

Three Phase Induction Motor -Model Design and Performance Analysis in ANSYS Maxwell

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Abstract - Three-phase squirrel-cage induction motors are widely used as industrial drives because they are self-starting, reliable and economical. To design more efficient induction motors, accurate predictions of the motor's behaviors are required. Finite element method provides us computing characteristics of induction motors without physically constructing a prototype. In this report, three phase squirrel cage induction motor is modeled, analyzed and simulated in ANSYS Electronics. Magnetic flux lines, Magnetic flux density and Magnetic field strength fields are analyzed and animated using three dimensional finite element method in ANSYS Maxwell 2D &3D. The development of power electronics devices and power converters provide smooth speed control of Induction Motors by changing the frequency of input supply. Variation of induction motor speed with frequency is also analyzed.

Key Words: Three Phase, Induction, Simulation.

1. INTRODUCTION

Three Phase Induction Motor-The most common type of AC motor being used throughout the world today is the "Induction Motor". Applications of three-phase induction motors of size varying from half a kilowatt to thousands of kilowatts are numerous. The advantages of three phase AC induction motor are listed below: Simple design, rugged construction, Reliable operation, low initial cost, easy operation and simple maintenance, simple control gear for starting and speed control, high efficiency. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFD) in variable-speed service. VFDs offer especially important energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump, and compressor load and even in Electric Vehicles. The variable frequency drive (VFD) varies the frequency and hence varies the speed or torque of the induction motor as per the requirements of the load. Squirrel-cage induction motors are very widely used in both fixed speed and variable-frequency drive applications. In this report, we have designed and modeled squirrel cage induction motor and performance analysis is done in various Ansys Software: Rmxprt, Maxwell 2D and Maxwell 3D.

1.1 Construction

- a) **Stator:** The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame. The phase windings are placed 120 electrical degrees apart.
- b) **Rotor:** The rotor of the squirrel cage motor contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core. The rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.

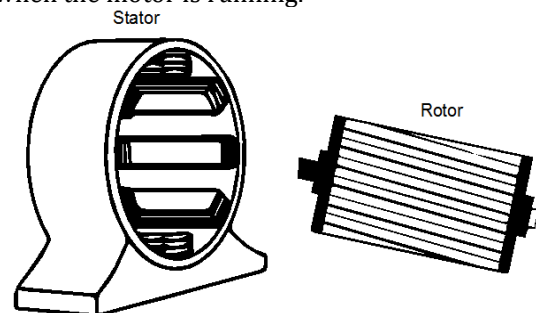


Fig -1: Stator and rotor

2. Working Principle of an Induction Motor

The motor which works on the principle of electromagnetic induction is known as the induction motor. The electromagnetic induction is the phenomenon in which the electromotive force induces across the electrical conductor when it is placed in a rotating magnetic field. This stationary rotor cut the rotating magnetic field of the stator, and because of the electromagnetic induction, the EMF induces in the rotor. As the current flows through the rotor conductor, the flux induces on it. The direction of rotor flux is same as that of the rotor current. Now we have two fluxes one because of the rotor and another because of the stator. These fluxes interact each other. On one end of the conductor the fluxes cancel each other, and on the other end, the density of the flux is very high. Thus, the high-density flux tries to push

the conductor of rotor towards the low-density flux region. This phenomenon induces the torque on the conductor, and this torque is known as the electromagnetic torque. The direction of electromagnetic torque and rotating magnetic field is same. Thus, the rotor starts rotating in the same direction as that of the rotating magnetic field.

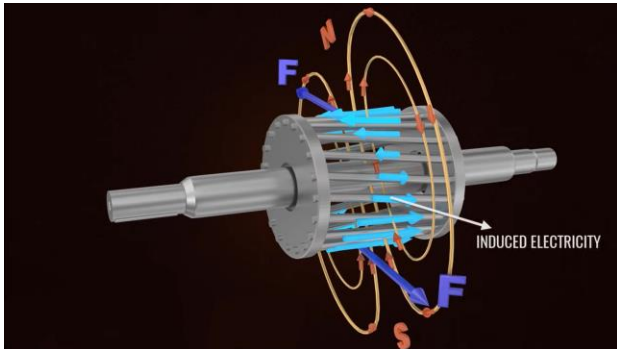


Fig -2: Working Principle of an Induction Motor

2.1 Rotating Magnetic Field Due to 3-Phase Currents

Each phase is fed with a sinusoidal AC current, which has a frequency of ω and a 120° phase difference between each other. Current I_{as} , I_{bs} , and I_{cs} in the three stator coils a-a, b-b, and c-c produce alternative mmfs, F_{as} , F_{bs} , and F_{cs} , which are space vectors. The resultant stator mmf vector F_{ss} , constitutes a vector sum of the phase mmf vectors.

$$F_{as} = F_{as} \sin \omega t$$

$$F_{bs} = F_{bs} \sin(\omega t - 120^\circ)$$

$$F_{cs} = F_{cs} \sin(\omega t - 240^\circ)$$

The resultant stator mmf vector, F_{ss} , is expressed as

$$F_{ss} = F_{as} e^{i0^\circ} + F_{bs} e^{i120^\circ} + F_{cs} e^{i240^\circ}$$

Assuming that the magnitude of the three phase mmfs are identical, equal to F_s ,

$$F_s = \frac{3}{2} F_s e^{i(\omega t - 90^\circ)}$$

The frequency ω , or angular velocity of the rotating stator mmf in the equation depends only on the frequency of the alternative current of the stator. Mechanical angular velocity can be expressed as

$$\omega_{ms} = \frac{2}{p} \omega = \frac{4\pi f}{p} \text{ rad/sec}$$

Where f is the frequency of the alternative current or angular velocity of the rotating stator mmf in cycles/sec.

If the rotor speed is ω_m rad/sec, then the relative speed between the stator rotating field and the rotor is given by

$$\omega_{sl} = \omega_{ms} - \omega_m = s\omega_{ms}$$

Where ω_{sl} is called slip speed. The parameter s , known as slip, is given by

$$s = \frac{\omega_{ms} - \omega_m}{\omega_{ms}} = \frac{\omega_{sl}}{\omega_{ms}}$$

Because of the relative speed between the stator field and the rotor, balanced three-phase voltages are induced in the rotor mentioned before. The frequency of these voltages is proportional to the slip speed

$$\omega_r = \frac{\omega_{sl}}{\omega_{ms}} \omega = s\omega$$

The speed of the rotor is always less than the rotating magnetic field or synchronous speed. The rotor tries to run at the speed of the rotor, but it always slips away. Thus, the motor never runs at the speed of the rotating magnetic field, and this is the reason because of which the induction motor is also known as the asynchronous motor. The torque developed by the motor can be determined by

$$T = \frac{P_{mech}}{\omega_m}$$

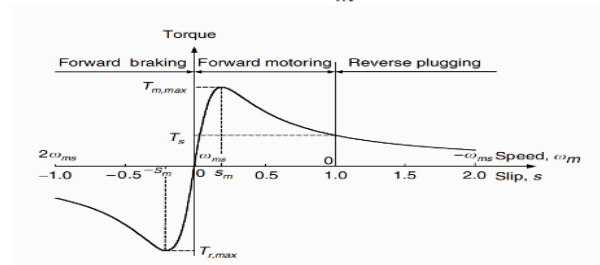


Fig -3: Torque-slip characteristics of an induction motor with fixed stator frequency and voltage

2.2 Constant Volt/Hertz Control

For traction application, the torque-speed characteristic of an induction motor can be varied by simultaneously controlling the voltage and frequency, which is known as constant volt/hertz control. By emulating a DC motor at low speed, the flux may be kept constant.

$$I_{mr} = \frac{E}{X_m} = \frac{E_{rated}}{\omega_r L_m}$$

To maintain the flux at constant, E/ω should be kept constant and equal to E_{rated}/ω_r . Ignoring the voltage drop in the stator impedance Z_s results in a constant V/ω until the frequency and voltage reach their rated values.

And then, the maximum torque is

$$T_{max} = \frac{3 E_{rated}^2}{2 L_r \omega_r^2}$$

With the constant E/ω , the maximum torque is constant with varying frequency. When motor speed is beyond its rated speed, the voltage reaches its rated value and cannot be increased with the frequency. In this case, the voltage is fixed to its rated value and the frequency continuously increases with the motor speed. The motor goes into the field weakening operation. The slip s is fixed to its rated value corresponding to the rated frequency, and the slip speed ω_{sl} increases linearly with motor speed. This control approach results in constant power operation as shown.

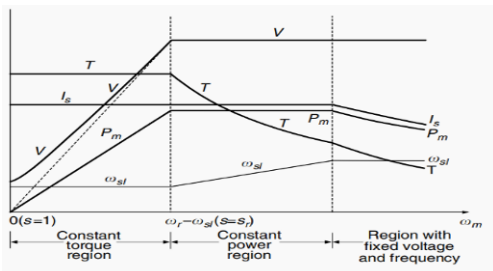


Fig -4: Operating variables varying with motor speed

2.3 Power Stages in an Induction Motor

The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are shown in figure 5:

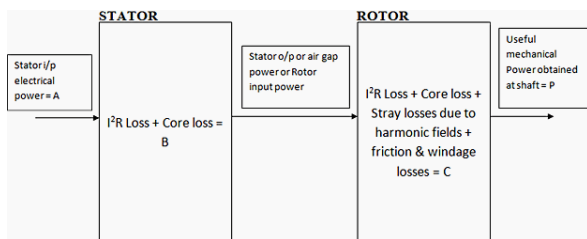


Fig -5: Power Stages in an Induction Motor

3. Design of Three phase induction motor in Ansys

Design, material selection, production and performance check (testing) are the main steps of manufacturing of any electrical motor. In “ANSYS Maxwell” programs we can make calculation model and get electromagnetic parameters in a visual convenient form, It also consider the nonlinearity of the magnetic material, losses in the iron as well as the influence of the winding slots etc. RMxpert is a template-based electrical machine design tool which provides fast analytical calculations of machine performance and 2-D and 3-D geometry creation for detailed finite element calculations. This report focuses on use of ANSYS RMxpert software for material selection, machine design and obtaining performance characteristics of three-phase induction motor.

Table -1: General Data
Type of load: Constant power

Given Output Power (kW)	1.1	Frequency (Hz)	50
Rated Voltage (V)	380	Stray Loss (W)	11
Number of Poles:	2	Frictional Loss (W)	11
Given Speed (rpm)	1450	Windage Loss (W)	11

3.1. Stator Design Details

Stator Slot dimensions are as follows
 hs_0 : 2 mm, hs_2 :15 mm, bs_0 : 1mm, bs_1 :5 mm, bs_2 : 5 mm
 Details of stator winding:
 Winding type – whole coiled
 Number of conductors per Slot: 30
 Wire Resistivity (ohm.mm²/m): 0.0217
 Wire size -0.683mm

Table -2: Stator Design

Number of stator slots	36	Length (mm)	250
Outer Diameter of Stator (mm)	140	Stacking factor	0.95
Inner Diameter of Stator (mm)	78	Type of steel	D21_50

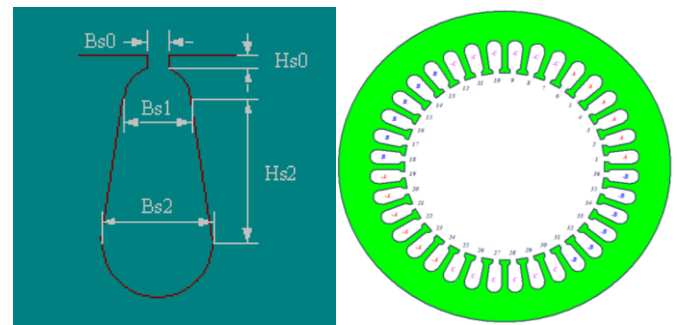


Fig -6: Stator slot and stator winding design

3.2. Rotor Design Details

Rotor slot dimensions:
 hs_0 : 2 mm, hs_{01} : 2 mm, hs_2 : 8 mm, bs_0 : 3 mm, bs_1 : 4 mm bs_2 : 5 mm

Table -3: Rotor Design

Number of Rotor slots	28	Length (mm)	250
Outer Diameter of Rotor (mm)	76	Stacking factor	0.95
Inner Diameter of Rotor (mm)	1	Type of steel	D21_50

Rotor winding: Bar conductor type – copper
 Winding arrangement: The 3-phase, 1-layer winding can be arranged in 36 slots as below:

AAAAAZZZZZBBBBBBXXXXXXCCCCCYYYYYY

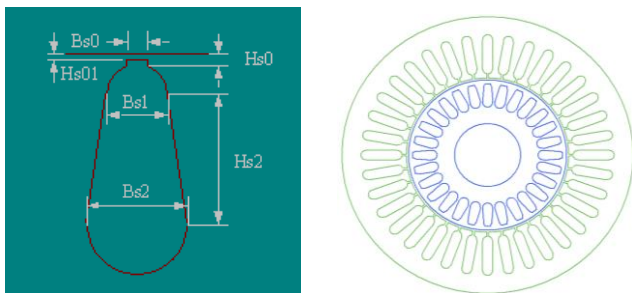


Fig -7: Rotor slot and rotor winding design

After providing all the input parameters to Ansys Rmxprt, Design is analysed as shown in figure 9

	Name	Value	Units
1	Stator Ohmic Loss	156852	mW
2	Rotor Ohmic Loss	71460.8	mW
3	Iron-Core Loss	54492.3	mW
4	Frictional and Windage Loss	103418	mW
5	Stray Loss	11000	mW
6	Total Loss	397223	mW
7	Output Power	1099600	mW
8	Input Power	1496830	mW
9	Efficiency	73.4623	%
10	Power Factor	0.681748	
11	Rated Torque	3.70806	NewtonMeter
12	Rated Speed	2831.79	rpm
13	Rated Slip	0.0560705	

Fig -8: Rated performance of induction motor

4. Performance Curves of Induction Motor

4.1. Voltage vs. Speed curve

Three phase induction the motor starts from zero speed. As it increases to its base speed. Here, Base speed is 2800rpm. So, the voltage increases with increase in speed up to 2800rpm to its rated value while the flux remains constant. Beyond the base speed, the voltage remains constant and the flux is weakened. This results in constant output power.



Chart 1: Voltage vs. Speed curve

4.2. Torque-Speed Curve

The starting torque is about 150 percent of the full-load torque. The motor can start carrying any load that it normally handles at full power. There is a maximum

possible torque that the motor cannot exceed. This torque is called the Pull-out torque or breakdown torque and is 2 to 3 times the rated full torque of the motor. The torque-speed curve is linear between no load and full load. In this range, the rotor reactance is much smaller than the rotor resistance, so the rotor current, magnetic field, and induced torque varies linearly with slip. Torque declines hyperbolically with speed above base speed. There is no induced torque at synchronous speed.

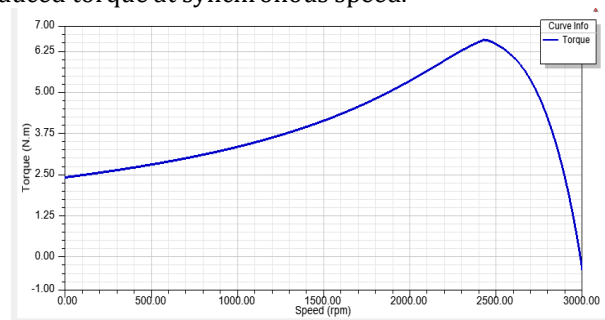


Chart 2: Torque-Speed Curve

4.3. Family of Torque vs. Speed curves

The Variable Frequency Controller (V.F.D.) generates a whole family of Torque vs. Speed curves, each one with a synchronous speed corresponding to the frequency supplied to the motor at any instant. Supply voltage to the motor must be adjusted in proportion to the frequency, to keep the current in the magnetizing path constant. This is referred to as maintaining a constant V/f ratio. It is this magnetizing current which creates the magnetic field, which induces rotor current and creates torque. Thus to enable the motor to develop full torque at any speed, this current must be maintained.

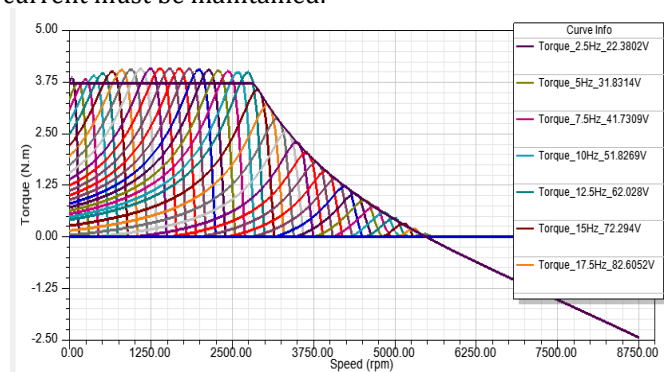


Chart 3: Family of Torque vs. Speed curves

5. Maxwell 2D geometry

By using Maxwell's advanced electromagnetic field solvers and linking them to the systems simulation, we can understand the performance of electromechanical systems long before building a prototype in hardware. Meshing of motor designed in Rmxprt is done in Ansys Maxwell 2D. FEA of three phase of induction motor is also done in Ansys Maxwell 2D

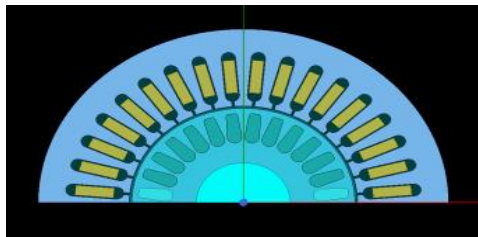


Fig -9: Maxwell 2D geometry of induction motor

5.1. Power vs. Time Curve

Sometimes, squirrel cage induction motors exhibits a tendency to run at very slow speeds. This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics. Due to this when running under low speed unusual torque and power variation in observed. After reaching its base speed, motor provides constant power. As we can observe from the chart below

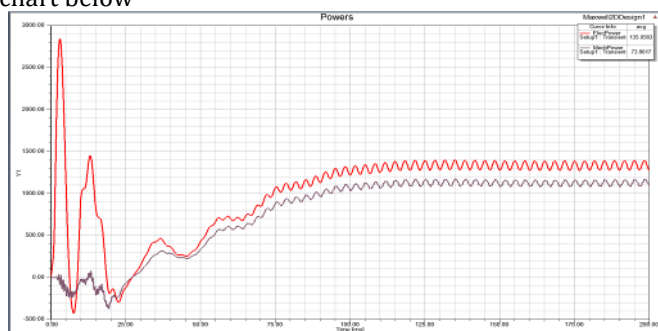


Chart 4: Power vs. Time Curve

5.2. Current in Stator

The current waveform indicates that an extremely large current is produced during the initial start-up. This is because the reverse voltage at initial start-up is small and almost all of the power supply voltage is applied to the stator coils. At a steady state, the three-phase AC has an amplitude of less than 5 A. We can observe that rotating magnetic field (RMF) is set up in stator winding.

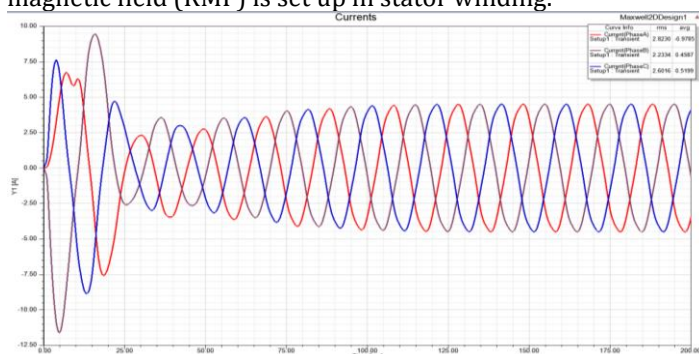


Chart 5: Current in stator with time

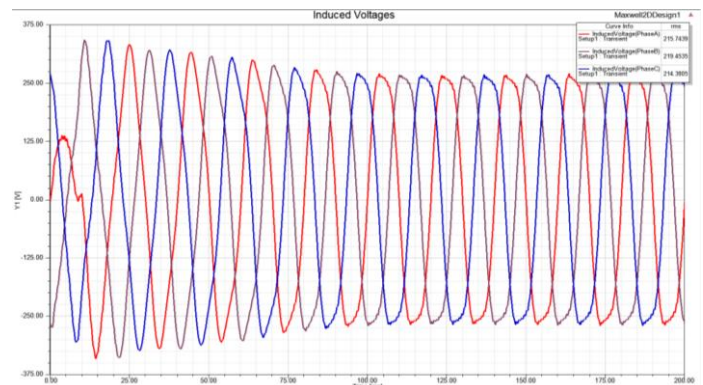


Chart 6: Voltage in stator with time

6. Flux Line Details

Each alternating phase current produces its own flux which is sinusoidal. Here the intensity and direction of flux lines generated in stator and rotor of squirrel cage induction motor. The lines of flux are continuous, forming closed loops. At the poles the flux lines are denser and as we move further flux lines fade away.

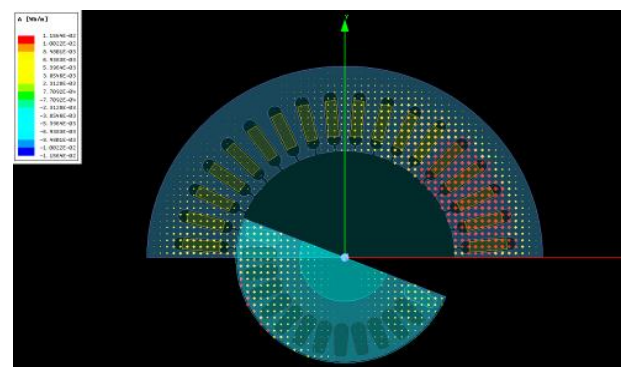


Fig -10: Simulation of flux lines generated

6.1. Flux Density Details

At the poles of a magnet, for example, where the magnetic field is strong, Flux density is higher. Farther away, where the magnetic field is weak, they fade out, becoming less dense.

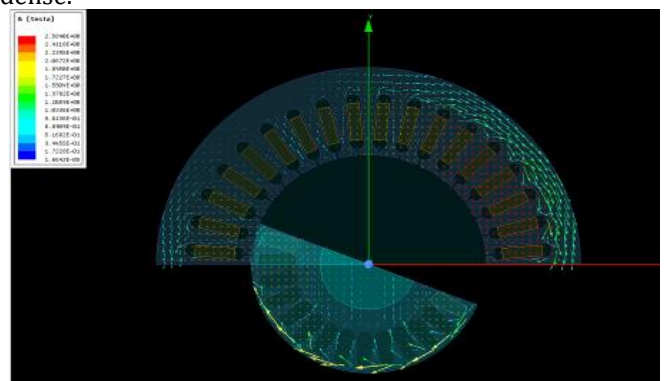


Fig -11: Simulation of Vectors of flux density generated

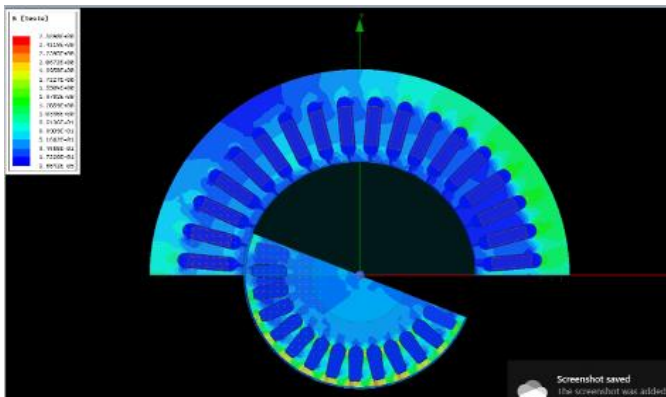


Fig -12: Simulation of flux density generated

7. 3D Design of squirrel cage three phase induction motor

In Ansys Maxwell 3D design. We can observe from different views of motor stator, stator winding, winding slots and rotor.

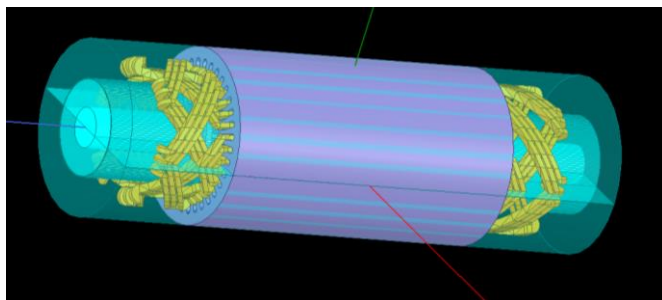


Fig -13.a: 3D Design of three phase induction motor

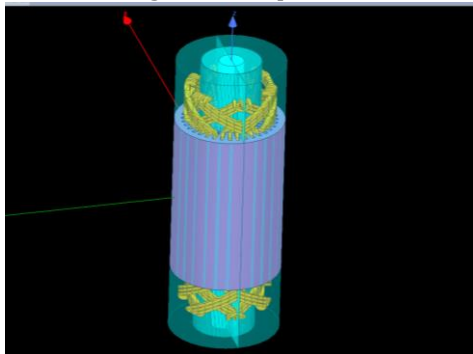


Fig -13.b: Front view

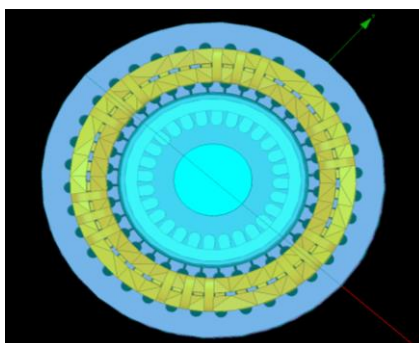


Fig -13.c: Top view

8. Variable frequency induction motor drives

Variable frequency induction motor drives are mostly used in industries for large induction motor (dealing with variable load) whose power rating ranges from few kW to few MW. Variable Frequency Drive is used in traction system. In India it is being used by Delhi Metro Rail Corporation. For a designed model of induction motor effect of change of frequency on various factors like Torque, Output mechanical power, efficiency and most important speed is studied. Individual induction motors are designed in Ansys Rmxprt considering saturation, stray losses, and skin effect for Frequencies 50Hz, 60Hz, 70Hz, and 75Hz. Values of different parameters mentioned above are noted and then graphs are plotted with respect to variation in frequency in EXCEL SHEET.

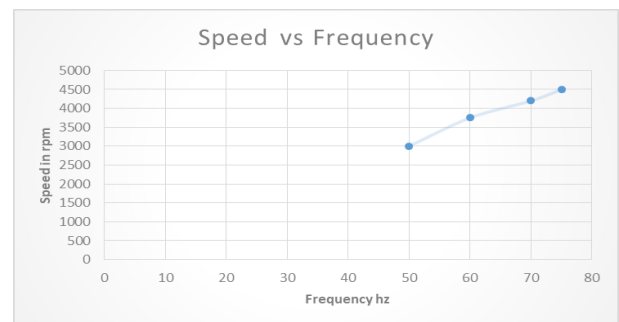


Chart 7.a: Speed vs Frequency curve of VFD

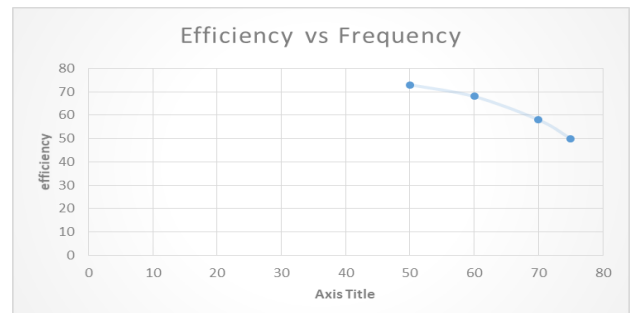


Chart 7.b: Efficiency vs Frequency curve of VFD

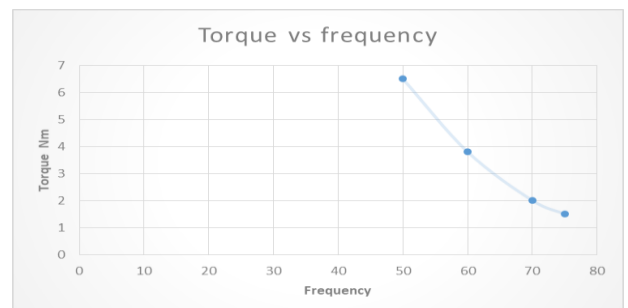


Chart 7.c: Torque vs Frequency curve of VFD

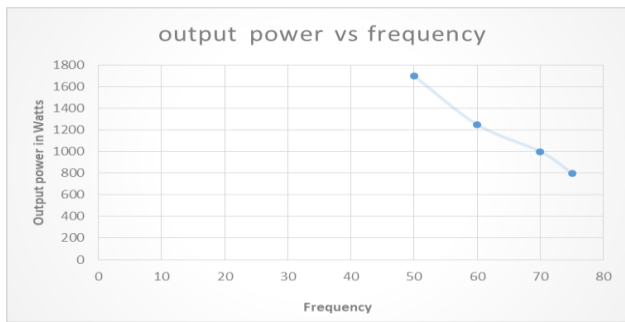


Chart 7.d: Output power vs Frequency curve of VFD

Table -4: Variation of motor characteristics with frequency

Frequency (Hz)	Power (w)	Efficiency (%)	torque (Nm)	speed (rpm)
50	1700	73	6.5	3000
60	1250	68	3.8	3750
70	1000	58	2	4200
75	800	50	1.5	4500

9. Observations:

1. As frequency increase speed of motor increases, thus offering various speed on drive.
2. Torque capability of motor decreases with increase in frequency Output power of motor decrease with increase in frequency.
3. Poor operation efficiency due to the poor power factor. Hence while controlling a motor with the help of VFD or Variable Frequency Drive we always keep the V/f ratio constant.

10. CONCLUSIONS

Accurate design and proper material selection is most important in Manufacturing of high performance and economical motor. RMXprt is useful machine design tool which provides fast analytical calculations of machine performance. ANSYS RMXprt machine Best option to design and calculate performance motor before production. It provides the option of proper material selection, material consumption details, provides 2-D and 3-D geometry of designed motor, consider the nonlinearity of the magnetic material, losses and also allows to make any changes to optimize the design. ***VFD adjustable-speed drive used to control electric motors driven by an alternating current (AC). VFD saves energy, highly reliable, soft starting and provides speed variations. VFD are used in traction system, modern lifts, escalators and pumping systems. Nowadays they are being also used in energy efficient refrigerators, AC's and Outside-air Economizers.

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