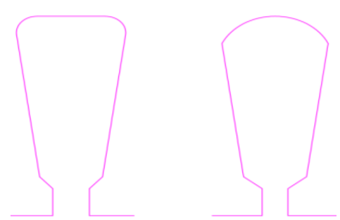
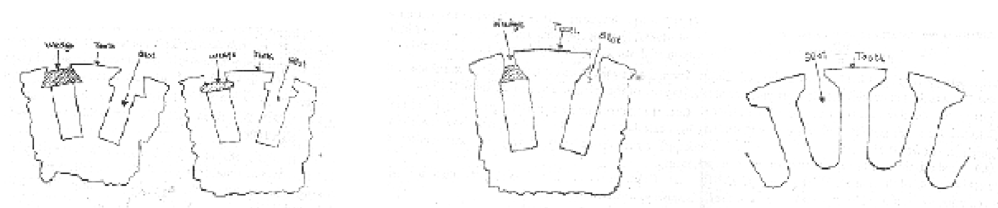


Figure 2-3 :- semi closed slot selected for design



(i) Open type (ii) Semiclosed type (iii) Tapered type .

Figure 2.4 :-different shapes of stator slots

Step 7:-calculating number of stator slots

Stator design depends upon number of stator slots. The emfs induced in coil sides placed in neighboring slots are thus phase shifted by an angle, α_{es}, expressible in electrical radians as follows: [13]

$$\alpha_{es},=pi*p/Ss \tag{2.6}$$

General expression for number of stator slot is given by Ss=(m/2)*p[2=K] slots

where Ss= No of stator slots

m=No'of machine phases

pno of machine poles

K=1,2,3…..for asymmetrical winding

K=0,2,4….. for symmetrical winding

The selected number of slots should satisfy the consideration of stator slot pitch at the air gap surface, which should be between 1.5 to 2.5 cm.

Stator slot pitch at the air gap surface = $\lambda_S = \pi * D/Ss$ where Ss is the number of stator slots

$$\lambda_S = \pi * D/Ss \tag{2.7}$$

Step 8:-calculating Turns per phase

EMF equation of an induction motor is given by:-

$$E_{ph} = 4.44 f \phi T_{ph} kw \tag{2.8}$$

Hence turns per phase can be obtained from emf equation

$$T_{ph} = E_{ph} / 4.44 f \phi kw \tag{2.9}$$

Generally the induced emf can be assumed to be equal to the applied voltage per phase Flux/pole,

$$\phi = Bav * \pi * D*L/P \tag{2.10}$$

winding factor kw may be assumed as 0.955 for full pitch distributed winding unless otherwise specified. Number conductors /phase, $Z_{ph} = 2 * T_{ph}$, and hence Total number of stator conductors

$$Z = 2*m\ Tph \tag{2.11}$$

conductors /slot Zs = Z/Ss or 6 T_{ph}/Ss , where Zs is an integer for single layer winding and even number for double layer winding.

Step 9:- Calculating of conductor cross section

Area of cross section of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings. Sectional area of the stator conductor

$$a_s = I_s / \sigma_s \quad (2.12)$$

where σ_s is the current density in stator windings

Stator current per phase

$$I_s = Q / (m*Vph* \cos\phi) \quad (2.13)$$

A suitable value of current density has to be assumed considering the advantages and disadvantages.

- ✓ Advantages of higher value of current density:
  - i. reduction in cross section
  - ii. reduction in weight
  - iii. reduction in cost
- ✓ Disadvantages of higher value of current density
  - i. increase in resistance
  - ii. increase in cu loss
  - iii. increase in temperature rise
  - iv. reduction in efficiency

Hence higher value is assumed for low voltage machines and small machines. Usual value of current density for stator windings is 3 to 5 amps/mm^2. Based on the sectional area shape and size of the conductor can be decided. If the sectional area of the conductors is below 5 mm^2 then usually circular conductors are employed. If it is above 5mm^2 then rectangular conductors will be employed.. In case of rectangular conductors width to thickness ratio must be between 2.5 to 3.5

Step 10:-selecting Area of stator slot

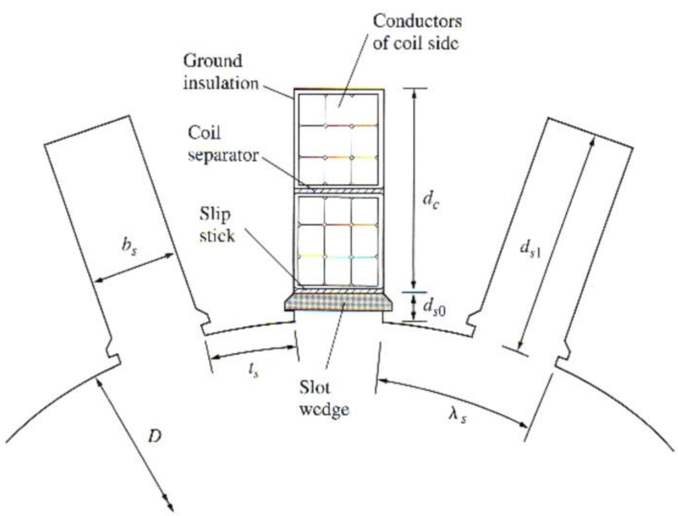
Slot area is occupied by the conductors and the insulation. Out of which almost more than 25 % is the insulation. Once the number of conductors per slot is decided approximate area of the

$$\text{Area of each slot} = Zs*a_s/\text{space factor} \quad (2.14)$$

slot can be estimated. Slot space factor = Copper area in the slot /Area of each slot This slot space factor so obtained will be between 0.25 and 0.4. The detailed dimension of the slot can be estimated as follows.

Step :- selecting Size of the slot

Normally different types of slots are employed for carrying stator windings of induction motors. Generally full pitched double layer windings are employed for stator windings. For double layer windings the conductor per slot will be even. These conductors are suitably arranged along the depth and width of the winding. Stator slots should not be too wide, leading to thin tooth width, which makes the tooth mechanically weak and maximum flux density may exceed the permissible limit. Hence slot width should be so selected such that the flux density in tooth is between 1.6 to 1.8 Tesla. Further the slots should not be too deep also otherwise the leakage reactance increases. As a guideline the ratio of slot depth to slot width may assumed as 3 to 5. Slot insulation details along the conductors are shown in Fig.



$$\lambda_s = \frac{\pi D}{S}$$

$$0.7\text{in} \le \lambda_s \le 1.5\text{in}$$

$$2b_s \le d_{s1} \le 4b_s$$

$$0.4\lambda_s \le b_s \le 0.6\lambda_s$$

$$r_s = \frac{b_s}{\lambda_s}, \quad 0.4 \le r_s \le 0.6$$

$$t_s = \lambda_s - b_s \qquad (2.14)$$

Figure 2.5 :-Slot insulation details along the conductors

Proper slot insulation as per the voltage rating of the machine has to be provided before inserting the insulated coil in the slots. This slot insulation is called the *slot liner*, thickness of which may be taken as 0.5 mm to 0.7 mm. Suitable thickness of insulation called coil separator separates the two layers of coils. Thickness of coil separator is 0.5 mm to 0.7 mm for low voltage machines and 0.8 mm to 1.2 mm for high voltage machines. Wedge of suitable thickness (3.5 mm to 5 mm) is placed at the top of the slot to hold the coils in position. Lip of the slot is taken 1.0 to 2.0 mm. Figure shows the placed in slots

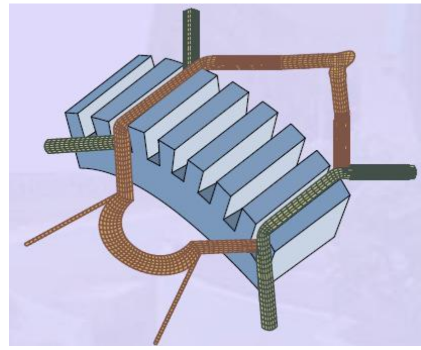



Figure 2.-6:- Stator coils, placed in slots

Step 12:-Calculating Length of the mean Turn

Length of the mean turn is calculated using an empirical formula

$$l_{mt} = 2L + 2.3\,\tau p + 0.24 \quad (2.15)$$

where L is the gross length of the stator and τp is pole pitch in meter.

Step 13:-Calculating Resistance of stator winding

Resistance of the stator winding per phase is calculated using the formula

$$R_s = (\rho_c * l_{mt} * T_{ph})/\alpha_s \quad (2.16)$$

where *Resistivity of copper*, $\rho_c = 0.021\Omega m$ as where $l$mt is in meter and as is in mm^2. Using so calculated resistance of stator winding copper losses in stator winding can be calculated as Total copper losses in stator winding = m $(Is)^2$ R_s. (2.17)

Step 12:-choice of Flux density in stator tooth

Knowing the dimensions of stator slot pitch, width of the slot and width of the stator tooth flux density in the stator tooth can be calculated. The flux density in the stator tooth is limited to 1.8 Tesla. As the stator tooth is tapering towards the bottom, the flux density is calculated at 1/3rd height from the narrow end of the tooth. The flux density at the 1/3rd height from the narrow end of the tooth can be calculated as follows.

- ✓ Diameter at $1/3^{rd}$ height from narrow end can be explained

$$D' = D + 1/3 * h_{ts} * 2 \quad (2.18)$$

- ✓ Slot pitch at $1/3^{rd}$ height (τ'_s)equals to

$$\tau'_s = \pi * D' / Ss \quad (2.19)$$

- ✓ Tooth width at this section (b'_t)

$$b'_t = \tau'_s - b_s \quad (2.20)$$

- ✓ Area of one stator tooth (a'_t)

$$a'_t = b'_t * l_i \quad (2.21)$$

- ✓ Area of all the stator tooth per pole A'_t

$$A'_t = b'_t * l_i * \text{number of teeth per pole} \quad (2.22)$$

- ✓ Mean flux density in stator teeth (B'_t)

$$B'_t = \phi/A'_t \quad (2.23)$$

- Maximum flux density in the stator teeth may be taken to be less than 1.5 times the above value

Step 12:- Calculating Depth of stator core below the slots

There will be certain solid portion below the slots in the stator which is called the depth of the stator core. This depth of the stator core can be calculated by assuming suitable value for the flux density B_c in the stator core. Generally the flux density in the stator core may be assumed varying between 1.2 to 1.4 Tesla. Depth of the stator core can be calculated as follows.

- Flux in the stator core section (ϕ_c)

$$\phi_c = ½ \phi \quad (2.24)$$

Area of stator core (Ac)

$$Ac = \phi / 2B_c \quad (2.25)$$

- Area of stator core (Ac)

$$Ac = L_i \times d_{cs} \quad (2.26)$$

Hence, depth of the core = A_c / L_i

Using the design data obtained so far outer diameter of the stator core can be calculated as

$$Do = D + 2*h_{ss} = 2d_{cs} \quad (2.27)$$

Where h_{ss} is the height of the stator slot.

Step 13 :-Design of Rotor

Rotor For Induction can be construct in two ways those are:- One is the squirrel cage rotor and the other is the slip ring rotor. In case of its advantages it has rugged, simple in construction and comparatively cheaper *squirrel cage* rotor type selected Most of the time . However they have the disadvantage of lower starting torque. In this type, the rotor consists of bars of copper or aluminum accommodated in rotor slots. In *case slip ring induction motors the rotor complex in construction and costlier with the advantage that they have the better starting torque*. This type of rotor consists of star connected distributed three phase windings. Between stator and rotor is the air gap which is a very critical part. The performance parameters of the motor like magnetizing current, power factor, over load capacity, cooling and noise are affected by length of the air gap.

- Hence length of the air gap is selected considering the merit and demerit of *larger air gap* length.

- ***merits***

  (i) Increased overload capacity

  (ii) Increased cooling

  (iii) Reduced unbalanced magnetic pull

  (iv) Reduced in tooth pulsation

  (v) Reduced noise

- ***Demerits***

  (i) Increased Magnetizing current

  (ii) Reduced power factor

Step 14:-Calculating Length of Air-gap

Between stator and rotor is the air gap which is a very critical part. The performance parameter soft the motor like magnetizing current, power factor ,overload capacity ,cooling and noise are affected by length of the air gap.

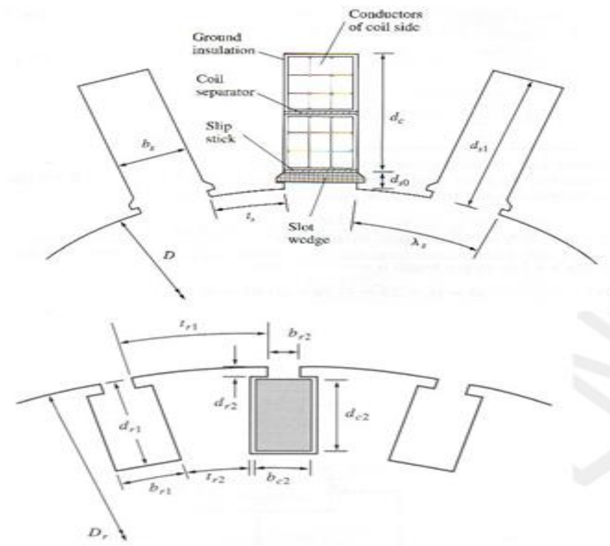


Figure2.7:- Rotor and stator internal structure

Step 15:-selecting Power Factor

The mmf required to send the flux through air gap is proportional to the product of flux density and length of air gap. Fig shows phasor diagrams of an induction motor with two different air gap lengths. With increase in air gap length, magnetizing mmf increases and hence greater the magnetizing current. Therefore, the Phase angle between applied voltage And stator current will increase which Gives *low power factor*.

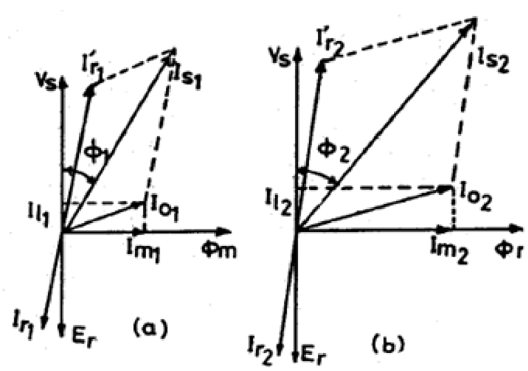


Figure2. 7 :- phasor diagram of induction motor

a)Magnetising current and power factor being very important parameters in deciding the ***performance*** of induction motors, the induction motors are designed for optimum value of air gap or minimum air gap possible. Hence in designing the length of the air gap following empirical formula is employed.

Figure 2 -8:- squirrel and sling ring rotor

b)Overl oad Capacity:-Over load capacity of induction motor is the ratio of maximum output to rated output and the maximum output is obtained from circle diagram .The diameter of circle diagram is Vs/Xs where Xs is reactance of motor . The length of air gap affects the leakage reactance .If the length of air gap is large ,the leakage flux is reduced ,hence reduced value of leakage reactance .*With decrease in the value of leakage reactance the diameter of circle diagram increases and hence the over load capacity increases.*

c)Pulsation loss:-The tooth pulsation losses , which is produced due to variation in reactance of the air gap , is reduced with large air gap.

d)Cooling: -The large air gap provide better facilities for cooling at the gap surfaces due to the cylindrical surface ,so stator and rotor are separated by large distance.

e)Noise:-noise in induction motor reduced with increase in air gap length due to reduction in leakage flux which is the cause of noise. if the length of the air gap is selected use larger air gap length it becomes ,increase over load capacity, increase cooling ,reduced unbalanced magnetic pull and reduced in tooth pulsation ,however ,it increased magnetic current and reduced power factor it is some advantages to considering larger length of air gap length .

Magnetising current and power factor being very important parameters in deciding the performance of induction motors , the induction motors are designed for optimum value of air gap or minimum air gap possible .Hence in designing the length of the air gap following empirical formula is employed.

Air gap length $lg = 0.2 + 2\sqrt{DL}$ mm (2.28)

Step 16: Number of slots

Proper numbers of rotor slots are to be selected in relation to number of stator slots otherwise undesirable effects will be found at the starting of the motor. Cogging and Crawling are the two phenomena which are observed due to wrong combination of number of rotor and stator slots. In addition, induction motor may develop unpredictable hooks and cusps in torque speed characteristics or the motor may run with lot of noise. Let us discuss Cogging and Crawling phenomena in induction motors.

a) **Crawling:** The rotating magnetic field produced in the air gap of the will be usually non-sinusoidal and generally contains odd harmonics of the order 3rd, 5th and 7th. The third harmonic flux will produce the three times the magnetic poles compared to that of the fundamental. Similarly the 5th and 7th harmonics will produce the poles five and seven times the fundamental respectively. The presence of harmonics in the flux wave affects the torque speed characteristics. The Fig. below shows the effect of 7th harmonics on the torque speed characteristics of three phase induction motor. The motor with presence of 7th harmonics is to have a tendency to run the motor at one seventh of its normal speed. The 7th harmonics will produce a dip in torque speed characteristics at one seventh of its normal speed as shown in torque speed characteristics.

b) **Cogging** If the number of rotor slots is not proper in relation to number of stator slots the machine *refuses to run and remains stationary*. Under such conditions there will be a locking tendency between the *rotor and stator*. Such a phenomenon is called cogging. Hence in order to avoid such bad effects a proper number of rotor slots are to be selected in relation to number of stator slots. In addition rotor slots will be skewed by one slot pitch to minimize the tendency of cogging, torque defects like synchronous hooks and cusps and noisy operation while running. *Effect of skewing will slightly increase the rotor resistance and increases the starting torque*. However this will increase the leakage reactance and hence reduces the starting current and power factor.

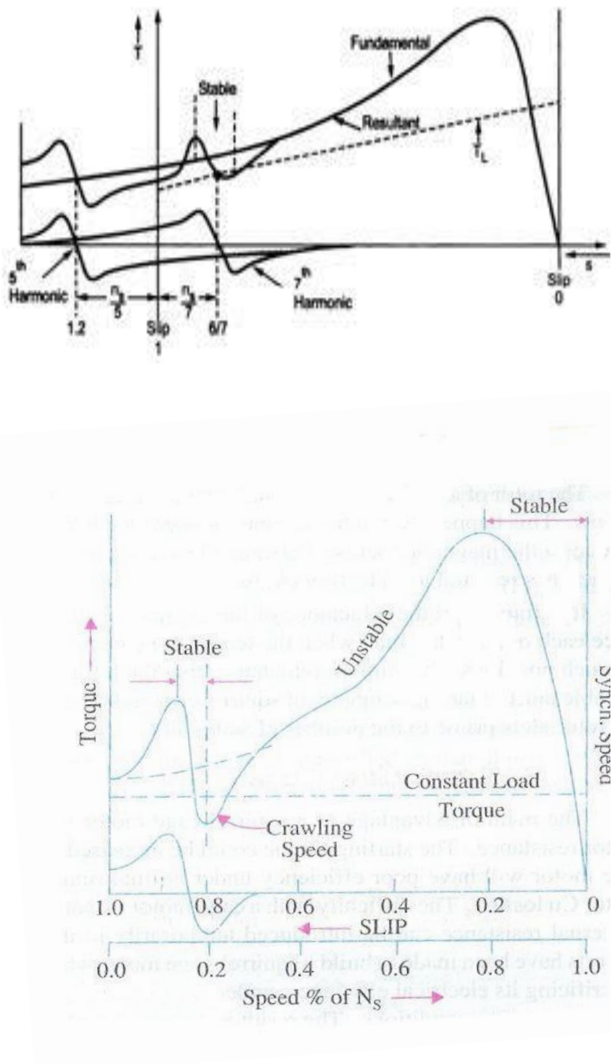


Figure 2-9:- Torque speed characteristic

Step 17:-Selection of number of rotor slots

The number of rotor slots may be selected using the following guide lines.

i. To avoid cogging and crawling: (a)Ss ≠ Sr (b) Ss - Sr ≠ ±3P
ii. To avoid synchronous hooks and cusps in torque speed characteristics ≠ ±P, ±2P, ±5P.
iii. To noisy operation Ss - Sr ≠±1, ±2, (±P ±1), (±P ±2)

Step 18 :- Calculating Rotor Bar Current

Bar current in the rotor of a squirrel cage induction motor may be determined by comparing the mmf developed in rotor and stator . The stator mmf is about 15% higher because of the magnetizing mmf.,Rotor mmf =0.85(stator mmf);Number of rotor bars=Nb; Sr=number of rotors slots; Rotor bar current=Ib;Rotor mmf =Ib.Sr/2

Stator mmf=$m*I_{ph}*T_s$ (2.29)

Ib.Sr/2=0.85*(m.Is.Ts)or I_b=0.85*(2*m*Is*Ts/Sr) (2.30)

Step 19 calculating Cross sectional area of Rotor bar

Sectional area of the rotor conductor can be calculated by rotor bar current and assumed value of current density for rotor bars. As cooling conditions are better for the rotor than the stator higher current density can be assumed. Higher current density will lead to reduced sectional area and hence increased resistance, rotor cu losses and reduced efficiency. With increased rotor resistance starting torque will increase. As a guide line the rotor bar current density can be assumed between 4 to 7 Amp/mm^2 or may be selected from design data Hand Book.

Hence sectional area of the rotor bars can be calculated as

$$Ab = Ib / \sigma_b \, mm^2 \quad (2.31)$$

Once the cross sectional area is known the size of the conductor may be selected form standard table given in data hand book.

Step 20:-Shape and Size of the Rotor slots

Generally semi-closed slots or closed slots with very small or narrow openings are employed for the rotor slots. In case of fully closed slots the rotor bars are force fit into the slots from the sides of the rotor. The rotors with ***closed slots*** are giving better performance to the motor in the following way

(i) As the rotor is closed the rotor surface is smooth at the air gap and hence the motor draws lower magnetizing current. ,(ii) Reduced noise as the air gap characteristics are better ,(iii) Increased leakage reactance and, (iv) Reduced starting current.,(v) Over load capacity is reduced, (vi) Undesirable and complex air gap characteristics. From the above it can be concluded that ***semi-closed*** slots are more suitable and hence are employed in rotors.

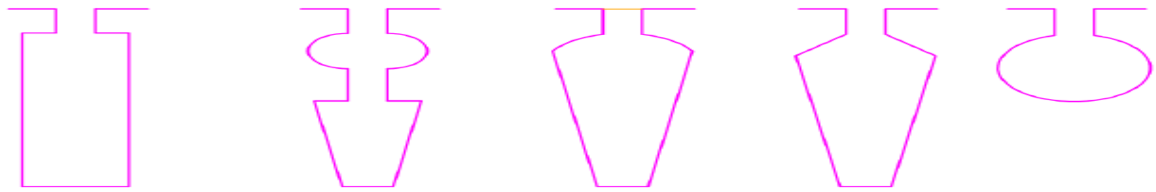


Figure 2-10 :- Types of rotor slots

Step 21:- Calculating Copper loss in rotor bars

Knowing the length of the rotor bars and resistance of the rotor bars, cu losses in the rotor bars can be calculated.

Length of rotor bar l_b = L + allowance for skewing (2.32)

Rotor bar resistance = 0.021 * l_b / A_b (2.33)

Copper loss in rotor bars = $I_b^{2*} r_b$ *Sr (2.34)

***Step 22:- Calculating* End Ring Current**

All the rotor bars are short circuited by connecting them to the end rings at both the end rings. The rotating magnetic field produced will induce an emf in the rotor bars which will be sinusoidal over one pole pitch. As the rotor is a short circuited body, there will be current flow because of this emf induced. The distribution of current and end rings are as shown in Fig. below. Referring to the figure considering the bars under one pole pitch, half of the number of bars and the end ring carry the current in one direction and the other half in the opposite direction. Thus the maximum end ring current may be taken as the sum of the average current in half of the number of bars under one pole.

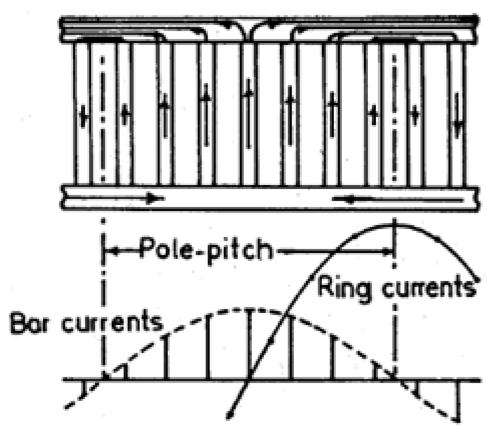


Figure 2-11:- current in cage rotor Bars and end rings

Maximum end ring current *Ie*(max)

Ie(max) = ½ (Number rotor bars / pole) $I_b(av)$

= ½ * Sr/P * *Ib*/1.11 (2.35)

Hence rms value of *Ie* = $1/2\sqrt{2}$* Sr/P * *Ib*/1.11.

= $1/\pi$ * (Sr/P) * I_b/1.11 (2.36)

Step 23:- Calculating Area of end ring

Knowing the end ring current and assuming suitable value for the current density in the end rings cross section for the end ring can be calculated as Area of each end ring

$A_e = I_e / \sigma_e \ mm^2$ (2.37)

Ae=te*de (2.38)

where te=thickness of end ring and de=depth of end ring current density in the end ring may be assume as 4.5 to 7.5 amp/mm^2.

Step 24 :- Calculating Copper loss in End Rings

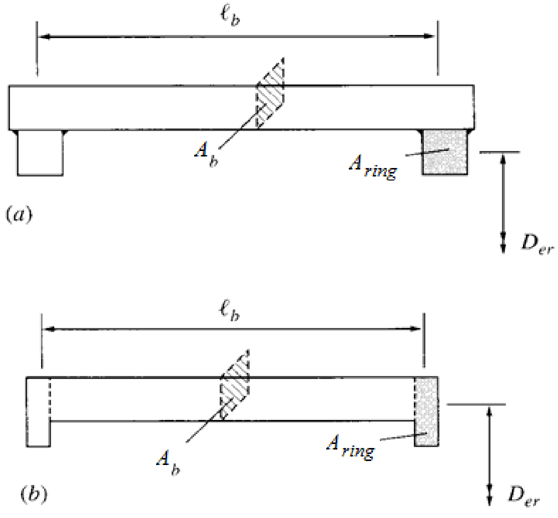
Mean diameter of the end ring (D_{me}) is assumed as 4 to 6 cms less than that of the rotor. Mean length of the current path in end ring can be calculated as

$l_{me} = \pi D_{me}$ (2.39)

The resistance of the end ring can be calculated as

$re = 0.021 \times l_{me} / A_e$ (2.40)

Total copper loss in end rings = 2 * Ie^2 * *re* (2.41)



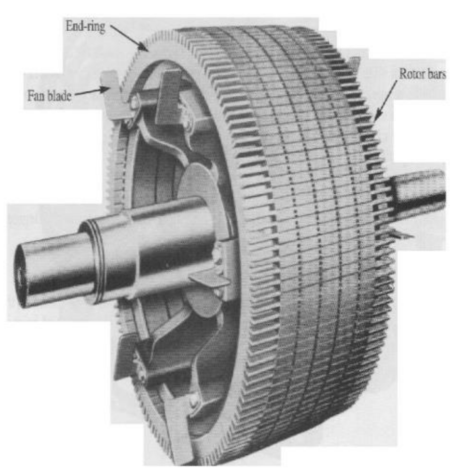


Figure 2-12:-end ring rotor dimension

Step 25:- Calculating Equivalent Rotor Resistance

Knowing the total copper losses in the rotor circuit and the equivalent rotor current equivalent rotor resistance can be calculated as follows.

Equivalent rotor resistance

R_r = Total rotor copper loss /(m*(Ir')^2)maximum (2.42)

Calculate rotor bar and end ring resistances and hence copper losses. Equivalent rotor resistance is equal to total rotor copper losses divided by rotor current. Value of slip at full load is determined by rotor resistance.

Step 26: Calculation of Magnetizing current

Magnetizing MMF is obtained as. .

$$Fm=2*(Kc*lg*(Bg/\mu o) +F_{mts} +F_{mtr} +F_{mcs}+F_{mcr}) \quad (2.43)$$

where, *Kc* - the Carter coefficient to account for the effective air gap length increase due to slot opening which is usually range from1.0 to 1.5

F_{mts} - MMF drop along stator teeth

F_{mtr} - MMF drop along rotor teeth

F_{mcs} - MMF drop along stator core

F_{mcr} - MMF drop along rotor core

MMF drop along stator teeth, stator core, rotor teeth and rotor core are estimated from assigned flux density and B- H curve. Based on the total ampere turns of the magnetic circuit, the magnetizing current is calculated as

$$I_m= \frac{0.427*P*Fm}{Tph*Kw} \quad (2.44)$$

Step 27: Calculation of no load losses

Iron loss has two components, hysteresis and eddy current losses, occurring in the iron parts depend upon the frequency of the applied voltage. The frequency of the induced voltage in rotor is equal to the slip frequency which is very low and hence the iron losses occurring in the rotor is negligibly small. Hence the iron losses occurring in the induction motor is mainly due to the losses in the stator alone. The total iron loss in induction motor is taken as the sum of iron loss in stator core and iron losses in stator teeth. The iron loss in stator teeth and core is obtained by calculating their respective weights. In addition to iron losses, friction and windage loss is to be taken into account by assuming it as 1.0 to 2.0 % of the output of the motor.

total no load losses = Total iron losses + Friction and windage loss (2.45)

Step 28: Calculation of no load current

The no load current of an induction motor has two components, magnetizing component, *Im* and iron loss component, *Iw* and is calculated as,

$$I0 = \sqrt{Im^2 + Iw^2} \quad (2.46)$$

where, *Iw = Total no load loss/(m x phase voltage),where m=number phase*

Step 26: Calculation of no load Power Factor

No load power factor is calculated knowing the components of no load current.

$$Cos\phi_o = I_w/I_o \quad (2.47)$$

Step 29: Calculation of stator leakage reactance

The leakage reactance is calculated by considering several components by using some equations and some empirical formulas.

$$X_{sl}=2\pi\mu o f\, L(T_{ph}^2/Pq) *(\lambda_{sls}+\lambda_{ds}+\lambda_{ecs}) \quad (2.48)$$

where q – Stator slots/pole/phase

λ_{sls} -Stator slot leakage coefficients

λ_{ds} -Stator differential leakage coefficients

λ_{ecs} -Stator end leakage coefficients

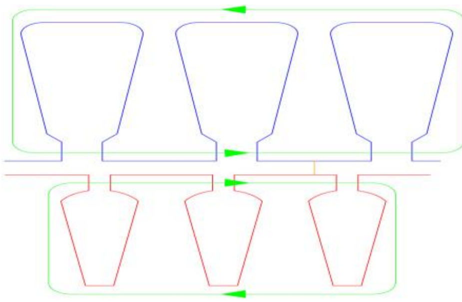
$$Xsl= 2\pi\mu o f_1\, L(T_{ph}^2/Pq) *(\lambda_{sls}+\lambda_{ds}+\lambda_{ecs})=Cs(\lambda_{sls}+\lambda_{ds}+\lambda_{ecs})= X_{sls}+ X_{ds} + X_{ecs} \quad (2.49)$$

where X_{sls}-Stator slot leakage reactance

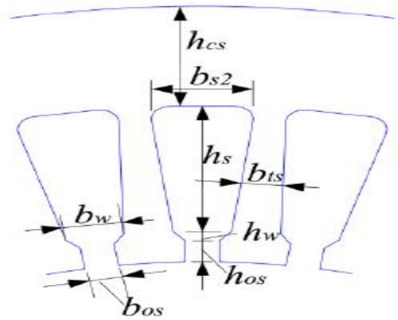
X_{ds}-Stator differential leakage reactance

X_{ecs} -Stator end leakage reactance

Slot leakage coefficients: Deeper slot indicates larger slot leakage reactance and wider slot means smaller leakage reactance. Figs.(a) and(b) show the slot leakage flux in slots and slot dimensions.



(a)



(b)

Figure 2-13 :-(a) Slot leakage flux in slots (b) Slot dimensions

$$\lambda_{sls}=[2*h/3(bs1+bs2)+\frac{2hw}{(bas+bs1)}+\frac{hos}{bos}]((1+3\beta)/4) \qquad (2.50)$$

***Differential leakage coefficients**:*

Fig 2.14 shows the zig-Equation 0.3zag stator and rotor leakage flux lines.

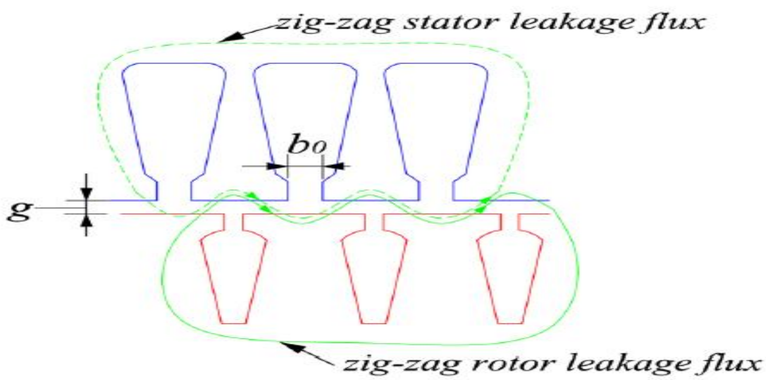


Figure 2.14 :-zig-Equation zag stator and rotor leakage flux

$$\lambda_{ds}=\frac{5lgKcIbo}{5+4lgKcIbo}\,(3\beta+1)/4 \qquad (2.51)$$

CHAPTER 3

3. DYNAMIC MODELLING OF MULTI PHASE INDUCTION MOTOR

3.1 Construction and Working Principle of Multiphase Induction Motor

The way to check analytical tool for the analysis of unbalanced operation of electric machines has been the well-known symmetrical component method, this method is the most commonly used. In this method, a balanced structure is assumed after the machine loses one or more of its phases. However, as far as the dynamics of machine is concerned, the method loses its utility due to the fact that the interaction between the lost phases and remainder of the machine windings no longer exists and this drastically alters (change) the dynamic behavior of the machine.

By using open circuit excitation we can identifying the dynamic behavior of machines for balanced and unbalanced ;m-phase machine Stator winding can be designed in such a way that the spatial displacement between any two consecutive stator phases equals, $\boldsymbol{\alpha} = \frac{\mathbf{2\pi}}{\boldsymbol{n}}$ in this case a symmetrical multiphase machine results. This analytical system can operate if the number of phases is an odd prime number. In three phase induction machine the three phases are spatially displaced by 120 degree whereas in five phase machine by 72 degrees.
[14], However, if the number of phases is an even number or an odd number that is not a prime number (e.g. 6 or 9) , stator winding may be realized in different manner, as „k‟ windings having „a‟ sub-phases each.(where $n = a \cdot k$). Typically, $\alpha = 3$ (although $\alpha = 5$) also exist as well nd k = 2,3,4,5,….. In such case, the spatial displacement between the first phases of the two consecutive „a‟ sub-phase windings is $\alpha = \pi/n$, leading to an asymmetrical distribution of magnetic winding axes in cross section of the machine.(i.e. asymmetrical multi-phase machine) .

using squirrel cage rotor is has its own advantage that, it can adjust to any number of phases but for wound rotor not possible.

Two kinds of converter can be used for mult- phase machines: a half–bridge and a full– bridge converter. Using full bridge converter two main advantages: (i) the phase currents are independent; (ii) there is not electrical interaction among phases,

3.1.2. Characteristics of multi-phase induction motor

Increasing numbers of phases induction motors are not connected directly to three-phase supplies. Instead, they derive their excitation from a power electronic converter, the input stage of which is connected to a three-phase supply There has been an upsurge of interest in multiphase machines, that is machines with more than three phases. There are several reasons for this, the principal ones being; the stator excitation in a multiphase machine produces a field with a lower space-harmonic content, so that the efficiency is higher than in a three-phase machine. Multiphase machines have a greater fault tolerance than their three-phase counterparts. If one phase of a three-phase machine becomes open-circuited the machine becomes single-phase. It may continue to run but requires some external means for starting, and must be massively de-rated. If one phase of a 15-phase machine becomes open circuited, it will still self-start and will run with only minimal de-rating. Multiphase machines are less susceptible than their three-phase counterparts to time-harmonic components in the excitation waveform. Such excitation components produce pulsating torques at even multiples of the fundamental excitation frequency.

[2] Utilization of multiphase motor drives also enables improvement in the noise characteristics, when compared to three-phase motor drives For this purpose the stator current is assumed to consist of a fundamental component, of frequency v, together with a host of time harmonic components at integer multiples of v. The excited 2P-pole n-phase stator winding is modeled by blocks of current, which are resolved into rotating harmonic surface current distributions of the form. Demonstrate that as the number of phases is increased, so the orders of the mmf harmonics produced by the stator excitation, often referred to as the phase belt harmonics, also increase.

The claim of improved efficiency may be explored by assuming, in the first instance, sinusoidal excitation. Consider two machines of identical design, other than the fact that their stator coils are connected differently to give different numbers of phases, n1 and n2. If both machines are to develop the same torque at the same speed, then it follows that they will have the same rotor joule loss, the same air-gap field and the same fundamental component of stator current loading, that is they will have the same value of $J^{-1P}{}_{S}$

[2] The data presented in Table 1 demonstrate that as the number of phases is increased, so the orders of the mmf harmonics produced by the stator excitation, often referred to as the phase belt harmonics, also increase. The magnitude of these harmonic components is also shown in (3) to vary in inverse proportion to n, so that the increase in pole number is accompanied by a reduction

in magnitude. Values of q other than 1 reveal the field components produced by the time-harmonic currents caused by the inverter switching. Table 2, for example, gives the pole numbers of the harmonic fields produced by the 11th excitation harmonic. The data presented in Table 2 show how time-harmonic components of excitation current can result in field components that will interact with those produced by the fundamental frequency component of excitation. For example, in a six-phase machine, an 11th time-harmonic component of excitation will produce fields that have the same pole numbers as those produced by the fundamental-frequency component, but which rotate in the opposite direction, resulting in pulsating torques of frequency 12v.

Table 2 demonstrate that as the number of phases and mmf harmonics produced by the stator excitation relation

Number of n	Number of poles				
	i=0	i=1	i=-1	i=2	i=-2
3	+p	-5p	+7p	-11p	+13p
5	+p	-9p	+11p	-19p	+21p
6	+p	-11p	+13p	-23p	+25p
9	+p	-17p	+19p	-35p	+37p
12	+p	-23p	+25p	-47p	+49p
15	+p	-29p	+31p	-59p	+61p

Table 3: Harmonic fields produced by the 11th time-harmonic component of excitation in multi phase machines for the common phase numbers

Number of n	Number of poles				
	i=0	i=1	i=-1	i=2	i=-2
3	+11p	+5p	+17p	-1p	+23p
5	+11p	+p	+21p	-9p	+31p
6	+11p	-1p	+23p	-13p	+35p
9	+11p	-7p	+29p	-25p	+47p
12	+11p	-13p	+35p	-37p	+59p
15	+11p	-19p	+41p	-49p	+71p

will also produce additional rotor joule loss and iron loss. The use of higher phase numbers increases the pole number of these harmonic components, and thereby reduces their magnitude, and this will reduce the corresponding losses accordingly. The significance of this as a loss reduction mechanism will be highly design-dependent,

3.2 Mathematical modelling of multi-phase Induction machine

The parameter equations such as voltage and torque that describe the dynamic behavior of an induction motor are time-varying in nature. Such equations involve complexity while solving as differential equations. A change of variables from time varying to time invariant can be used to minimize the complexity from the voltage equations of motor due to relative motion of electric circuit. By this technique, a multi-phase winding can be reduced to a set of two phase winding (d-q) which are in quadrature to each other. In other words, the stator and rotor variables (voltage, current and flux linkages) of an induction motor are transferred to arbitrary reference frame .The steady state model and equivalent circuit of induction motor are useful for studying the performance of the machine in steady state. Fig. shows a q-d-0 equivalent circuit of an Induction motor. The circuit comprises of various time varying inductances which are to be simulated to analyze the dynamic behavior of five-phase Induction motor.

M-phase machine can be represented as a two phase equivalent with d_s-q_s corresponding to stator direct and quadrature axes that are fixed on the stator axis and d_r-q_r corresponding to rotor direct and quadrature axes that are rotating with a fixed speed on the rotor axis. The effect of time varying inductance can be eliminated by referring the stator and rotor variables to a common reference frame which rotates at any speed.

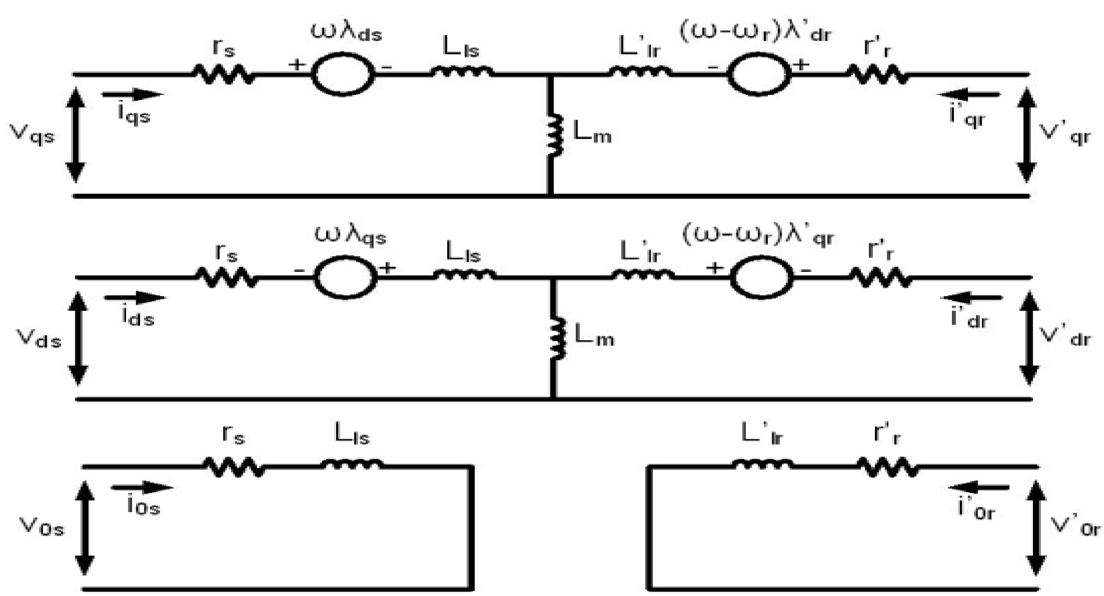


Figure 3-1:- Equivalent circuit q,d voltages

A nine phase induction motor voltage supply can be modeled by the following steps as follows

Va=Vcos Θe

Vb=Vcos$(\Theta e - a)$

Vc=Vcos$(\Theta e - 2a)$

Vd=Vcos$(\Theta e - 3a)$

Ve=Vcos$(\Theta e - 4a)$

Vf=Vcos$(\Theta e - 5a)$

Vg=Vcos$(\Theta e - 6a)$

Vh=Vcos$(\Theta e - 7a)$

Vi=Vcos$(\Theta e - 8a)$

$Vj = V\cos(\Theta e - 9a)$

$Vk = V\cos(\Theta e - 10a)$

$Vl = V\cos(\Theta e - 11a)$ (3.1)

$\boldsymbol{a} = \frac{2\pi}{12}$, $\Theta e = \int we$ (3.2)

To transform the 12-Φ stationary reference frame variables to 2-Φ stationary reference frame variables

$$\begin{bmatrix} Vqs \\ Vds \\ Vxs \\ Vys \\ Vx1s \\ . \\ . \\ . \\ V0s \end{bmatrix} = \sqrt{2/n} \begin{bmatrix} 1 & \cos a & \cos 2a & \cos 3a & . & . & . & . & \cos n a \\ 0 & \sin a & \sin 2a & \sin 3a & . & . & . & . & \sin na \\ 1 & \cos 2a & \cos 4a & \cos 6a & . & . & . & . & \cos 2na \\ 0 & \sin 2a & \sin 4a & \sin 6a & . & . & . & . & \sin 2na \\ 1 & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \\ Vd \\ . \\ . \\ . \\ . \\ Vn \end{bmatrix} \quad (3.3)$$

Stator variables in stationary reference frame are transformed to synchronous reference frame. In this transformation the q- axis of the voltage variable is aligned to zero and only the d- axis variable is present for easy control.

$$\begin{bmatrix} Vqe \\ Vde \end{bmatrix} = \begin{bmatrix} cos\ \Theta e & sin\Theta e \\ -sin\Theta e & cos\Theta e \end{bmatrix} \begin{bmatrix} Vqs \\ Vds \end{bmatrix} \quad (3.4)$$

As stator to rotor coupling takes place in only d-q equations, rotational transformation is applied to these two pairs of equation. The nature of this equation is identical to the three phase machine equations. Assuming that the machine equations are transformed into arbitrary frame of references rotating at angular speed ,ωe , the model of m- phase induction machine with Stator side voltage equations in d- and q- reference frame are given as follows

$V_{ds} = R_s\, i_{ds} - \omega_e\varphi_{qs} + \rho\varphi_{ds}$ (3.5)

$V_{qs} = R_s\, i_{qs} + \omega_e\, \varphi_{ds} + \rho\varphi_{qs}$

- ✓ Rotor side voltage equations in d- and q- reference frame are given as,

$V_{dr} = Rr\ idr - (\omega r - \omega r)\ \varphi qr + \rho\varphi dr$

$Vqr = Rr\ iqr + (\omega e - \omega r)\ \varphi dr + \rho\varphi qr$ (3.6)

The flux linkage expressions in terms of currents can be written as follows

$\Psi_{ds}^{e} = \int Vds - R_s * i_{ds} + \omega_e * \psi_{qs}^{e}$

$\Psi_{qs}^{e} = \int Vqs - R_s * i_{qs} + \omega_e * \psi_{ds}^{e}$

$\Psi_{dr}^{e} = \int Vdr - R_r * i_{dr} + (\omega_{e-}\ \omega_r) * \psi_{qr}^{e}$ (3.7)

$\Psi_{qr}^{e} = \int Vqr - R_r * i_{qr} - (\omega_{e-}\ \omega_r) * \psi_{dr}^{e}$

$\psi_{qm} = L_m(i_{qs} + i_{qr})$

$\psi_{dm} = L_m(i_{ds} + i_{dr})$

Current expression in terms of flux linkage and leakage inductance of the motor

$i_{qs}^{e} = (\psi_{qs} - \psi_{qm})/L_{1s}$

$i_{qr}^{e} = (\psi_{qr} - \psi_{qm})/L_{1r}$

$i_{ds}^{e} = (\psi_{ds} - \psi_{dm})/L_{1s}$ (3.8)

$i_{dr}^{e} = (\psi_{dr} - \psi_{dm})/L_{1r}$

Transformation of stator current in synchronous reference frame to stationary reference frame

$$\begin{bmatrix} iqs \\ ids \end{bmatrix} = \begin{bmatrix} cos\ \Theta e & sin\Theta e \\ -sin\Theta e & cos\Theta e \end{bmatrix} \begin{bmatrix} iqe \\ ide \end{bmatrix} \quad (3.9)$$

To obtain the multi- phase stator current from the stator currents in stationary reference frame by 2-Φ to 12-Φ transformation

$I_a = i_{qs} \cos\Theta e + i_{ds} \sin\Theta e$

$I_b = i_{qs} \cos(\Theta e - \alpha) + i_{ds} \sin(\Theta e - \alpha)$

$I_c = i_{qs} \cos(\Theta e - 2\alpha) + i_{ds} \sin(\Theta e - 2\alpha)$

$I_d = i_{qs} \cos(\Theta e - 3\alpha) + i_{ds} \sin(\Theta e - 3\alpha)$

$I_e = i_{qs} \cos(\Theta e - 4\alpha) + i_{ds} \sin(\Theta e - 4\alpha)$

$I_f = i_{qs} \cos(\Theta e - 5\alpha) + i_{ds} \sin(\Theta e - 5\alpha)$

$I_g = i_{qs} \cos(\Theta e - 6\alpha) + i_{ds} \sin(\Theta e - 6\alpha)$

$I_h = i_{qs} \cos(\Theta e - 7\alpha) + i_{ds} \sin(\Theta e - 7\alpha)$ (3.10)

$I_i = i_{qs} \cos(\Theta e - 8\alpha) + i_{ds} \sin(\Theta e - 8\alpha$

$I_j = i_{qs} \cos(\Theta e - 9\alpha) + i_{ds} \sin(\Theta e - 9\alpha)$

$I_k = i_{qs} \cos(\Theta e - 10\alpha) + i_{ds} \sin(\Theta e - 10\alpha)$

$I_l = i_{qs} \cos(\Theta e - 11\alpha) + i_{ds} \sin(\Theta e - 11\alpha)$

Electromechanical torque and rotor speed of the five phase induction motor is obtained by (3.11) and (3.12) respectively

$$T_e = P * L_m * (I_{qs} I_{dr} - i_{ds} i_{qr}) \quad (3.11)$$

$$\omega_r = \int \frac{p}{2} * \frac{Te - Tl - B}{J} \, dt \quad (3.12)$$

Simulink modelling of 12-phase induction motor

This Simulink model is modeled from supply voltage to speed and torque production processes way, then conversion first start from supply phase voltage changing in two phase alpha beta or stationary, and the stationary reference frame changed into synchronous reference frame by means of angle ‘’ ϴe’’ and also continuous up to the torque production and rotor speed.

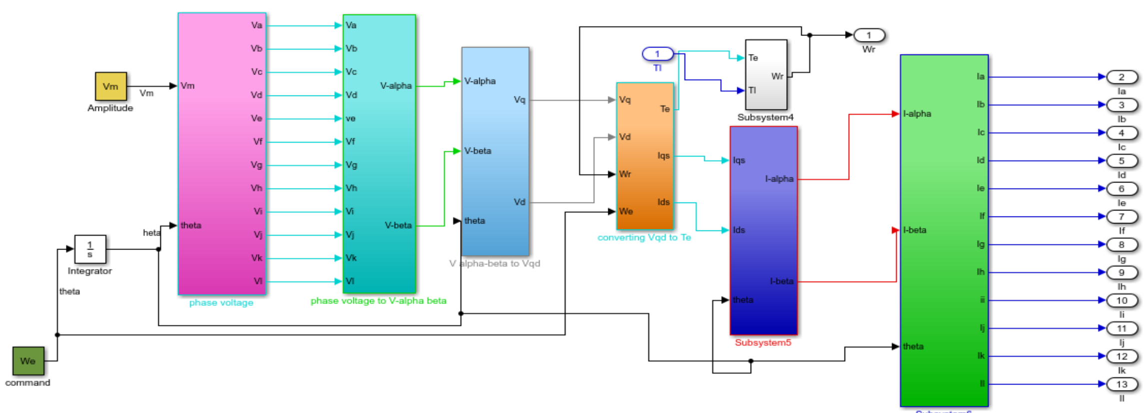


Figure 3-2 :-Simulink model of 12-phase induction motor

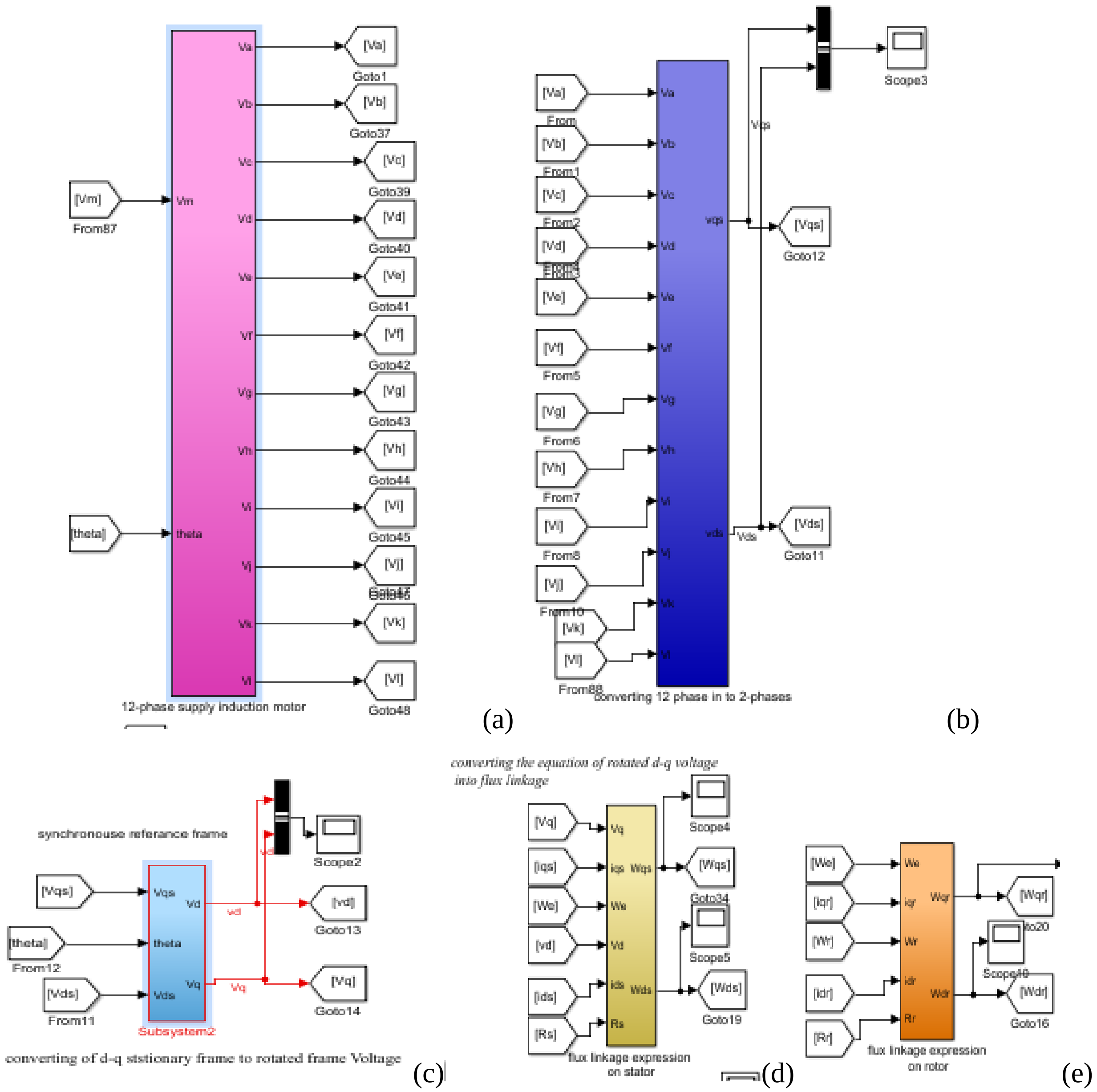


Figure 3-3 :- a) supply voltage b) conversion of voltage from m-phase to 2-phase c) changing 2-phase stationary into 2-phase synchronous voltage d)flux linkage conversion on stator e) flux linkage conversion on rotor

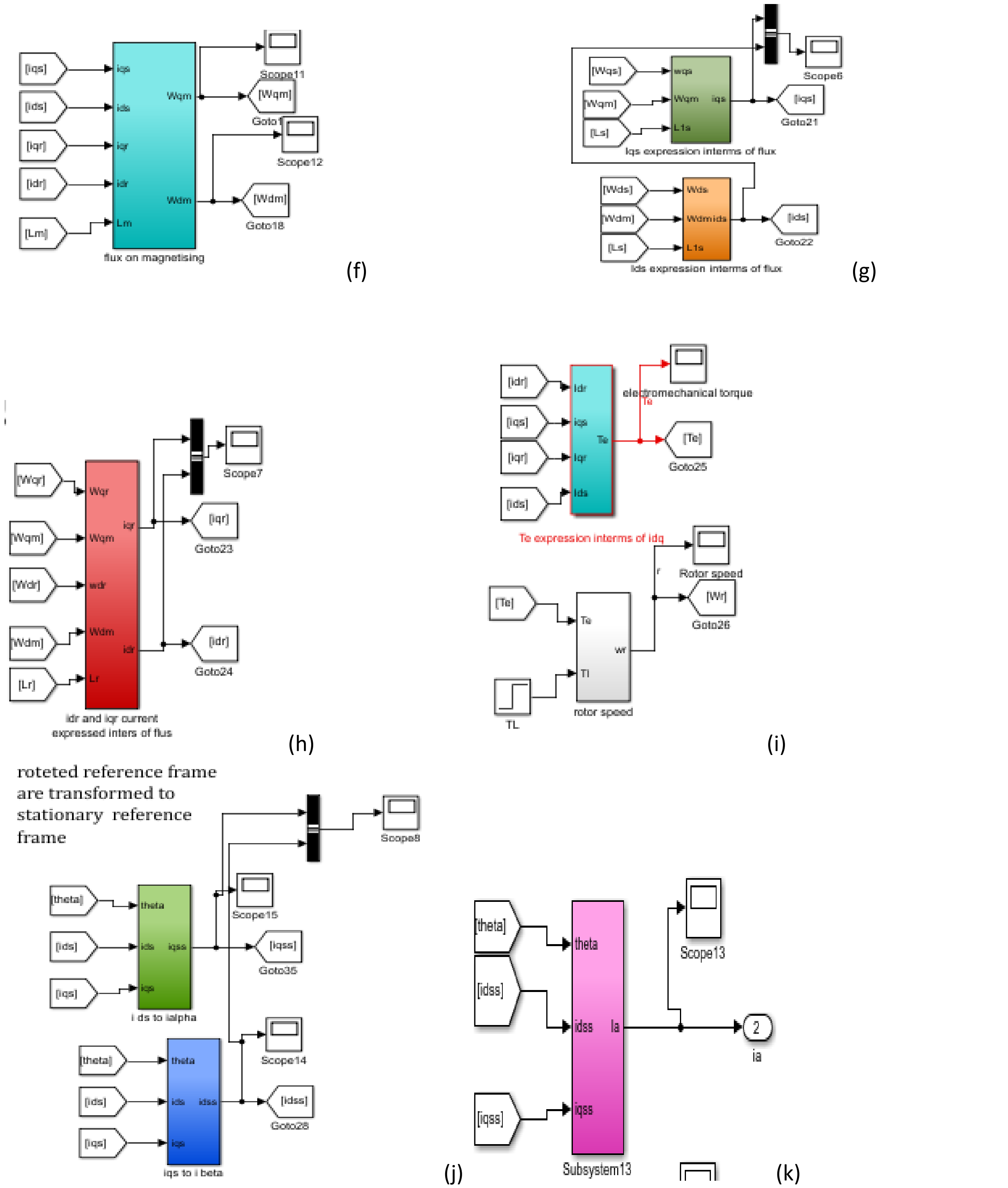


Figure 3-4:- f) mutual flux linkage conversion g) synchronous stator current conversion h) synchronous rotor current conversion i) Electromagnetic torque conversion j) changing of stationary current conversion

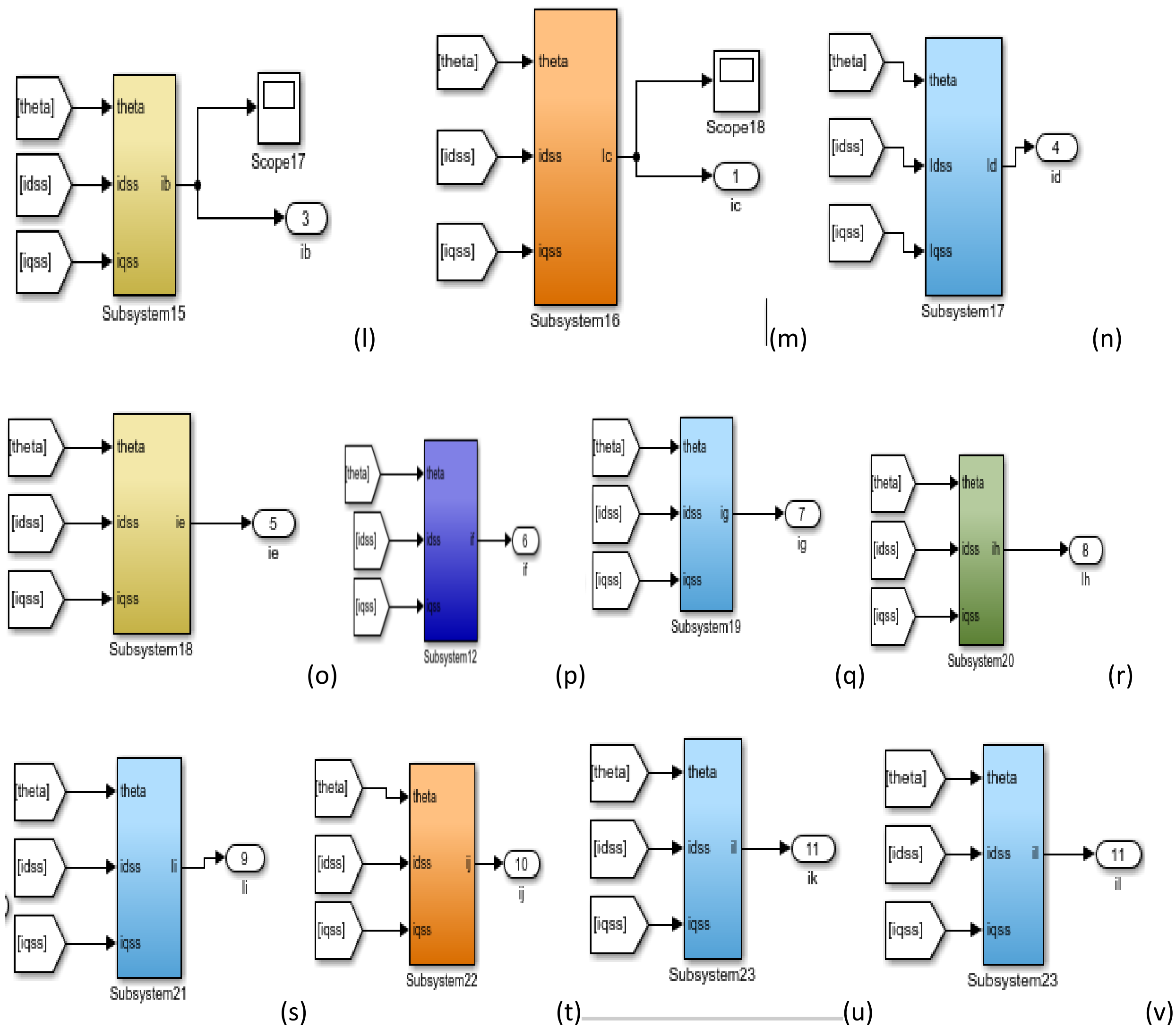


Figure 3-5 :-12-phase current i_a-i_l simulink model diagram of (k-v)

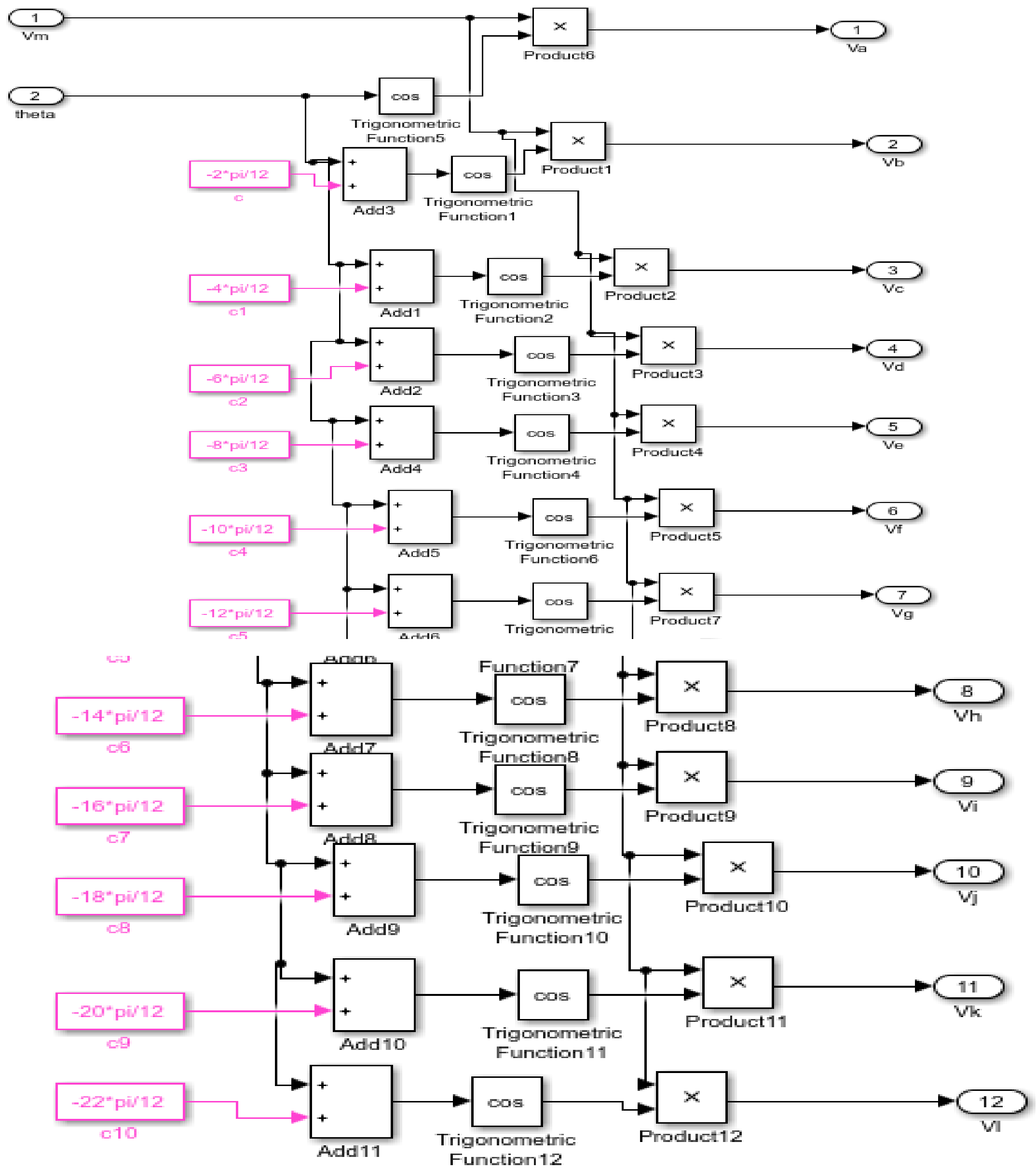


Figure 3-6 :-12-phase voltage supply simulink diagram Convertion 12-phase into 2-phase of stationary referance frame simuling diagrame by using the phase shifting internal structure

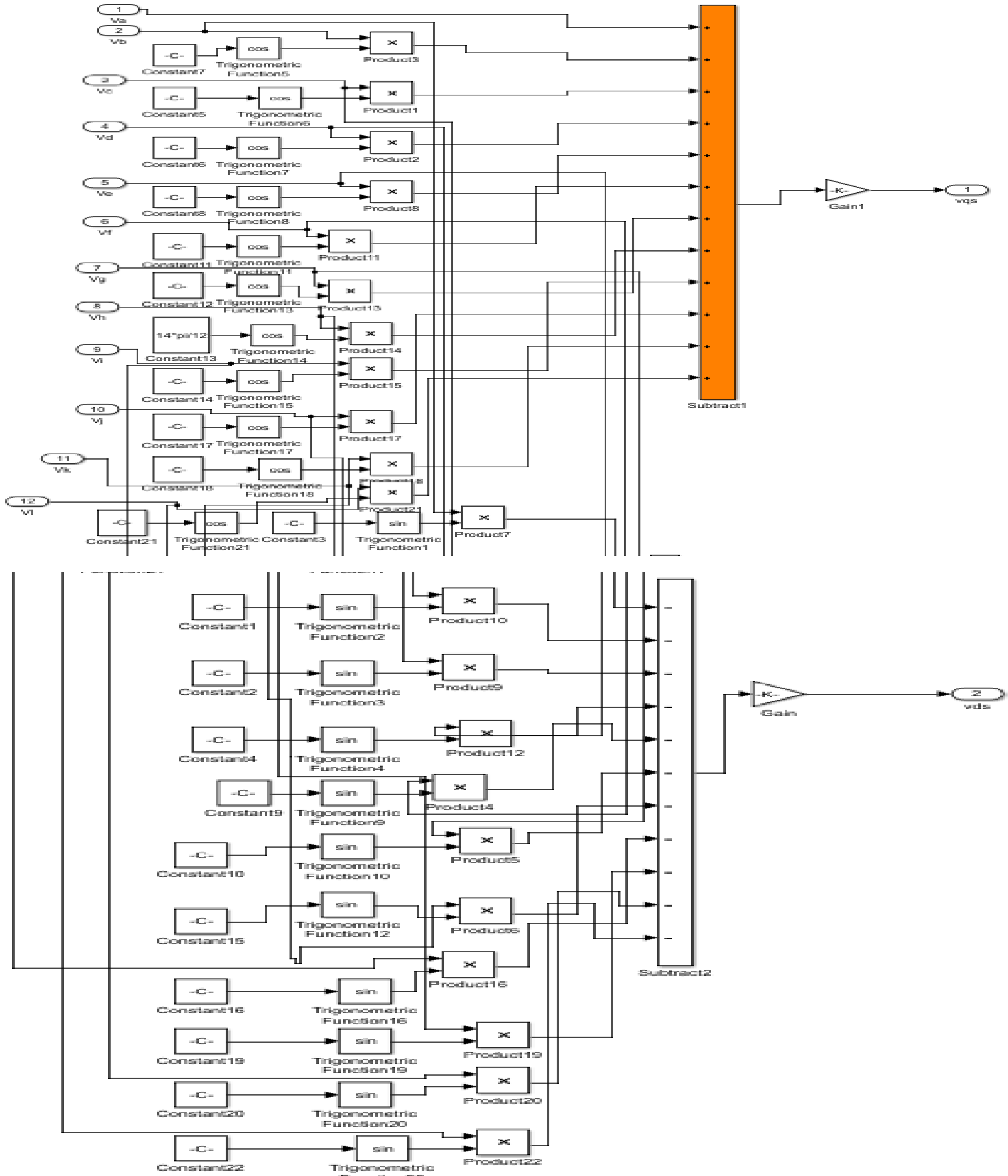


Figure 3-7 :- conversion of 12-phase in two stationary referance frame simulink model of internal structure

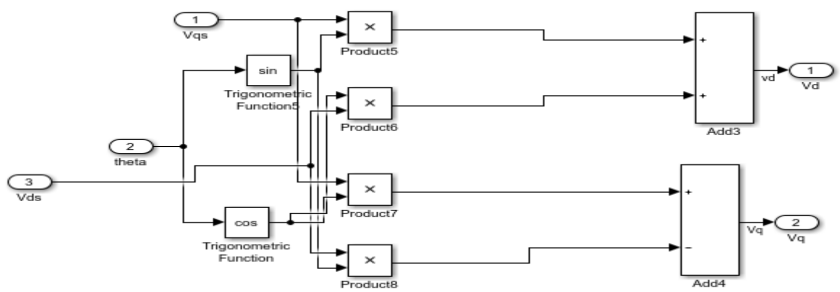


Figure 3-8:- conversion of stationary 2-phase to synchronous 2-phase voltage internal structure

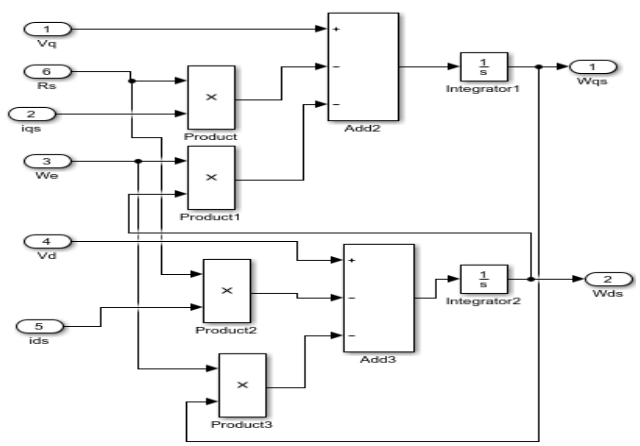


Figure 3-9 :-conversion of synchronous voltage into stator flux of internal structure

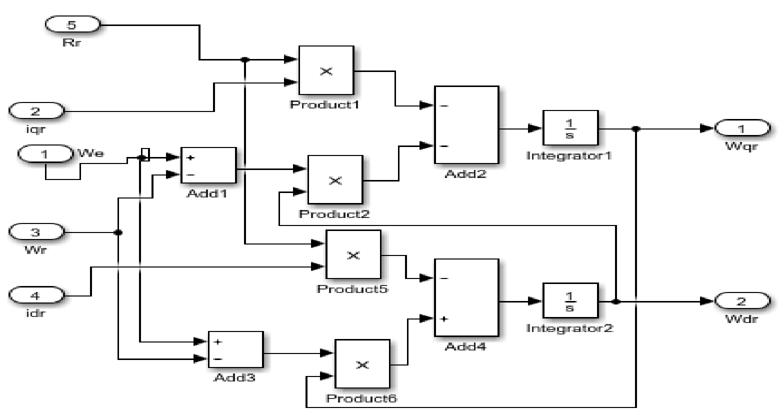


Figure 3-10 :-conversion of synchronous voltage into rotor flux of internal structure

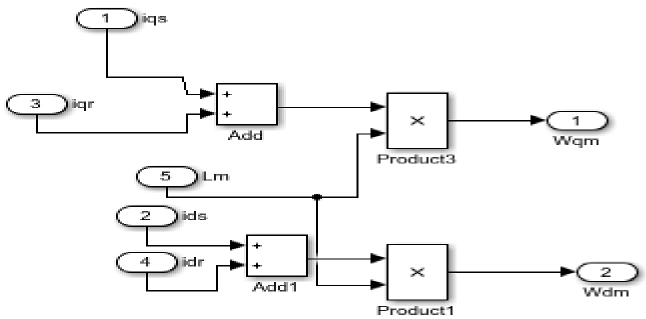


Figure 3-11:- simulink diagrame of magnetising flux along d and q axis intrnal stucture

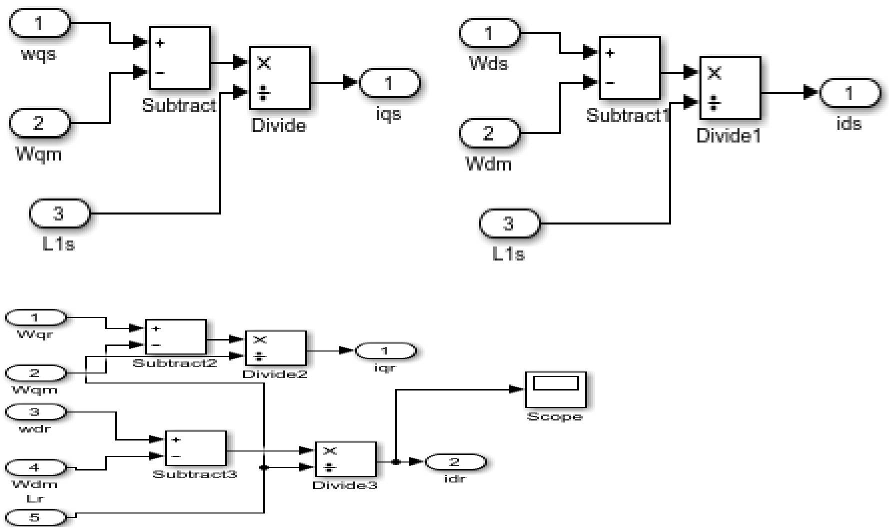


Figure 3-12 :- simulink diagram of current along d and q axis of stator and rotor interms of flux model intrnal structure

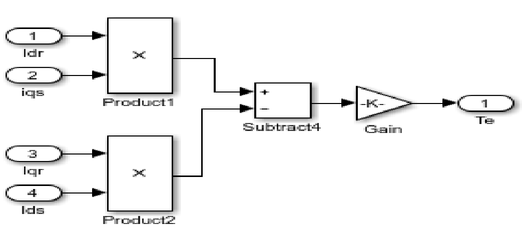


Figure 3-13 :- simulink model of electro mechanical torque

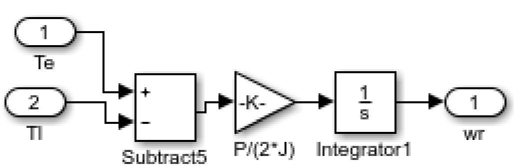


Figure 3 -14:- simulink model of rotor speed

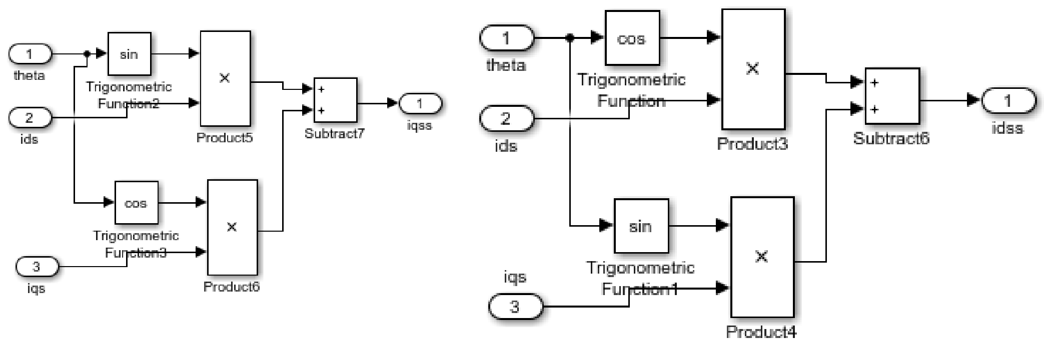
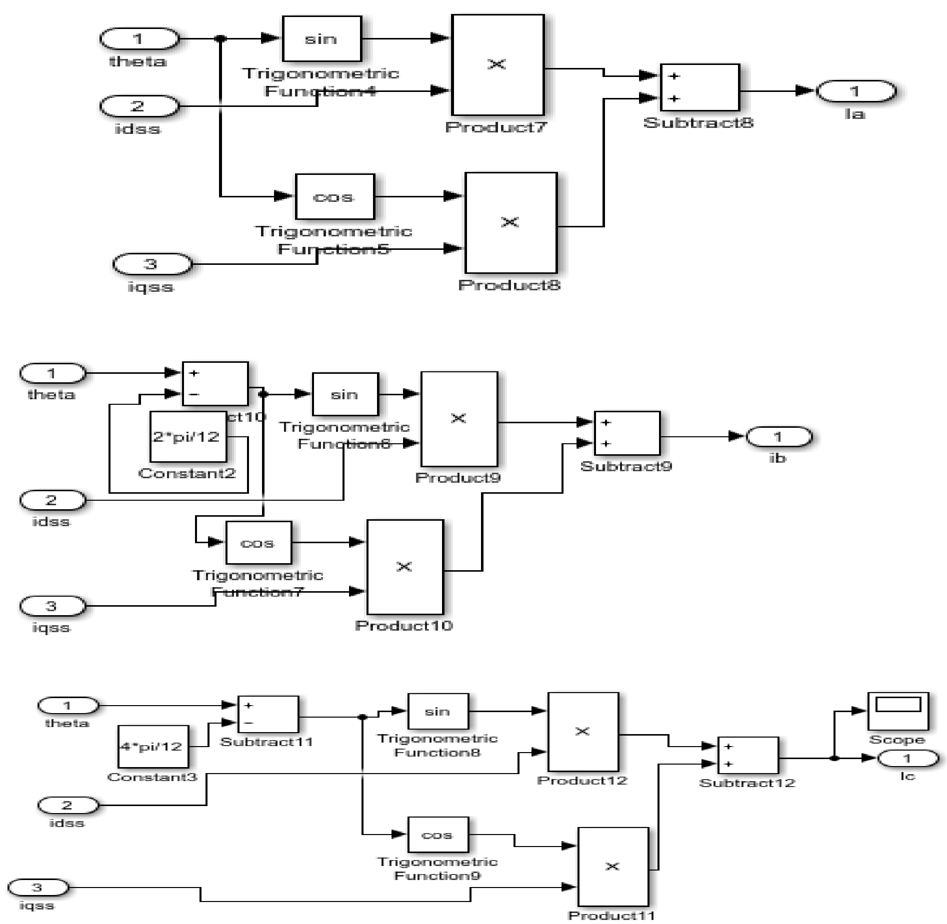
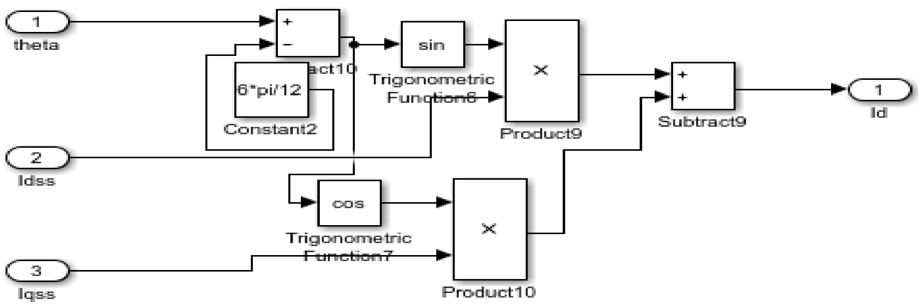


Figure 3-15:- simulink model of the convertion of synchronous refrance frame to stationary referance frame of current

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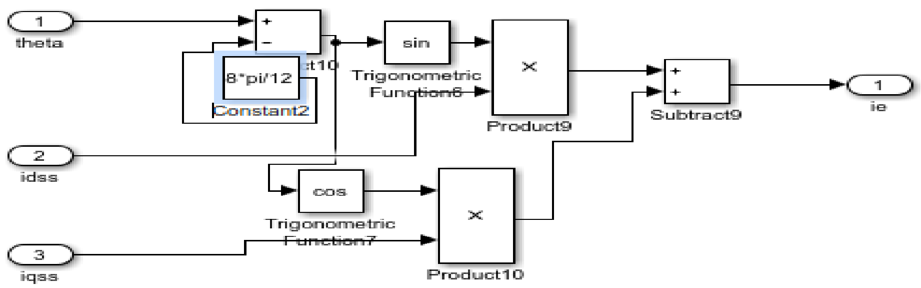
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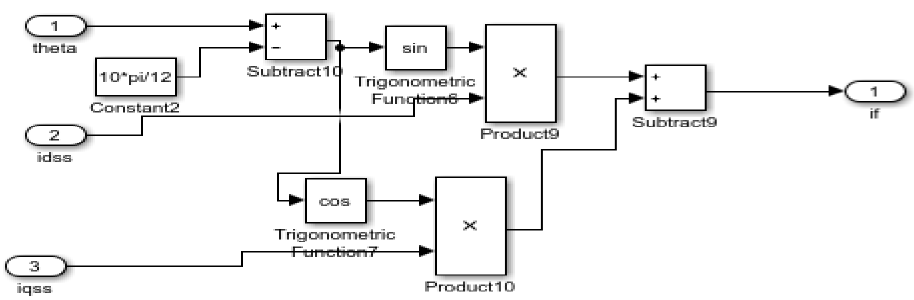
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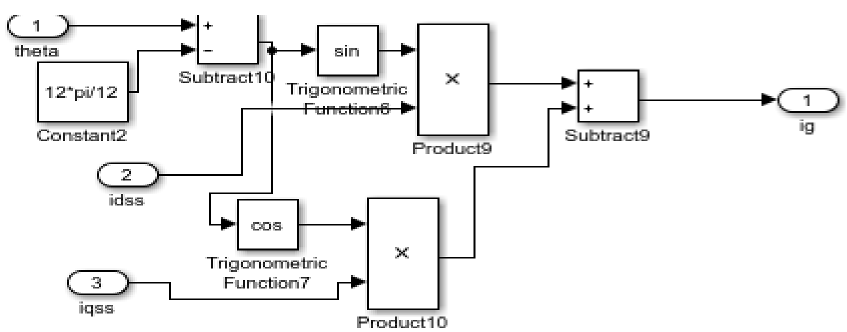
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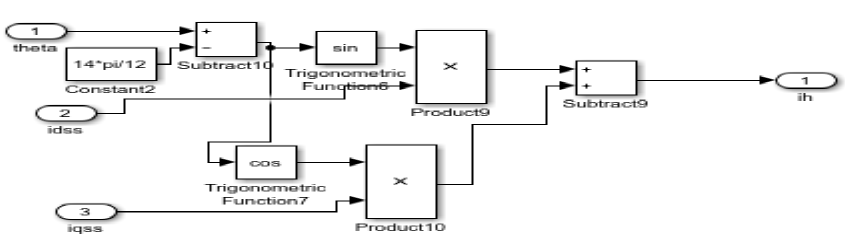
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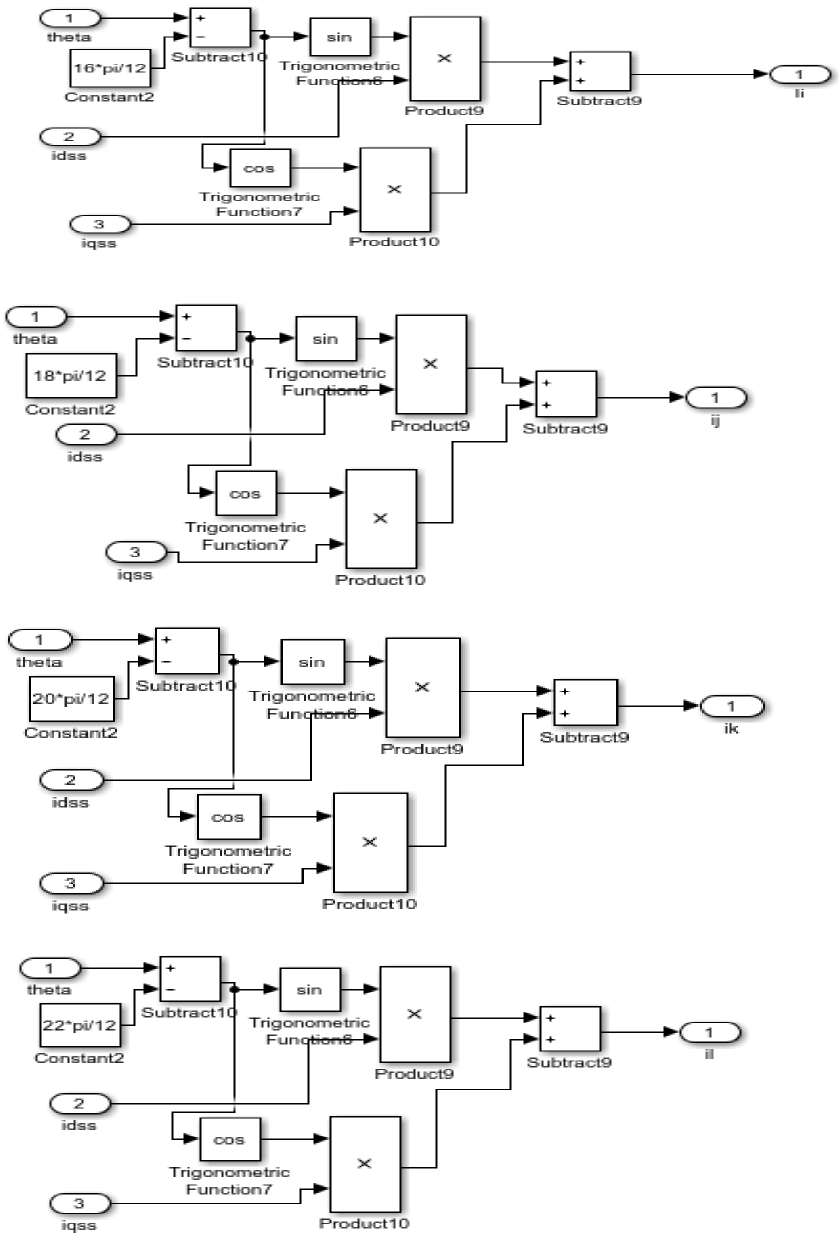

Figure 3-16 :- simulink modell of 12-phase current (i_a-i_l)

CHAPTER 4

SIMULINK RESULT AND DISCUSSION

Multi-phase induction motor design and modelling from above chapters can be discussed in the form mathematical calculation on design and modelling m-phase when we combine both of them they can fit the operational characteristic of induction machine property or not by investigate on the Simulink results and then selecting the appropriate phase for electric vehicle , as phase increase from convectional three phase to m-phase … appropriated value that calculated on

appendix value is at 12-phase the minimum slot size is ends ,so at ,that means the designed multiphase induction motor parameters that calculated at constant current and power is ,when we model depending up on the value get from designing machine parameter is operated or not we can discussed depend up on the results starting from input voltage per phase and the commanded value what we calculated from designed parameter depending the machine capacity ,then the result discussion can be follow as below.

As explained on designing of multiphase induction machine at which constant current and power as the number phase increase the voltage supply is decreases therefore, depending up on the mathematical calculation on appendix 1 ,for the current 26.5A and 5000w power the 12-phase induction motor per phase voltage is 19.5 V for the same machine size with in three phase induction design for the minimum slot size reached at 0.15 cm .then the voltage 12-phase is became at which angle Θe become:-

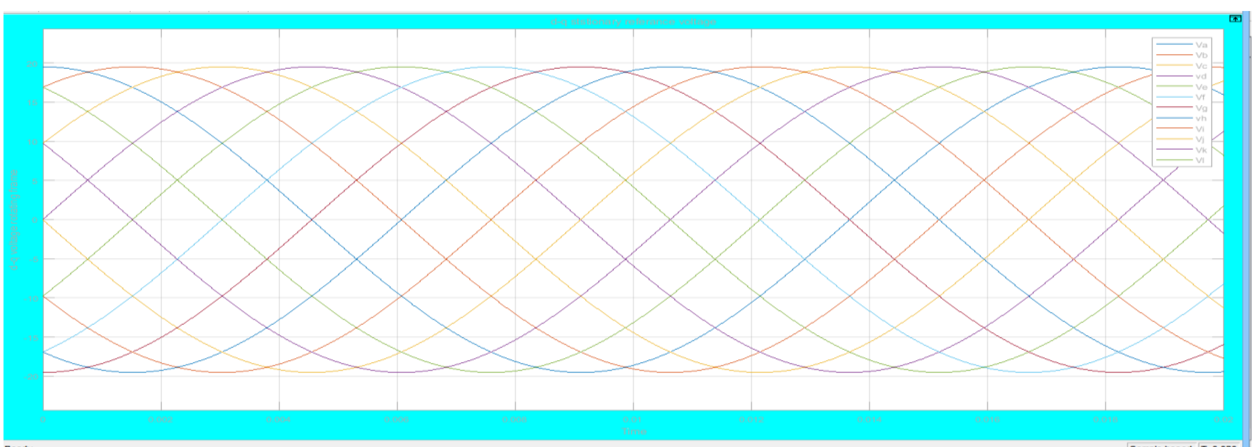

Figure 4-0-1:-12-phase voltage

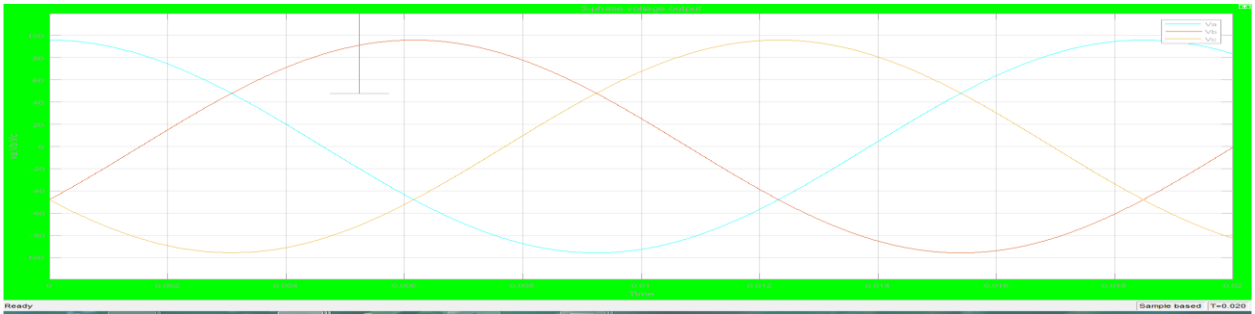

Figure 4-0-2 :- 3-phase supply voltage Simulink result

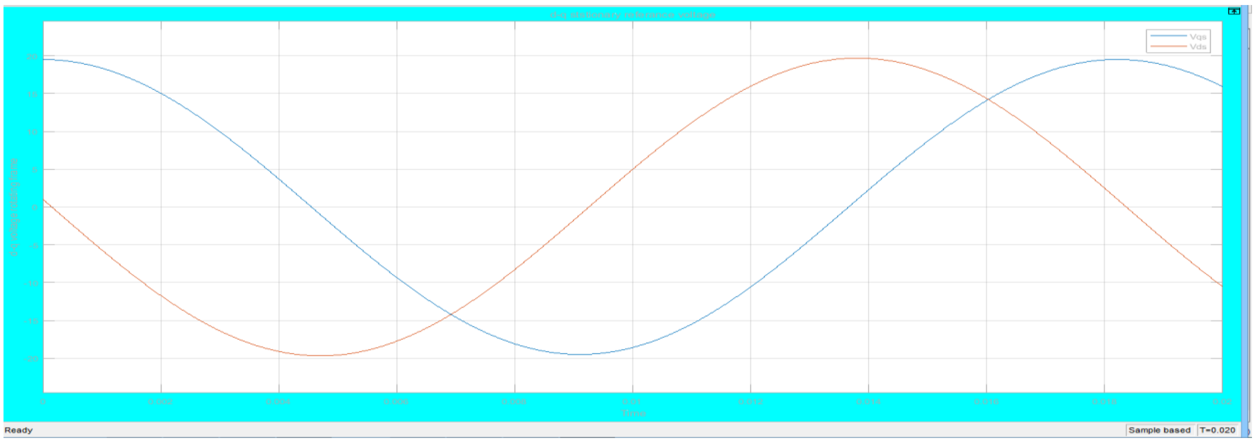

Figure 4-0-3 :- converting of 12-phase voltage in to stationary reference voltage of 2-phase

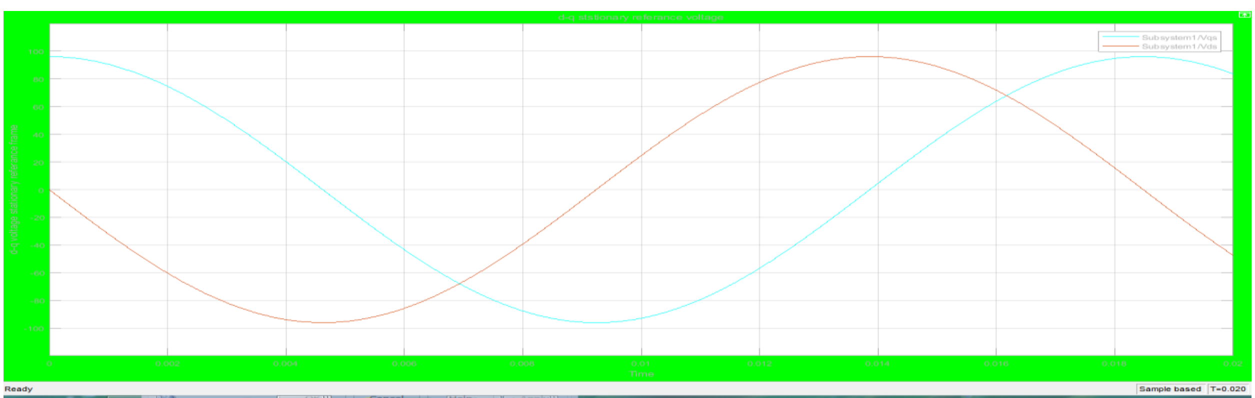

Figure 4-0-4 :- converting of 3-phase voltage in to stationary reference voltage of 2-phase

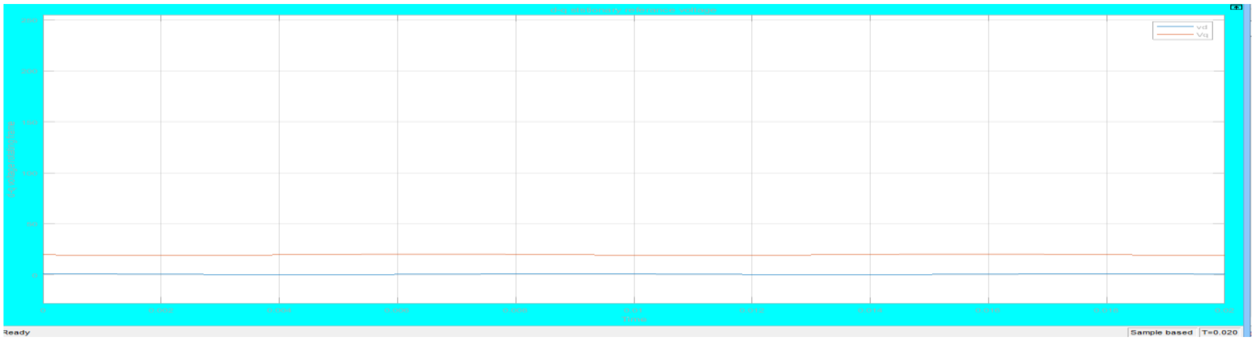

Figure 4-0-5:- conversion of 2-phase stationary to 2-phase synchronous voltages (iαβ to iqd)

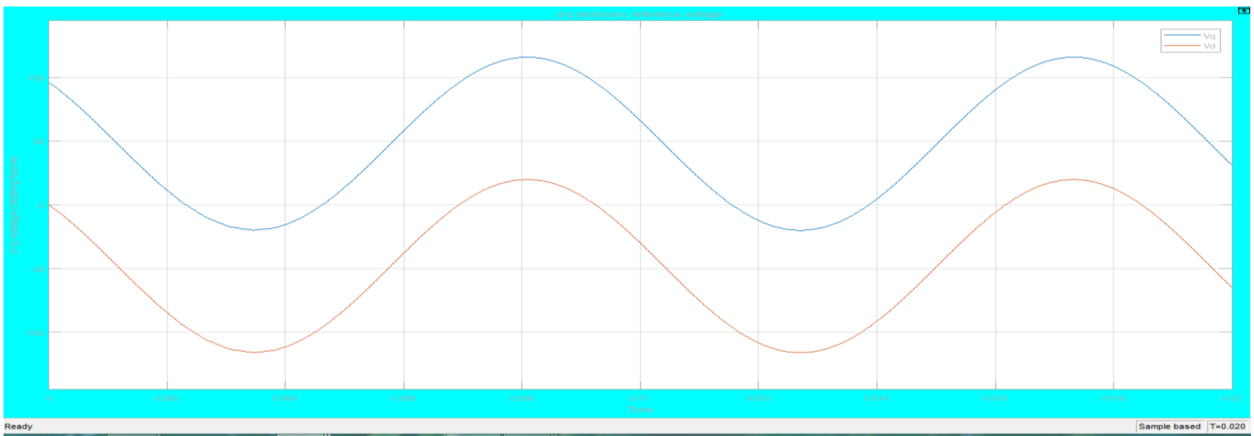

Figure 4-0-6 :- conversion of 2-phase stationary to 2-phase synchronous voltages (iαβ to iqd)

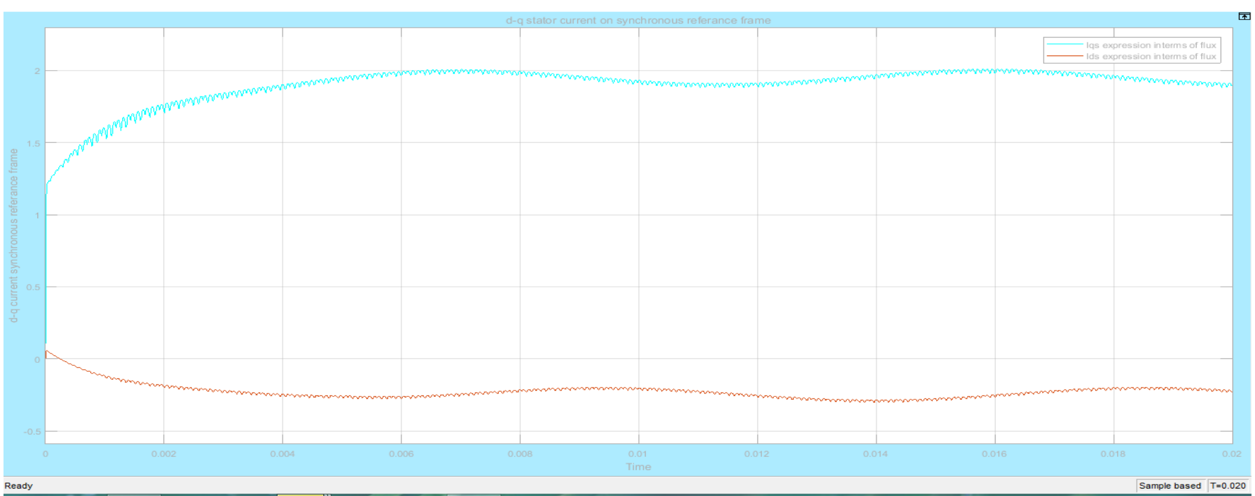

Figure 4-0-7:- I_{qds} current on synchronous reference frame of 12-phase

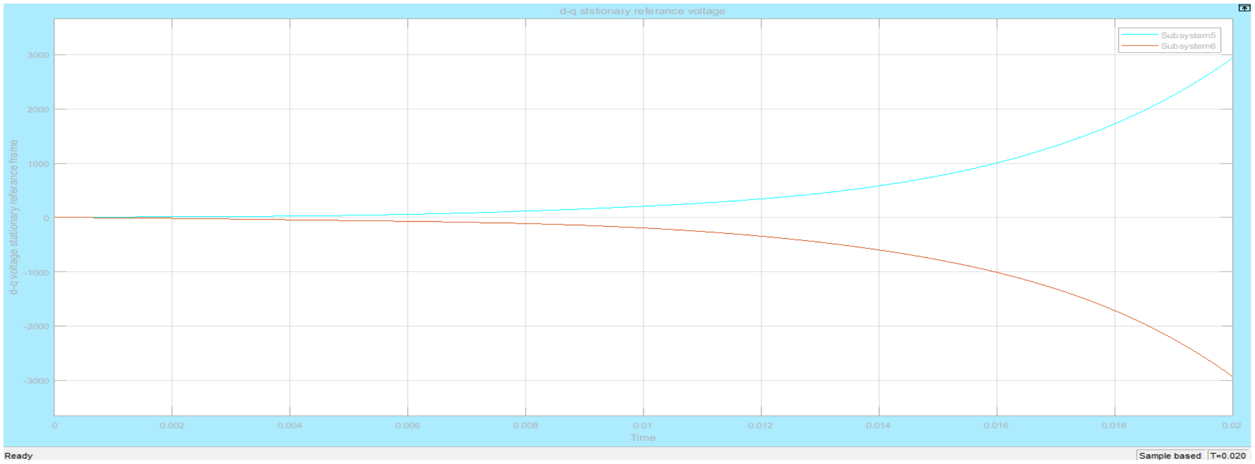

Figure 4-0-8:- I_{qds} current on synchronous reference frame of 3-phase

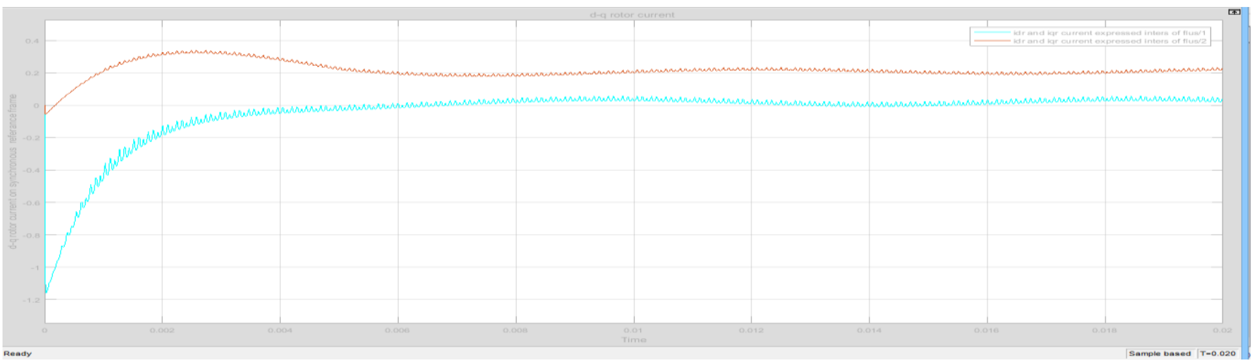

Figure 4-0-9:-I_{qdr} rotor current of 12-phase

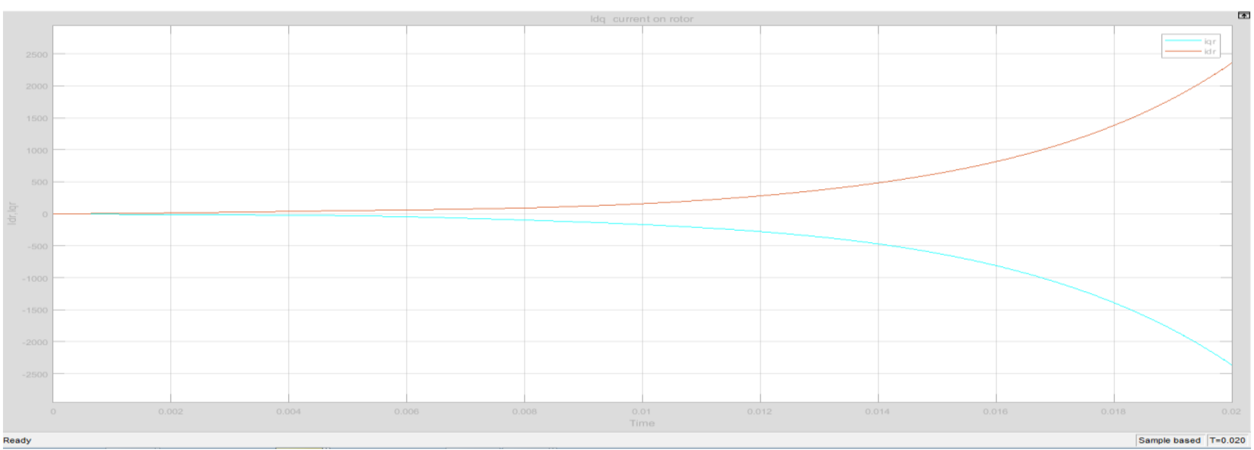

Figure 4-0-10:-I_{qdr} rotor current of 3-phase

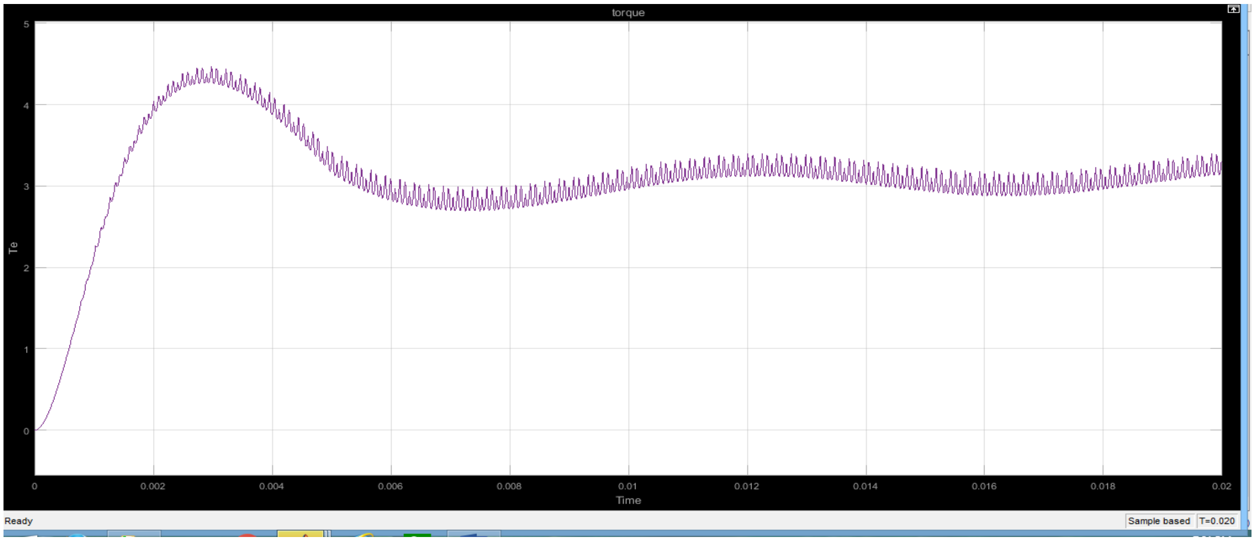

Figure 4-0-11:- 12-phase electro-mechanical torque

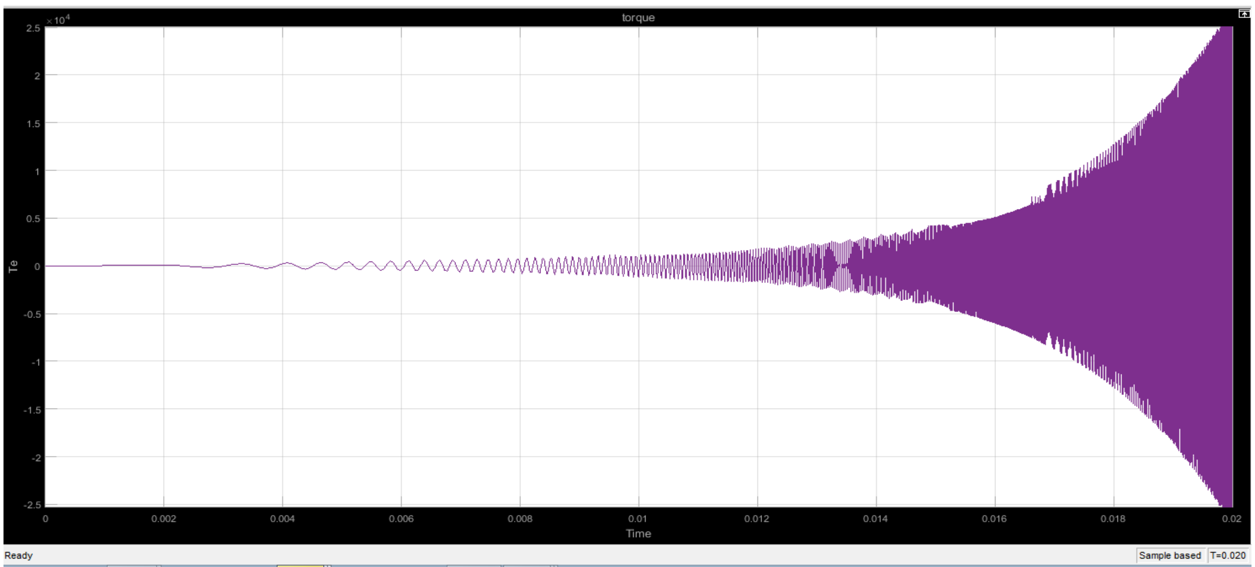

Figure 4-0-12 :- 3-phase electro-mechanical torque

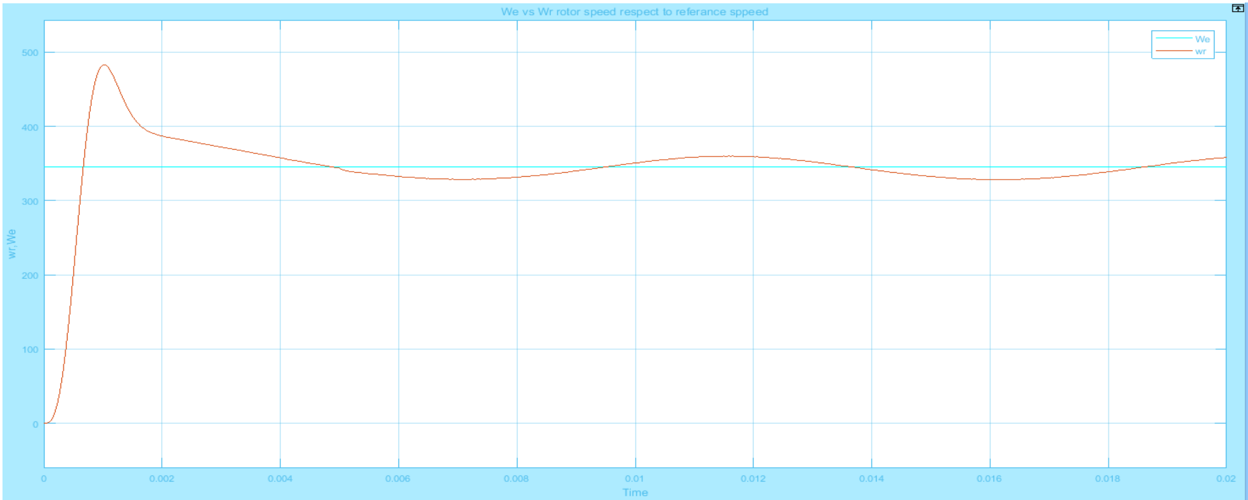

Figure 4-0-13:- rotor speed(wr)and reference speed(We)vs time Simulink result of 12-phase

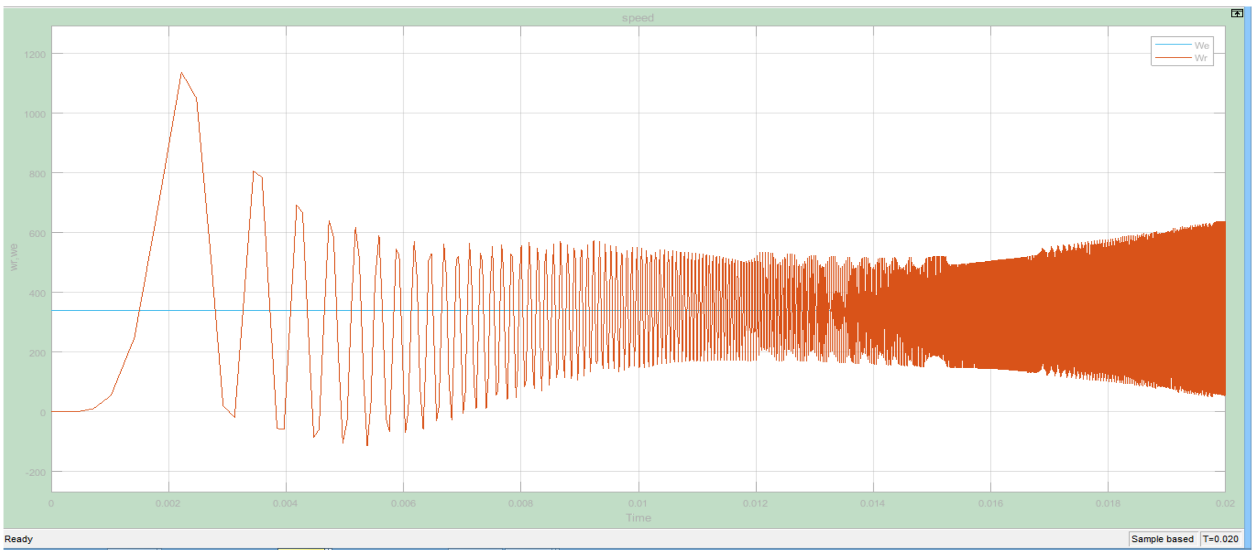

Figure 4-14:- rotor speed(wr)and reference speed(We)vs time Simulink result of 3-phase

Discussion

For analyzing of multiphase induction motor that preferable for electric vehicle depending in our results, so from the result we starting from the supply voltage , the supply voltage comparison for 3-phase to 12-phase is decreased ,at the condition the designing of the machine the current and power is constant ,at 3-phase supply voltage is the amplitude is 96V and for 5-phase __V , 9-phase _____V and 12-phase ___V and for consequence of that the number battery is decreased , the designed machine for modelling must be fit the induction machine operational characteristics at 12-phase as load increase the the speed is decrease and also starting torque is decreased as phase increased that one the advantage of mult-phase induction motor so at 0.005 second the load Added then the speed becomes decreased and also as phase increases the pulsating is decreased become constant value

CHAPTER 5

CONCLUSION

This paper presents selecting the appropriate multiphase induction motor for electric vehicle application so, the model is depend up on designed machine at constant current and power calculated by mathematical relationship between the machine size and electrical circuit relationship. The model is based on the *d-q* axis equivalent circuit. The simulation model is developed using simpower system block set of the Matlab/Simulink software.

The comprehensive model of the *n*-phase induction motor for electric vehicle (EV) is simulated varying phase, making power and current kept constant until the minimum slot size ends. The model is simulated to study as phase increase at the condition current and power is constant, the voltage supply needed for m-phase machine is decreases, and dynamic behavior of the multi-phase induction motor. The simulation results are presented for 3, *5*, *9* and *12* phases under varying phase conditions. The steady state are observed under different phase supply voltage .The model performs effectively for different number of phases and the 12-phase induction motor is selected for different condition is the best for electric vehicle . The fault tolerant simulation results show, with the additional degrees freedom of multiphase structure.

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APPENDIX 1

```
% modelling of multiphase induction motor At connistant power and
%current,by varying the number phases IM, until the minimume slot pitch,and
%calculate the value of voltage per phases for each phases,
%//////////////////////////////////////////////////////////////////////////////
%/////////////////////////////////////////////////////////////////////////
%fprintf('\n INPUT THE SPECIATIONS OF THEINDUCTION MOTOR\n')
p=5000;
f=input('frequency f=');
theta=40.966;
m=input('number of phase m=');
po=4;
Iph=26.75;
K=1;
pf=0.85;
Bav=0.6;
q=16000;
Kw=0.955;
eff=0.8;
% calculate the phase voltage at connistant current and power
Vph=p/(m*Iph*eff)
% to find speed
Ns=120*f/po
% to findinput kvA
Q=p/(eff*pf)
% to find out put co-efficient
Co=11*Kw*Bav*q*10^-3
% To find D&L
%i. To obtain minimum over all cost 1.5 to 2.0
%ii. To obtain good efficiency 1.4 to 1.6
%iii. To obtain good over all design 1.0 to 1.1
%iv. To obtain good power factor 1.0 to 1.3
X=input('design consideration of the ratio L/Yss=')
D=abs((Q*po/(Co*Ns*X*pi))^(1/3))
L=X*pi*D/(po)
% to find pole pitch
Pp=(pi*D)/po
% to find pspeed
pspeed=(pi*D*Ns)
% Li net length
Li=0.9*(L-2*0.01)
% stator design
fm=Bav*(pi*D*L)% fm=flux
fmp=Bav*(pi*D*L)/po % fmp=flux per pole
% turns per phase
Tph=Vph/(4.44*f*fm*Kw)
%calculating of number conductors
Zph=2*Tph
% number of stator slots
Ss=(m/2)*po*(2+K)
% stator current per phase
Is=Iph
% Calculation of air gap length from empirical formula
lg=(5*10^-3)*D*sqrt(pi/2*po)
```

```
% Cross sectional area of the stator conductor since current
densty=3to5A/mm2,
as=input('current density=')
As=Is/as %If the As of the conductors is below 5 mm2 then usuallycircular
conductors are employed.
% The total conductor per stator slot is calculated
% total number of conductor
Zs=2*m*Tph
% stator conductor per slot can be calculated
Zss=2*m*Tph/(Ss)
% Calculation of stator slot pitch is( note that b/n 1.5-2.5cm)
Yss=pi*D/(Ss)% gap surface per total number of stator slot ratio
% Calculation of area of stator slot
sf=input('space factor sf=')%b/n 0.25and.35;using lower space factor for high
voltage ,hewer we are designing of lower voltage
% copper area per slot=Zss*As
Ass=Zss*As/(sf)% area of each stator slot
 % Check for specific electric loading
 ac=2*m*Tph*Iph/(pi*D)% compare q and ac
 % Select suitable values of flux density in stator
  Bcs=input('flux density stator core Bcs=')
  dcs=fm/(2*Bcs*Li) % depth of stator core
  % Outside diameter of stator laminations
  h=input('\nheight of the core in m= \n')% 25-30mm
  %h=Space occupied by insulated conductor,>= 23.6 mm+ Coil insulation,>= 4.0
mm; Slot liner,>=0.6 mm
 % Coil separator,>=0.5 mm +Top liner,=0.5 mm+Clearance= 1.3mm
  lip=input('\nlip in meters =\n')% the valu b/n 1-2mm
  wedge=input('\nwedge in meters = \n')% the value b/n 3.5 to 5mm
  dss=h+lip+wedge
  % Length of the mean Turn:
  Lmt=2*L+2.3*Pp+0.24
  % Calculation of stator winding resistance
  Rs =0.021*Tph*Lmt/As
  % Total copper losses in stator winding
  Qcl=m*Is^2*Rs
  % calculation of Flux density in stator tooth:
  tmapp=fm/1.7 %tmapp=minimumetooth area per pole
 wst=tmapp/((Ss/po)*Li) %wst=minimume stator tooth is must be nearest to gap
surface
  hts=dss
  d=D+((1/3)*hts*2)% Diameter at 1/3rd height from narrow end
  Ys=(pi*d)/Ss % Slot pitch at 1/3rd height
  at=wst*Li %Area of one stator tooth
  Ws=Ys-wst
  ntp=Ss/po % ntp= number tooth per pole,A't=Area of all the stator tooth per
pole
  At=wst*Li*ntp
  Bt=fm/At
  Bmax=1.5*Bt
  % to find the value of dss depending up on lip,Wedge,Conductor
insulation,Slot liner,Coil separator,Coil insulation
% Co nductor the sum of all discussed lip
  Do=D+2*dcs+2*dss% he ratio of slot depth to slot width is assumed 3to6
  dcs= 1/2*(Do-D-2*dss)
  Asc=Li*dcs %Asc=Area of stator core
  fmc=1/2*fm %Flux in stator core
```

```
  Bc=fmc/Asc
  %Width of the slot=Space occupied by insulated conductor,8.7mm + Coil
%insulation2.0mm +Slot liner0.4mm+Clearance 0.9 mm
soic=input('Space occupied by insulated conductor soic=')
coi=input('Coil insulation coi=')
sl=input('Slot liner sl=')
cl=input('clearance cl=')
bw=soic+coi+sl+cl
  bs2=dss/3
   bs1=dss/6
   hs=dss
   hw=wedge % the wedge of siutable thichness 3.5-5mm
   hos= lip % % the valu b/n 1-2mm
   lend=input('legth of conductor in end connection lend=')% the wedge of
siutable thichness 3.5-5mm
   bo=bs1;
   bt=Yss-Ws %the normal tooth width
   bos=input('the value will be aproximetly but no equal but less than
bs1<=')% stator slot opening
   kc=input('kartes coefficient kc=')%the value is b/n 1-1.5
   beta=input('coil pitch to pole pitch ratio beta=')% belt leakage conistant
0.5-1 depending of kbs andkbr
   k=Ss/po/m
   lsls=[2*hs/3*(bs1+bs2)]+[2*hw/(bos+bs1)+[hos/bos]*(1+3*beta)/4]
   lds= ((5*lg*kc/bo)/(5/4*lg*kc/bo))*(3*beta+1)/4
   les=(0.34*k/L)*(lend+0.64*beta*Pp)
   lss=lsls+lds+les
  % Rotor design
  Sr=Ss-po/2 % Rotor slot
  % Rotor bar current
  ab=input('\rotor bar current density ab=')
  Ib=0.85*((2*m*Is*Tph)/Sr)*cos(1.3)
  Ab=Ib/ab % Area of rotor bar

 %the current density in rotor bars which normally varies between4 to 7 A/mm2
  % For aluminum bar it is between 2.2 and 4.5 A/mm2,
 %For deep bar rotor it is between 5.5 and 7.5 A/mm2,For load with large
inertiaand high rated speed, it should not exceed 6.5 to 7 A/mm2.
  Afs=input('allowance for skewing Afs=')
 Lb = L + Afs
 Rb=0.021*Lb/(Ab)
 %rotor diameter calculation
 Dr=D-2*lg
 % rotor slot pitch calculation
 Yrs=pi*Dr/Sr
 % Calculation of copper losses in rotor bar(Qclr)
  Qclr=Sr*Ib^2*Rb
 % Calculation of end ring current
  Ibav=0.45045*Sr*Ib/po %Ibav=average current bar
  % rms value of end ring current,
  Ie=Sr*Ib/(po*pi*1.11)
  ae=input('end current dencity ae=')
  % area of end ring
  Ae=Ie/ae %ae=between 4.5 and 7.5 A/mm2
   Dme=input('Mean diameter of end ring Dme=')
     %should be b/n 4 to 6 cm
   % where end ring resistance,
```

```
  Lme=pi*Dme
   Re=0.021*Lme/Ae
   % Copper loss in end ring
   Qler=2*Ie^2*Re
   Ir=0.85*Is
   % total copper loss
   Qtotal=Qler+Qclr
  % Rotor resistance calculation
   Rr=Qtotal/(m*(Ir)^2)
   % height of slot is beween 2*bw and4*bw but for hs we must ta so insert
   %Outer diameter of end ring
 de=input('depth of end ring, mm de=')
 dsr=('depth of rotor slot, mm dsr=')
 Doe=Dr-2*dsr*10^-3
% Inner diameter of end ring
Die=Doe-2*de*10^-3
% Mean diameter of end ring
De=(Doe+Die)/2
%Rotor Teeth
% Actual Width of teeth provider=Awt
Wsr=input('rotor slot width wsr=')
Awt=pi*(Dr-2*dsr)/Sr-Wsr
% Rotor Core
Bcr=input('flux density 0f Bcr=')% b/n 1.2-1.4
dcr=fm/(2*Bcr*Li)
%calculating Inner Diameter of Rotor Laminations
Di=Dr+2*dsr+2*dcr
% calculating of magnetizing mmf in an induction machine.
% 1)MMF for air gap
kcs=kc;
kcd=kc;
% Gap Expansion Factor
Kgs=Yss/(Yss-kcs)
Kgd=L/(L-kcd*Ws)
Kg=Kgs*Kgd
B60=1.36*Bav
ATg=800,000*B60*Kg*lg
% Kcs and Kcd are the Carter?s gap co-efficient for slot and duct which
dependson the ratio slot or duct width / gap length.
% MMF for stator teeth
Wts=wst % Width of stator at 1/3 height from narrow end
Bts1 =fm/((Ss/po)*Li*Wts)% Flux density at 1/3 height of tooth from narrow
end
Bts60 =1.36*Bts1 % Calculation of mmf for stator teeth is based upon Bts60
atts=input('mmf per metre for stator teeth atts=')
ATts = atts*dss %MMF required for stator teeth,
%The mmf per metre atts for stator teeth is obtained from the graph, flux
density, B Wb/m versus ampere per meter, H A/m.
 %MMF for rotor teeth
 drs=input('deepthof rotor slot drs=')
Wrs=drs/3
Wtr1=tmapp/((Sr/po)*Li) %Width of rotor at 1/3 height from narrow end
Btr1=fm/((Sr/po)*Li*Wtr1)% Flux density in rotor teeth at 1/3 height of tooth
from narrow end
  %Calculation of mmf for stator teeth is based upon Bts60 Where
 Btr60=1.36*Btr1
 attr=input('mmf per metre for rotor teeth attr=')
```

```
 ATtr=attr*dsr % MMF required for rotor teeth attr mmf per meter from B-H
graph
 % MMF for stator core
 Lcs=1/3*Yss
 Lcs =pi*(D+2*dsr+dcs)/3*po % Length of flux path through the Stator core ,
 atcs=input('mmf per metre for stator core atcs=')
 ATcs=atcs*Lcs % Mmf required for stator core,
% MMF for rotor core
Lcr =pi*(D-2*dsr-dcs)/3*po % Length of flux path through the rotor core
atcr=input('mmf per metre for rotor core atcr=')
ATcr=atcr*Lcr %Mmf required for rotor core,
AT60= ATg+ATts+ATtr+ATcs+ATcr % Total magnetizing MMF per pole for B60
Im=0.427*po*AT60/(Kw*Tph)
% checking Operating Characteristics of multiphase induction M
% Machine Parameters
Rs =0.021*Tph*Lmt/As
Rr=4*m*Tph^2*Kw^2*(Lb/(Sr*Ab)+2*De/(pi*P^2*Ae))% The Rotor resistance per
phase referred to stator
xss = 8*pi*f*Tph^2*L*(lss/(k*Po))%Stator slot leakage reactance and lss is
specific slot permeance for stator
xrs=8*pi*f*Tph^2*L*(lrs/k*pPo)
lrs =Kw^2*lss*Ss/Sr % where lrs is slot permeance for slot
xo = 8*pi*f*Tph^2*Lo*(lo/(k*Po))% Overhang leakage reactance
lo=mu*Ks*Pp^2/(Lo*pi*Yss)% where lo specific overhang permeance,ks=slot
leakagefactor w/cis obtained from graph,lo length of conductor in over hang
xz=(5/6)*(xm/m^2)*((1/ks^2)+(1/qr^2))
xm=Vph/Im
Ro1=Rs+Rr %Total Equivalent Resistance referred to stator
Xo1=xss+xrs+xo+xz %Total Equivalent Reactance referred to stator
Zo1=sqrt(Ro1^2+Xo1^2)
% performance characteristics
% calculating of No Load Current Io condition
Io=Im+I1
% No load current Io per phase
I0perm=sqrt(Im^2+I1^2)
% No load power factor,
cos(f)=Il/Io

% Loss Component current Il
Wi=Wsp/Bm*Wtc
% Friction and Windage loss Wf
%The friction and windage losses are generally expressed in terms of output.
Itis assumed that the friction and windage losses are approximately 4% of the
Output.
Wnl=Wi+Wf % wf 4% ofthe out put
I1=Wn1/m
Isc=Esc/Zo1 % short circuite per phase
cos(fw) = Ro1/Zo1
```