Nyachulue Njita

3-Phase PM Synchronous Motor

High Speed with Low Torque

Helsinki Metropolia University of Applied Sciences

Bachelor of Engineering

Degree Programme in Electronics

Bachelor’s Thesis

November 2015

Author Title Number of Pages Date	Nyachulue Njita 3 - Phase PM Synchronous Motor 34 pages + 5 appendices 3rd November 2015
Degree	Bachelor of Engineering
Degree Programme	Degree Programme in Electronics
Instructor(s)	Kai Lindgren, Senior Lecturer

The objective of this project was to design a 3-phase PM Synchronous motor with a constant speed at a specific frequency value supplied from a variable frequency drive (VFD) source. The thesis explains in detail the effect of varying the frequency values supplied from the VFD system on the motor's speed. This study also aims for determining the torque-speed characteristic curve of this motor and analysing some of the importance and advantages of synchronous motors over induction motors.

The success of this project was enabled by first calculating values for all important parts of the motor. These include the stator and rotor lengths, total slots, diameters, number of poles, current density and more by the use of MATHCAD program which gave way for the successful realization of the main parameters needed for the motor's setup. By using the variable frequency drive (VFD) unit, it was easy to vary the output voltage and supply frequency to suitable values so that the motor runs at a constant speed.

A 3-phase PM Synchronous motor was designed in accordance with the requirements and objectives of the thesis. The theoretical standard of this project was reached successfully by comparing its main features to that of already existing synchronous motors having similar datasheets. Thus, the study shows a unique and clear functional pattern in the manner of operation, table of values, synchronized speed, power factor improvement, high efficiency when compared to that of existing PM synchronous motors.

Keywords	Synchronized Speed Motor, High Efficiency, Torque-Speed Characteristics, VFD Unit, Cooling Methods, Enclosure Type

Content

Appendices

Appendix 1.	Calculation of Motor’s Parameters Using Mathcad Programme
Appendix 2.	Setup for Varying Frequency of Motor Using VFD.
Appendix 3.	Catalogue of Existing PM Synchronous Motor.
Appendix 4.	Totally Enclosed Large Synchronous Motor.
Appendix 5.	Basic Structure of a PM Synchronous Motor

Abbreviations

IEE	Institute of Electrical Engineer
PM	Permanent Magnet
DC	Direct Current
AC	Alternating Current
Ns	Synchronous Speed
Cos Ø	Power Factor
Dr	Rotor Diameter
Q	Total Slot
q	Slot per Phase per Pole
α	Slot Angle (In electrical degrees)
ϕf	Magnetic Flux
Λp	Permeance
KVAr	Kilo-Volts Ampere Reactive
Ra	Armature Resistance
E.M.F	Electro-Motive Force
T	Torque
V_T	Terminal Voltage
ΨS	Rotating Flux Linkage
VFD	Variable Frequency Drive
P_{in}	Input Power
η	Efficiency
P_o	Output Power

1 Introduction

In general, electric motors are machines used in driving different loads. Motors convert electrical energy fed at the armature into mechanical energy measured at the output, referred to as the rotor (shaft). In this project, the focus was on the design and operation of a special type of motor called 3-phase PM Synchronous motor. The demand for motors which are capable to produce a relatively high torque in driving different mechanical loads is rapidly increasing in both factories and commercial areas. Moreover, the 3-phase PM Synchronous motor is very suitable for use where a precise constant speed is required by varying the frequency of the source to a nominal value which then allows the motor to operate at its rated speed [1, 283-330].

Generally the construction of the synchronous motor is electrically more efficient than a non-synchronous motor. In the basic structure, synchronous motors can be started by a separately excited DC motor, connected to the rotor of the synchronous motor. When the speed is near the synchronous speed, then the synchronous rotor is excited with DC supply. It is also possible to construct self-starting synchronous motor by adding cage winding into the rotor. In this case, the motor is started as induction motor until when the slip is sufficiently small, rotor is excited with DC supply. For proper design and establishment of these special machines, the circuit parameters are calculated to meet the required precision which ensures the smooth running of the motor. These initial parameters include; rotor length, rated output power, rotor diameter, current loading (Am), operating frequency etc (Appendix 1).

Determining the motor sizing is an important part of the project in order to meet up with the operating standards. A final measurement report will be made during laboratory testing based on a successful accomplishment of the target of the project, which can only be made possible if precision in the circuit parameters is achieved through successful calculations and measurement setup done according to the datasheet for this special electric drive (PM Synchronous motor). Enclosure for durability and safe operation is an important part of the project. In order to prevent irrelevant noise, interference with other mechanical parts, leakage current and environmental hazards must be respected as stated by the IEE regulations on equipment and standardization [2].

2 Theoretical Background

With the invention of the battery by Alessandro Volta around 1800, the generation of a magnetic field from electric current by Hans Oereted around 1820 and the electromagnet by William Turgeon around 1825, the foundation for building electric motors was laid. During that time, it was still an open question whether electric motors should be rotating or reciprocating machines, by simulating a plunger rod of a steam engine. Hence, the first rotating electrical device driven by electromagnetism was built by the Englishman Peter Barlow in 1822 (Barlow wheel). In May 1884 the German-speaking Moritz Jacobi created the first real rotating electric motor that actually developed a remarkable mechanical output power.

Today, the 3-phase synchronous motor is used mostly in highly dynamic applications (for example in robots) and in electric cars. It was developed first by Friedrich August Haselwander in 1887. Moreover in the year 1821 British scientist Michael Faraday explained the conversion of electrical energy into mechanical energy by placing a current carrying conductor in a magnetic field which resulted in the rotation of the conductor due to torque produced by the mutual action of electrical current and fields. It is the most primitive version of the electric motor, where rotating torque is produced due to flow of current through the conductor inside a magnetic field.

Nowadays the A.C electrical motors are driven by alternating current, for example the synchronous motor which always runs at synchronous speed. In today’s synchronous motor, the rotor is an electro-magnet which is magnetically locked with stator rotating magnetic field and rotates with it together. The speed of these special motors is varied by changing the frequency and the number of poles of the motor. When the operating frequency rises, the speed of the motor rises and can only drop drastically when the number of poles is increased. Unless the frequencies of synchronous motors are varied otherwise the synchronous speed remains constant in operating mode.

Synchronous motors are rated at different synchronous speeds depending on the need and areas where it is most likely to be used. For areas where high toques are required in driving large conveyors, lifters and elevators the speed of the motor in these cases is usually very low due to heavy loading. Also it is most suitable in driving heavy loads and high torque parts. For high speed synchronous motors, the operating torque is usually low. [3.]

2.1 Operating Principle

When a 3-phase set of voltages is applied to the stator of the machine, it produces a three phase current flow in the windings. This three phase set of currents in the armature winding produces a uniform rotating magnetic field B. The magnetic field which is set up in the armature, will rotate at a certain speed called the synchronous speed. Hence, if an electromagnet is present in these rotating fields, the electromagnet is magnetically locked with this rotating magnetic field and rotates with same speed of rotation. For a high speed but low torque motors as in this project, the speed can be varied by varying the supply frequency (f) or by changing the numbers of poles for the motor.

The speed of the rotor of this motor is same as the rotating magnetic field, hence has a fixed speed which is called the synchronous speed and therefore no intermediate speed is there or in other words it is operating in synchronism with the supply frequency. Synchronous speed is given by the relationship below, if speed is measured in revolutions per minute (rpm). The speed will, however not change as long as the frequency is maintain at the same value. But in situations where the need for varying speed is required, the frequency is varied and the effect can be seen in the operating speed of the motor

$$N_s = \frac{120f}{p} \qquad (1)$$

Where
Ns is the synchronous speed
f the frequency
p the number of poles.

Synchronous motors are basically the same in all aspect as synchronous generators, except for the fact that the direction of current and power flow is reversed. By definition, motors are fed with electrical power at the stator, convert it into mechanical power of the shaft (rotor), meanwhile generators generate mechanical power in their armature circuit then convert this power into electrical power that can be measured at the output terminals for transmission and distributions purposes. Synchronous motors require special enclosure methods to prevent them from mechanical damages and other environmental hazards such as passive and active components, noise and interference with other equipment around the areas where they are installed. [4.]

2.2 Motor Sizing and Dimensioning

Determining the appropriate dimensions for the rotor of synchronous motors as in this case, such as the rotor length, diameter of shaft, cross sectional area etc, gives way for a successful project. This is usually a starting point to consider when designing any electric motor. In this task, choosing suitable values for the operating voltage, current loading, magnetic flux, diameter coefficient, required output power for the motor has made further calculations easier and possible. The formula in equation (2) below explains in details how different parameters for the motor sizing and dimensions are being realized.

$$Ia = \frac{Pshaft}{m0 \cdot Va \cdot \eta \cdot cos\emptyset} \tag{2}$$

Where I_a is referred to as the phase current and is equal to the line current I_l ($I_a = I_l$) if motor winding is Wye connected.

$$Dr^2lst = e \cdot \frac{P\ shaft}{\frac{\pi^2}{2} \cdot kw \cdot nsec \cdot Bm \cdot Am \cdot \eta \cdot \cos\emptyset} \tag{3}$$

Equation (3) above shows the relationship between the output power and the volume constant (Dr^2lst), which is hence used in the calculation of the rotor diameter when the stator length constant (l_{st}) is known. See equation (4) below for the calculation of the rotor diameter proper.

$$Dr = \sqrt{\frac{Dr2lst}{lst}} \tag{4}$$

From the above equation (4), Dr is the actual diameter of the rotor for the motor measured in metres if SI unit is respected and will be mentioned on the machine's values specification and data sheet during request to the manufacturer for the supply of this special type of motor. lst is the length of stator in metres. The (K_W) seen in equation (4) above is the winding factor used in the calculation of the volume constant (Dr^2lst). The volume constant can be modified to different values if P shaft is changing since both are directly proportional (Appendix1).

2.2.1 Total Slots and Air Gap.

In this project, we assume the total number of slot for this 4 pole, 3-phase PM synchronous motor to be Q = 36. This enables the determination of the number of slot per phase per pole (q) using the expression stated below. The angle between slots can be verified by the following expressions as seen below.

$Q = 36$, $P = 4$, $m = 3$. Where m is the number of phases of the motor

$$Q = q \cdot p \cdot m \tag{5}$$

$$q = \frac{36}{4\ X\ 3} = 3$$

However, the slot angle in electrical degrees (α) is given by the expression below.

$$\alpha = 180^0 \left(\frac{1}{\mathrm{mq}}\right),$$

If $m = 3$, $q = 3$. Therefore the slot angle $\alpha = 20^0$

The total flux (ϕf) can be defined when the cross sectional area (A) is given with respect to the total flux density (B_{av}) of the magnetic circuit of the motor.

$$Area = \frac{\phi f}{Bav} \tag{6}$$

Where

$$\Phi f := \frac{2}{\pi} \cdot Bm \cdot \tau p \cdot lst = 0.03$$

B_m in the above equation refers to maximum magnetic flux density (B), as earlier discussed. The rotating magnetic field (ϕf) is a field, with moving polarities in which its opposite poles rotates about a central axis. Ideally, the rotation changes direction at a constant angular rate. It is however the key principle in the operation of alternating current motors like in this case for a 3 phase PM synchronous motor. [5, 30-31; 97-106.]. In transformers, propagating flux from primary to secondary enables the creation of the secondary current though transformed (I1< I2 or I1>I2) but at the same frequency value for both primary and secondary circuits where P1 = P2.

The air gap dimension for the motor can be derived from the expression below if the other parameters are measured according to the specifications given. Moreover, the air gap is needed in a motor circuit to prevent the rotor from rubbing on the stator and by this creates a hindrance (reluctance) for the flux to circulate easily. However, the air-gap is normally unavoidable and contains some amount of air, which offers high resistance to magnetic flux and requires undesirable increase in magnetizing current and the associated electrical losses.

$$\Lambda_p = \frac{\mu 0 \cdot \pi \cdot D \cdot L}{2\delta} \tag{7}$$

δ=The sum of the air gap for the motor.

2.2.2 Synchronous Reluctance.

If the rotating field of a large synchronous motor with salient poles is de-energized, it will still develop 10 or 15% of the synchronous torque. This is due to variable reluctance throughout a rotor revolution. Hence, there are some practical designs for large synchronous reluctance motor. It however induces non-permanent magnetic poles on the magnetic rotor. Torque is generated through the phenomenon of magnetic reluctance. These special motors can deliver very high power density at low cost, making them ideal for many applications. One very big disadvantage is the production of high torque ripple when operated at low speed

$$R_m = \frac{1}{\Lambda p}$$

Therefore the reluctance for synchronous machine is given by the below expression seen on equation (8) below.

$$R_m = \frac{2 \cdot \delta}{\mu 0 \cdot \pi \cdot D \cdot L} \tag{8}$$

Where

D is the diameter and L the length.

2.2.3 Slot Area and N-loop

The slot area is determined by taking into consideration the total number of loops in one slot and the current density, which in this project is assumed to be δcu = 2.5A/mm^{2}. Alternatively, we could consider the current density for air cooled motors to be 3.5A/mm^{2}

$$A_{slot} = \frac{Nloop \cdot I}{\delta cu} \qquad (9)$$

N is the number of loops or number of times the winding is wound around the stator core in one slot.

$$\frac{\mathrm{Rm}}{5} = \frac{\boldsymbol{L}}{\mu \boldsymbol{r} \cdot \mu \mathbf{0} \cdot \boldsymbol{lst} \cdot \boldsymbol{w}}$$

$$w = \frac{5 \cdot L}{\mu r \cdot \mu 0 \cdot lst \cdot Rm} \qquad (10)$$

The width (w) is the thickness of the stator yoke as seen on the figure 1 below. Assuming we plot an inclined line at about 45^{0} from the central point of the core below, and another intersecting line drawn from the central point to the x-axis direction of the core. From the point where the line will touch the rotor core to the point where it touches the stator core, we can refer to that small distance as the width. [6.]

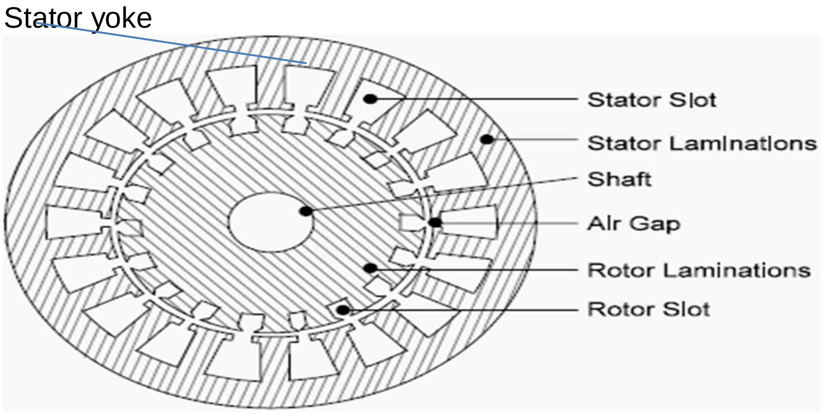


Fig 1. Dimensional Structure of the Stator and Rotor for Synchronous Motor

By linking both the inclined and the horizontal lines together outside the stator core, we simply measure the length (L) which is used in the formula of equation (10) above. There are two identical parallel paths for flux to propagate in the stator. We demand that the total stator reluctance is 10% of air gap reluctance and that gives the value 5 seen in the above equation (10).

2.2.4 Motor Internal Structure

The internal structure for a 3-phase PM synchronous motor gives a clear understanding how the magnetic poles, stator, rotor and windings are placed in for coupling and then starting. Fig 2 below gives a general idea for the structural arrangement of this Machine. In this case we can observe the 2 pole ends of the motor (being North and South Poles), the stator, rotor and the excitation DC supply which energizes the rotor circuit of the motor after starting. When the 3 phase voltage is applied at the stator, it produces current which intends creates magnetic fields in the motor circuit allowing it to run at synchronous speed if the frequency is not varied. Figure of appendix 5, shows a core structure of the rotor and stator for PMSM with the magnetic poles.

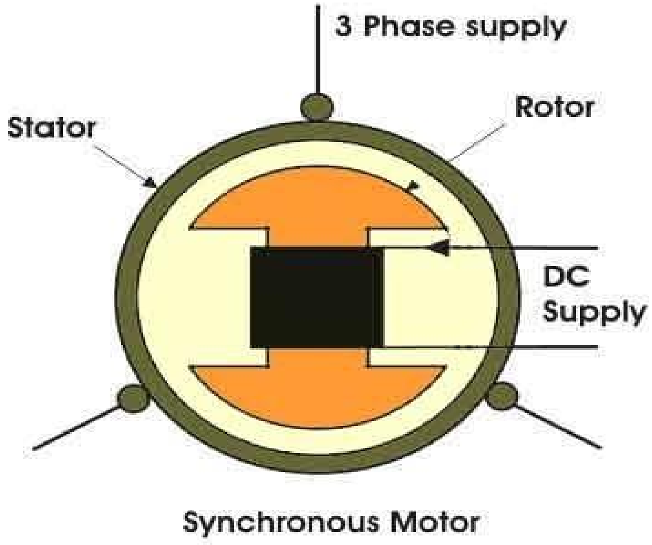


Fig 2. Internal Structure of Synchronous Motor. (Copied from Electrical4u.com [7])

If the starting current is large enough, then it is recommended to always consider connecting a set of starting resistances in series with the motor along each of the phases to limit the starting current which can damage the motor windings. In a more detailed structure, we shall see how the windings are placed around the stator and the motor slots and air-gap positions clearly shown. The structure of Synchronous motor is not very much different from that of synchronous generator except for the fact that the direction of current is reversed. The combined name for synchronous motor and synchronous generator is referred to as synchronous machines.

Figure 3 below shows a practical arrangement of a 3-phase PM synchronous motor where the DC voltage source is shown.

A separately excited DC source is needed to energize the rotor of the motor after it has reached maximum speed. This produces a strong, constant magnetic field in the rotor, which locks in step with the rotating magnetic field of the stator. Because the rotor turns at the same speed as synchronous speed (speed of the rotating magnetic field), there is no slip since the speed of the motor is constant and does not vary if the load is constant. But if the load is changing, then the rotor can add or diminishes it's lagging from the stator field. Meanwhile the 3 Phase AC supply feeds the stator of the motor creating a three phase sets of current.

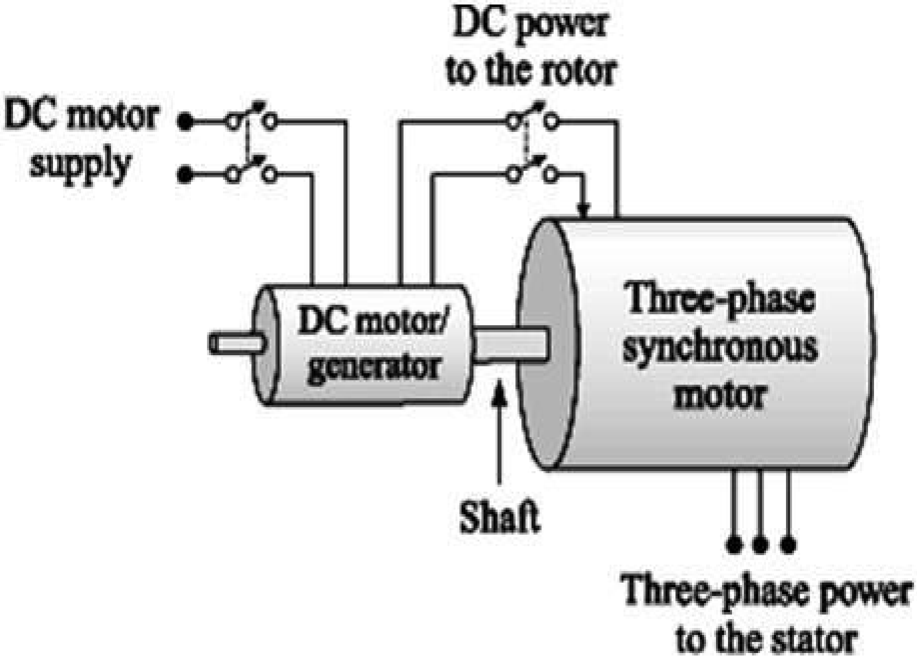


Fig 3. Starting Setup for a 3-Phase Synchronous Motor (Copied from Electrical Knowhow [8]).

The slip of the motor is however 0% since the slip speed is zero such that Ns = Nr where Ns – Nr = 0. In the case of induction motors where the rotor speed is defined differently from the synchronous speed, the difference between the two speeds is a small fraction from which the slip can be deduced by dividing the slip speed to the synchronous speed of the motor. As discussed earlier, synchronous speed will be increased if the number of poles for the motor is reduced since, synchronous speed and number of poles (p) are inversely proportional as seen in equation (1) above. [8.]

2.3 Power Factor Improvement

Generally synchronous motors are designed to operate at unity power factor (Cos Ø =1) or 0.8 leading power factor. By varying the DC excitation of the motor, the power factor of the motor can be varied widely. Over excited synchronous motors operate at leading power factor and provide reactive KVAR-like capacitors. This yields an improved power factor for the power supply system. Because most utility companies bill their industrial customers on the basis of their KVAR use, rather than solely kW an improved power factor provides large savings for the consumers.

The ability to adjust the power factor of a system like in this case can significantly affect the power dissipation of that power system. We have to note here that the lower the power-factor of any power system, the greater the losses in the power lines feeding it. Having one or more leading loads (over-excited synchronous motor) on a power system can be useful for the following reasons. The active, reactive and apparent powers are the three main powers in a system where power factor improvement is required.

a) A leading load can supply some reactive power Q_R for nearby lagging loads, instead of it coming from the generator (voltage source). Since the reactive power does not have to travel over long and fairly high resistance transmission lines, the transmission current is reduced and the power system losses are much lower.

b) A lower Equipment current rating reduces the cost of a power system significantly.
In addition, requesting a synchronous motor to operate with a leading power factor means that the motor must be run overexcited. This mode of operation increases the motor’s maximum torque and reduces the chances of accidentally exceeding the pull out torque.

The use of synchronous motors or other equipment to increase the overall power factor of a power system is called power factor correction. Since a synchronous motor can provide power factor correction in a power system, and then lower power systems costs. Many loads that can be associated to a constant speed motors, are driven by synchronous motors. Though synchronous motors may cost more but the ability to operate a synchronous motor at leading power factor for power factor improvement (correction) saves money for industrial plants. [9, 285.]

2.3.1 The Synchronous Condenser.

A synchronous motor purchased to drive a load can be operated overexcited to supply reactive power Q_R for a power system. In fact, at some times in the past a synchronous motor was purchased and run without a load, but simply for power factor correction in a power system. However a synchronous condenser is a device quite similar to the synchronous motor, whose shaft is not connected to anything but freely rotates. The condenser is not aimed at converting a purely electrical power into mechanical power as the case with synchronous motors, but to adjust conditions on the electric power transmission grid.

Its field is barely controlled by a voltage regulator to either generate or absorb reactive power as needed to adjust the gird’s voltage or to improve power factor. By increasing the devices field excitation results in its furnishing reactive power to the system. One big advantage of the condenser is the ease to which the amount of correction can be adjusted. Large installation of synchronous condenser is sometimes used in association with high voltage direct current converter stations to supply reactive power to the alternation current grid only.

Unlike a capacitor bank, the amount of reactive power from a synchronous condenser can be continuously adjusted. Reactive power from a capacitor bank decreases when grid voltage decreases (directly proportional to each other), while a synchronous condenser can increase reactive current as voltage decreases (inversely proportional). One thing to note is that synchronous machines generally have higher energy losses than static capacitor banks. Most synchronous condensers connected to electric grids are rated between 20 MVAr and 200MVAr and mostly oil cooled. There is, no explosion hazard as long as the hydrogen concentration is maintained above 70% rate.

ABB’s synchronous condensers ensure efficient and reliable operation of power grids by providing reactive power compensation and additional short circuit power capacity. ABB tailors synchronous condenser modules to match system performance requirements and site conditions, and deliver optimum cost efficiency. To ensure reliable operation, ABB synchronous condensers are designed for high reliability, durability and the capability to operate for long periods of time between recommended service intervals. For the control of synchronous motors, the condenser can balance the transmission power grid to the motor to facilitate proper power factor correction in a power system. [10 149.]

2.3.2 Equivalent Circuit of Synchronous Motors.

In practice, the equivalent circuit diagram of a synchronous motor per phase is shown on figure 4 below, and the phasor diagram describe a situation when power factor is unity (Cos ø = 1). Unlike in RL circuit for the calculation of impedance (Z), the internal structure of synchronous motors equally comprise some resistance (R) and reactance (X_S). When current Ia is applied to excite the motor, is experiences some amount of resistance which ensures that the supplied current is safe enough to avoid damage of the armature circuit. V_O being the voltage drop across the armature and V_T being the terminal voltage supplied to the machine can however be related as follows.

$$V_T = V_O + Ia\,(Ra + jX_S) \qquad (11)$$

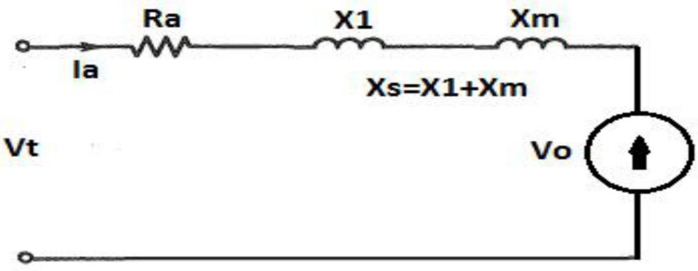


Fig 4 Equivalent Circuit of Synchronous Motor per Phase (Copied from [9, 273].)

Similarly, we can see from the phasor diagram of figure 5 below how the current and voltages are drawn in vector forms with respect to the angle, the armature current and the back E.M.F measured in the armature circuit.

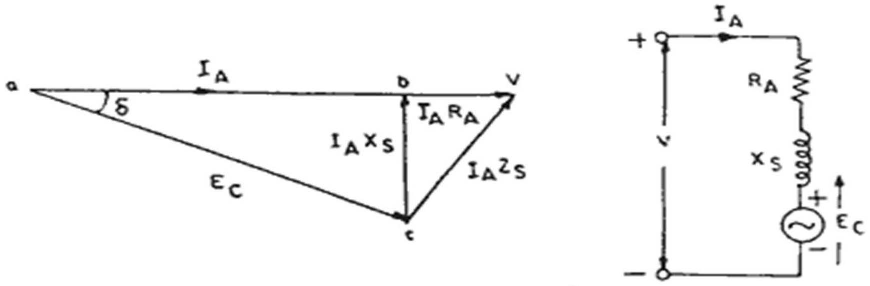


Fig 5. Phasor Diagram of per Phase Equivalent Circuit (Copied from [9,274]).

The sum of all the voltage drops of the machine and the E.M.F amount to the terminal voltage V_T. In this case, V_T is the phase voltage deduced from the supply line voltage V drawn from the mains in order to energize the stator windings, which then provokes the magnetic fields by creating a set of currents for the machine to run at synchronous speed.

2.3.3 Synchronous Motor Operating Curves.

When the synchronous motor operates with a constant input power, the variation of the armature current with field current is thus a V-shaped curve as shown below on figure 6. In general, over-excitation will cause the synchronous motor to operate at a leading power factor, while under-excitation will cause the motor to operate at a lagging power factor. Thus the synchronous motor then has a variable power factor characteristic.

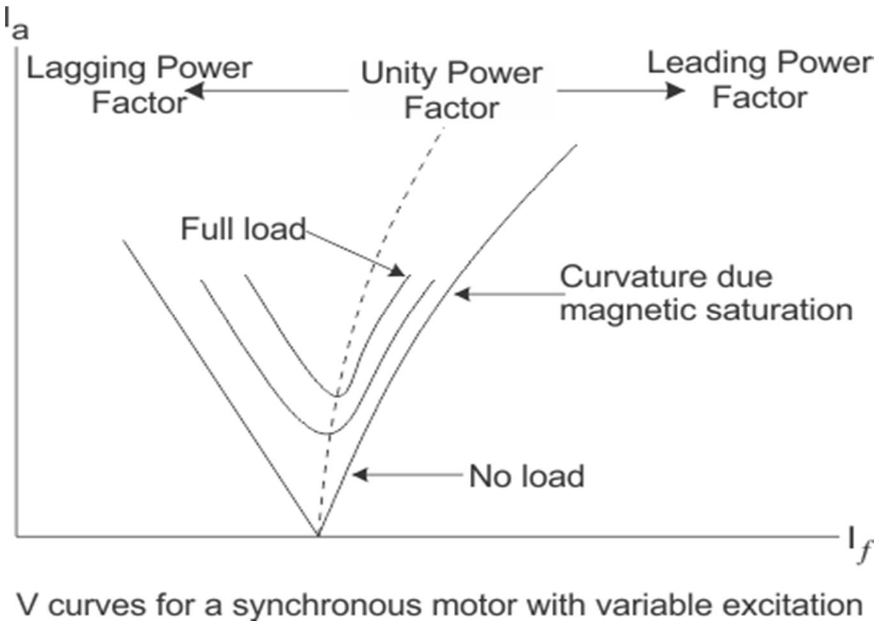


Fig 6: Synchronous Motor V-Curves. (Copied from Electrical4u [11])

When the motor power factor is unity, we can conclude that the motor is optimally magnetized and working under a perfect condition. The operating curves is however shown for three different instances that is when the motor is operating at No load, Half load and then finally when it is operating at a full load. Though the efficiency of synchronous motors will rarely be 100%, but it is often a good thing to attain a unity power factor which is the ratio of the active power to the apparent power of the supply line to the motor. At full load condition, very large synchronous motors operate with high reluctance as a result of high torque but with relatively low speed suitable for driving elevators, robots, conveyor belts where the mechanical parts to be driving require extremely high resistance motor to the turning effect of the system to be driven by the motor. [11.]

3 Starting Method of Synchronous Motors.

In principle, we acknowledged that synchronous motors are not self-started as the case with induction motors. The use of different starting methods is required to launch a synchronous motor into operation. Starting methods are introduced depending on the application area of the motor and other factors such as the nature of the supply available, environmental hazards and the load to be driven by the motor for effective torque production. Thus the starting of synchronous motor from its standstill position can be obtained by the following methods.

3.1 Starting using a DC Motor Coupled to the Synchronous Motor.

A synchronous motor can be started by using a DC motor. Firstly the synchronous motor is driven by a DC motor attached to the rotor and is then brought to synchronous speed. The motor is then synchronized with the bus bars. When the synchronous motor is connected in parallel with the bus bars, it then works as required after which the DC machine coupled to the rotor of the synchronous motor can then be mechanically disconnected from the system. Prior to understanding the synchronous motor DC excitation, it should be remembered that any electromagnetic device must draw a magnetizing current from the AC source to produce the required working flux.

This current lags by almost 90^0 to the supply voltage. In other words, the function of this magnetizing current or lagging VA drawn by the electromagnetic device is to set up the flux in the magnetic circuit of the device. Hence, the synchronous motor is doubly fed electrical motor since both its stator and rotor are powered separately from one another causing it to convert electrical energy into mechanical energy via magnetic circuit.
It receives 3 phase AC supply to its armature windings and a separate DC supply to its rotor circuit. [9, 278; 12.]

Synchronous motor excitation refers to the DC supply given to the rotor which is used to produce the required magnetic flux needed for the motor to operate. One very unique and major characteristics of this motor is that it can be operated at any electrical power factor leading, lagging or unity and this feature is based on the excitation of the synchronous motor

3.2 Starting Using a Damper Winding.

A damper winding is made on the pole face slots. Copper aluminium bars are inserted in slots, on pole shoes, on each side of the poles, end ring short circuit. A squirrel cage winding is formed by these short circuited bars, however a three phase supply is applied to the stator.

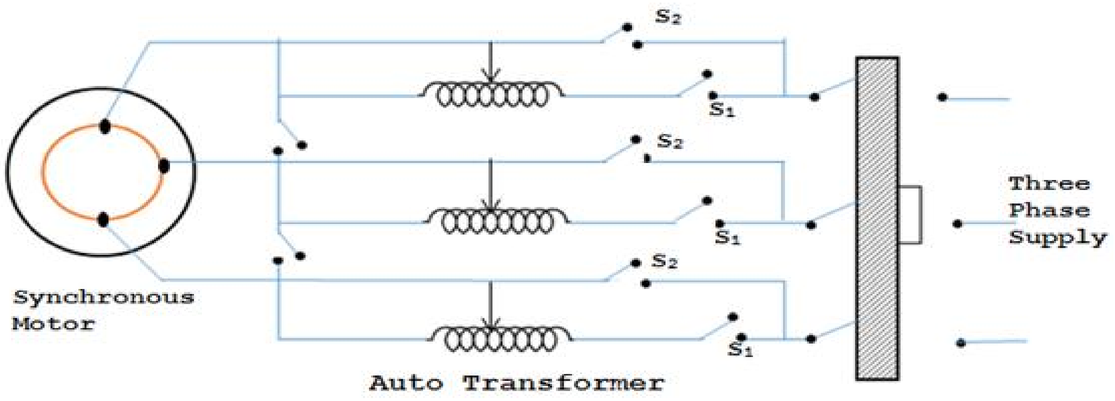


Fig 7. Limiting Starting Current Using Damper Windings (Copied from my tech-info [12])

The synchronous motor, provided with a damper winding, starts as an induction motor. This will run at a speed near the synchronous speed. At this stage, DC excitation is given to the field windings. The rotor will be pulled into synchronous speed. For higher output motors, the starting current drawn may be many times the full load current. Therefore the starting current has to be limited to a safe value to avoid damages.

For this purpose reduced voltage may be applied by an auto-transformer. The voltage applied should be about 50-80 percent of the full load line voltage. In figure 7 above, connections for the auto transformer are shown clearly. To reduce the supply voltage at start, the switch s1 is closed and s2 kept opened which ensures a safe starting for the motor under normal condition.

When the motor gains speed, then s1 is opened while s2 is closed to isolate the auto-transformer which intends provoke the motor to function at nominal speed. We can as well refer to this method as the auto transformer starting of 3 phase synchronous motors using damper winding. In this project, much emphasis shall be laid on the inverter circuit which produces a suitable voltage at variable frequency required in starting this special machine. [12.]

3.2.1 Table of Parameters and Characteristics

It is often very important to consider the choice of a particular motor by taking into consideration the name plate values and other important parameters that give full specification and description of the type of motor in demand when ordering. A comprehensive list or table of values is very useful in explaining the precision and accuracy of the motor based on its rated values. Table 1 below gives some clarification on the values obtained during calculation of the motor's parameters using MATHCAD program. This enables the manufacturer to produce a particular motor based on the rated values.

Table 1. Important Parameters for Design of this Motor (From Appendix 1).

parameters	value	unit	symbol
sync speed	5000	rpm	Ns
poles	4	-	p
frequency	167	Hz	f
torque	7.64	Nm	T
voltage	325	v	VDC
current loading	250	A/cm	Am
total slot	36	-	Q
current density	2.5	A/mm^2	δcu
rotor diameter	0.21	m	Dr
power output	1000	W	Po
efficiency	0.92	p. u	η
Phases	3	-	3-ø
Power factor	0.8	lead/lag	Cos ø
Phase voltage	132.68	V	U
magnetic field	0.7	T	B
phase current	3.13	A	Ia
power input	1086	W	P_{in}

The above table 1, gives clear understanding of the rated values of the motor as used in this project. These information provided on the table however helps the manufacturer to produce a motor with some precision and accuracy in order to meet the objective of the designer or customer. If the data sheet is not respected, then the target for the motor may not be achieved. Appendix 3 shows some of the values as used here on the table.

3.2.2 Operating Speed and Frequency.

As earlier discussed in the principle of operation, synchronous motors have constant speed at which the motor is operating, though can vary if the number of poles of the motor or the supply frequency is been varied respectively. With induction motors, the rotor speed is different for the actual speed (synchronous speed). However we have to observe the relationship between the synchronous speed (Ns), and the supply frequency and how they are directly proportional to one another which makes the motor to operate in synchronism with a steady speed. From Equation (1), it is observed that the expression below show the relationship between the two parameters.

$$\mathrm{Ns} = \frac{120 \cdot f}{p}$$

Frequency is the number of complete revolutions made in one second in an Alternating Current circuit. In standard form, most AC equipment are rated with 50Hz, or 60Hz frequency. But in this project, the value of frequency is solely dependent on the synchronous speed (Ns) and the number of poles of the motor which can be realized by varying the inverter to the appropriate value needed to synchronize the motor during operation under normal circumstances. As long as the frequency value changes, the motor speed is either reducing or increasing.

$$\mathrm{f} = \frac{Ns \cdot p}{120} \tag{12}$$

f = 166.66Hz,
Where p = 4, Ns = 5000rpm.

One very important thing to note also is that frequency is not measured when we are dealing with a DC voltage source. Therefore frequency is solely an AC quantity and can only be associated to AC circuits and equipment requiring AC supply to operate. In the distribution and supply of electrical energy, frequency is used to describe the number of complete cycles in one second of both the positive and negative half cycles. AC motors require some amount of frequency associated with the supply voltage in order to be energized for operation. [4.]

3.2.3 Operating Torque.

In general, torque is defined as the ability of a force to rotate an object about an axis, or fulcrum. Mathematically torque is define as the cross product of the lever-arm distance vector and the force vector, which tends to produce some rotation about an axis. For example, pushing or pulling the handle of a wrench connected to a bolt produces a torque that loosens or tightens the bolt. The magnitude of torque depends on mainly three parameters such as: Force applied, the length of the lever arm connecting the axis to the point of force application, and the angle between the force vector and the lever arm.

$$\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F} \qquad (13)$$

But in this project, we shall define the starting torque of a 3 phase synchronous motor as the torque that the motor must supply in order to drive a standstill load resistant torque, that is, it is the load starting torque. Pull in torque is the torque supplied by the motor to reach the correct speed, where the excitation field application will take the motor to the synchronism. Whereas pull out torque is the torque that the motor must supply to keep it under synchronism in case of momentary overloads with the excitation. When driving high inertia loads, synchronous motors are designed in larger frame sizes so as to meet acceleration condition.

$$T_{ind} = \frac{3 \cdot Vt \cdot EA \cdot Sin\,\beta}{\omega \cdot Xs} \qquad (14)$$

The steady-state speed of the motor is constant from no load, all the way up to the maximum torque that the motor can supply (called pull-out torque). Hence, the maximum torque occurs when $\beta = 90^{0.}$ Normally the pull out torque may be three times the full load torque of the machine. When the torque on the shaft of the machine exceeds the pull out torque, the rotor can no longer remain locked to the stator and net magnetic fields, instead the rotor starts to slip behind them. As the rotor slows down, the stator magnetic field ''laps'' it repeatedly, and the direction of the induced torque in the rotor reverses with each pass. [13.]

The resulting huge torque surges, first one way and then the other way, cause the whole motor to vibrate severely. The loss of synchronization after the pull out torque is exceeded is known as slipping poles. Hence, the maximum or pull out torque of the motor is given by the equation below. From these equations, we recall that the larger the field current (and hence E_A), the greater the maximum torque of the motor which provides the stability advantage to operate the motor with a large field current or large E_A. Where, V_P is the phase voltage, E_A is the magnetic back e m f, ω is the motor speed, β is the load angle and then X_S is the synchronous reactance.

$$T_{max} = \frac{3 \cdot Vt \cdot EA}{\omega \cdot Xs} \tag{15}$$

3.2.4 The Effect of Load Changes on a Synchronous Motor

If a load is attached to the shaft of a synchronous motor, the motor will develop enough torque to keep the motor and its load turning at the synchronous speed. Moreover when a load is changed, by increasing on a synchronous motor operating initially with a leading power factor, the rotor will initially slow down. As it does, the torque angle β becomes larger, and the induced torque increases. The increase in induced torque eventually speeds the rotor back up, and the motor again turns at synchronous speed but with a larger torque angle β.

The speed is constrained to be constant by the input power supply, and since no one has touched the field circuit, the field current is constant as well.
Therefore E_A must be constant as the load changes. Observing how the change in the shaft load on a synchronous motor affects the motor, there is one other quantity on a synchronous motor that can be readily adjusted which is it field current. Any increase in the field current of synchronous motors, increases the magnitude of E_A but does not affect the real power supplied by the motor.

The power supplied by the motor changes only when the shaft load torque changes. Since a change in I_P does not affect the shaft speed n, and since the load attached to the shaft is unchanged, the real power supplied is unchanged. Of course V_T is also constant, since it is kept constant by the power source supplying the motor. At low E_A, the armature current is lagging, and the motor is an inductive load. It is acting as an inductor-resistor combination, consuming reactive power Q_R and as the field current is increased further, the armature current eventually lines up with $V_{T.}$ [13, 276-277.]

3.2.5 Torque Speed Characteristic of Synchronous Motor.

It is very important to know the driven load data when specifying synchronous motors, since resistant torque curve and load inertia have direct influence on the motor starting characteristics. In areas where the load to be driven is relatively large, motors with high torque but low speed are most suitable for used in order to produce the required resistant to the mechanical parts such as in conveyors and elevators. In figure 8 below, in order for the synchronous motor to develop the same torque with different speeds and constant rotor current, the ratio Vs/ω must be kept constant such that the motor obeys the following equations.

$\Psi S = VS/j\omega$. $T = iR \times \Psi S$.

ΨS = Rotating flux linkage or winding flux of the motor.

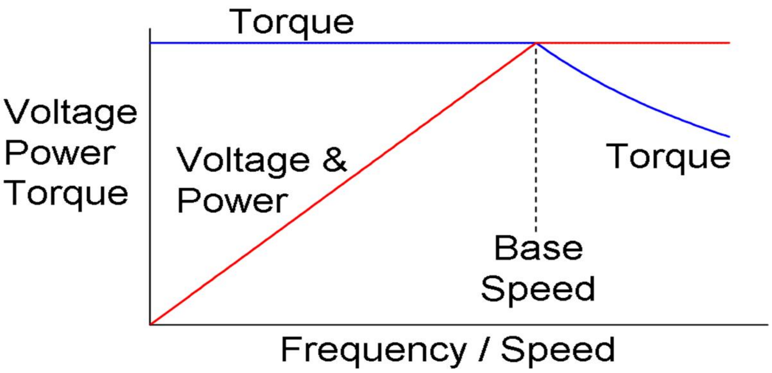


Fig 8. Torque - Speed Characteristic of a Synchronous Motor. (Copied from wiki/ASD [14]).

Since the speed of synchronous motor is constant whenever the frequency is not changing, the slip (s) is zero, such that the terminal voltage and the system frequency will be constant regardless of the amount of power drawn by the motor. The speed of rotation of the motor is locked to the rate of rotation of magnetic fields, and the rate of rotation of the applied mechanical fields is locked to the applied electrical frequency, this makes the speed of synchronous motor to be constant regardless of the load only if load does not change. In equation (14), it can be noticed that if the speed of the motor increases, then the torque will reduce since both are inversely proportional to one another. [14.]

3.3 Variable Frequency Drive for Synchronous Motor.

A variable frequency drive (VFD), is an adjustable device used in electromechanical drive systems to control AC motor speed and torque by varying the motor input frequency and voltage. About 25% of the world's electrical energy is consumed by electric motors in industrial applications. It is more conducive for energy saving using VFDs. Usually various types of synchronous motors offer advantage in some situations when using VFDs. The VFD controller is simply a solid state power electronics conversion system consisting of three distinct sub systems: a rectifier bridge converter, a direct current (DC) link, and an inverter. Each unit of the set up below seen on fig 9, plays an important part in the frequency and speed variation of the motor.

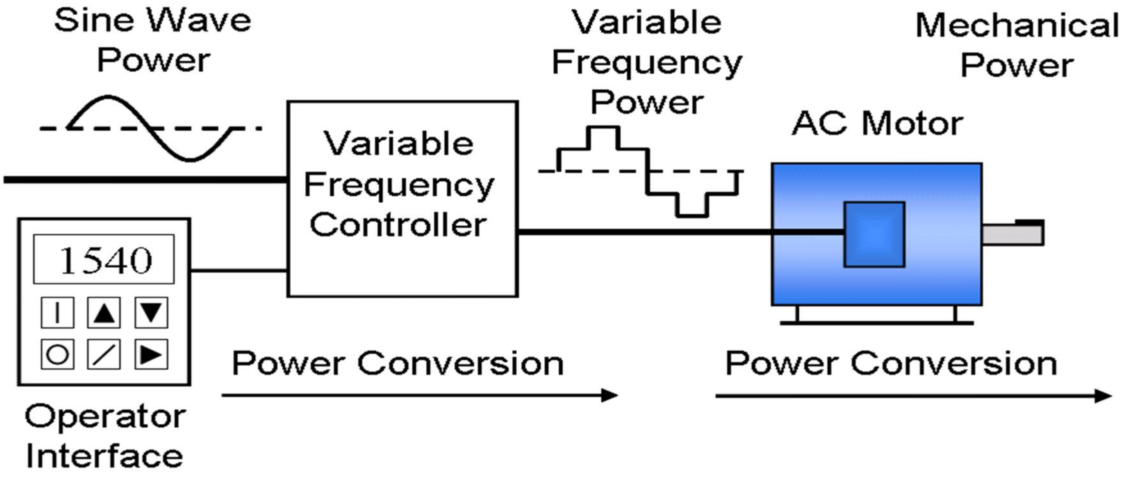


Fig 9. VFD System for AC Motors. (Copied from Solid State AC Motor Control [15]).

Most drives are AC-AC drives since they convert AC line input to AC inverter output. In a voltage source inverter (VSI), the DC link consist of a capacitor which smooths out the converter's DC output ripples and provides a stiff input to the inverter. This filtered DC voltage is converted to quasi-sinusoidal AC voltage output using the inverter's active switching elements. VSI drives provide higher power factor and lower harmonic distortion. In a variable torque application suited for volts per hertz (V/Hz) drive control, AC motor characteristics require that the voltage magnitude of the inverter's output to the motor be adjusted to match the required load torque in a linear V/Hz relationship. [15.]

3.3.1 The Operator Interface of VFD.

The operator interface provides a means for an operator to start and stop the motor and adjust the operating speed only by varying the frequency supplied by the inverter unit. Additional operator control functions might include reversing, and switching between manual speed adjustment and automatic control from an external process control signal. The operator interface often includes an alphanumeric display or indication light and meter to provide information about the operation of the drive. Most are often provided with input and output (I/O) terminals for connecting push buttons, switches, and other operator interface devices or control signals.

In this project, a suitable inverter (HNC Automation Frequency Inverter), with model name HV1000 to provide the desired frequency to supply the motor is studied and believed to have the appropriate functioning characteristics such as output frequency of 167Hz, needed to run this 3-phase PM synchronous motor at synchronous speed of 5000rpm. The inverter of figure 10 below, is a general purpose inverter that can vary the output frequency for both induction motor and synchronous motor enabling them to run at any desired synchronous speed. The HV1000 series of VFD has equal quality and feature with Emerson EV3000 but much more cost effective.

Fig 10. VFD (HNC Automation for PMSM), (Copied from hisupplier.com [16]).

This inverter has an anti-tripping function and capabilities of adapting severe power network, temperature, humidity, and dusty environment which exceeds those of similar products made by other companies, and improves the product reliability noticeably. It satisfies high performance requirements by using a unique control method to achieve high torque, high accuracy and wide speed adjusting range. Some of the features of HV1000 frequency inverter are as follows; Precise self-learning of motor parameter, static mode (stator/rotor) time constant, dynamic mode (magnetic flux parameter) and hence the best dynamic control. The functioning setup can be seen on appendix 2 attached.

3.3.2 Optimizing of Motor Noise and Heat.

This special inverter device has a unique modulation technology which decreases current harmonics, frequency spectrum balance technology which adjust the motor tone. Ensuring suitable decrease of common-mode voltage and reducing the leak current which ensures smooth running of the motor at the appropriate voltage and supply frequency for a steady synchronous speed. Carrier wave dynamic adjustment, which reduces the temperature of the motor when running. Also reducing the switching frequency, when high frequency of the module increases provokes heat. Can provide very high torque output for the motor. Table 2 below shows some properties and characteristic elements of HNC Automation inverter HV1000 series model.

Table 2. Main Composition of the HNC Automation Frequency Inverter

Properties	Characteristic	Value
Frequency range	AC mains	0……..650Hz
Voltage	1-phase, 3-phase	220v / 380v
Current	-	7.5A
Power Output	-	0.75kw….560kw
Speed range	-	1:100
Storage temperature	-	- 40^{0}c …. + 70^{0}c
Supply	AC	3-phase

The HNC Automation inverter HV1000 series has variety of advantages in motor control such as perfect deceleration and acceleration features enabled by the perfect current control ability. Has high torque in low frequency, due to complete motor parameter autotune and delay time compensation, with strong overload current which could suffer maximum 2.3 times rated current instantly, and with very good feature in high frequency, enabled by optimized over-modulation technology.

The control panel has the ability for total lock or partiality lock, in order to avoid malfunction and able to show many parameters, such as frequency setting, output frequency, output voltage, etc. Other applications of this special inverter include pump/fan, CNC machine tools, winder machine, grinding machine, injection machine, extruding machine, industry washing machine and many more areas where it is suitable for variable frequency of the motor driving the load system. [16.]

3.3.3 Power Stage Diagram and Losses.

In a three phase synchronous motor, the input power is the electrical power flow at the terminals. Power is then lost in the stator circuit, and the stator core when it tries to circulate through the motor. The remaining power is however transferred to the rotor such that by deducting the rotor losses, one can obtain the power converted to the mechanical system. At this point, stray losses and mechanical losses are deducted and the remaining power is the output power available to the mechanical load. In reality, core losses occur on both the rotor and the stator and stray losses (harmonic current and fluxes) are usually electrical losses distributed throughout the motor.

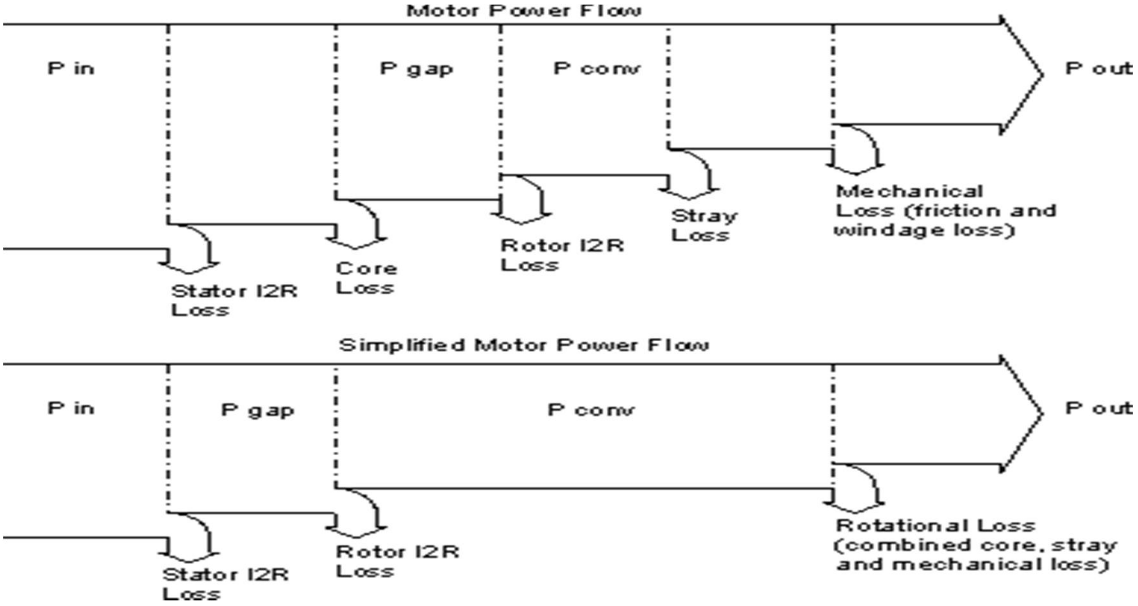


Fig 11. Power Flow Diagram for Synchronous Motor. (Copied from uclgary.ca)

It can be noted from the above diagram of figure 11 that any motor is usually fed with electrical energy at the input which then converts it into mechanical energy at the output. The rotational losses are due to the combined core, stray and mechanical loss of the motor when the shaft is rotating. Whereas the stator and rotor losses (I^2R) are usually due to heat dissipation in the motor when supplied with power from the network connected to the stator and rotor circuits. Iron losses are due to fundamental frequency ac flux in the core. These are mostly in the stator core of the machine.

3.4 Main Powers and Efficiency

In general, the input power for electric motors is usually the power drawn from the supply network to in order to excite the armature which then provokes the rotation of the shaft. During this process, losses are encountered in the motor circuit due to heat dissipation and general rotation losses. It is practically impossible to have an electric motor which operate with a 100% efficiency as there must often be some amount of losses in the machine during power conversion from electrical to mechanical powers. In a three phase synchronous motor, there are three power stages which include: Input power, mechanical power, and the output power.

$$P_{in} = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos\theta \qquad (16)$$

Where: V_L is the network line voltage
I_L is the line current drawn by the motor
Cos θ is the power factor of the system.

$$P_o = \text{input power} - (\text{Copper Losses} + \text{Stray Losses}) \qquad (17)$$

Alternatively, output power is such that, P_o = (Input power · Efficiency)
And the mechanical power P_M = (Input Power - Copper Losses)

$$\text{Efficiency } \eta = \frac{Output\ Power}{Input\ Power} (100)\ [\%] \qquad (18)$$

The output power (P_o) is however the power at which the shaft of the motor rotates when all the losses are subtracted. It is sometimes referred to as the operating power of the motor and can be calculated by taking into consideration the difference between power input, stray losses, copper losses or the product of the input power of the motor and the efficiency. The total copper losses in the motor are given as follows: ($P_J = 3 \cdot I^2a \cdot Ra$) Copper losses are due to heat in the motor and only occurs around the stator core. Meanwhile the stray and mechanical losses are due to the rotation of the shaft and sometimes when there is friction in the machine, we talk about frictional losses. [17.]

3.4.1 Applications of Synchronous Motors.

In principles, synchronous motors are purposely designed for application in areas where a constant speed is required to drive a particular load coupled to the fact that they are highly efficient in operation compared to other machines like induction motors. They are rarely used below 40KW output because of their high cost compared to induction motors. In addition to the high initial cost, synchronous motors equally need dc excitation source and starting and control devices are usually more expensive. The various classes for which synchronous motors are employed may be classified as follows:

Power factor correction
Voltage regulation
Constant speed, constant load drives.
Where high efficiency is required.
In areas where high kW power with high torque and low speed is needed.

Moreover, synchronous motors are used in generating stations and in substations connected to the bus bars to improve the power factor. For this purpose, they are run without mechanical load on them and in over-excited condition. These machines when over excited, delivers the reactive power to grid and helps to improve the power factor of the system. The reactive power delivered by the synchronous motors can be adjusted by varying the field excitation of the motor and hence can be referred to as the synchronous condensers for balancing the power in a grid network.

Due to very high efficiency compared to induction motors, synchronous motors are largely used in such drives as fans, blowers, line shafts, centrifugal pumps, compressors, reciprocating pumps, rubber and paper mills. More uses include the regulation of voltage at the end of transmission lines, whereas in textile and paper industries, synchronous motors are used to attain a wide range of speeds with variable frequency drive system. More application for synchronous motors are in laboratories to verify the speed and operating torques or the torque-speed characteristic curves of the motor during test and measurements experiments. [18.]

3.4.2 E.M.F Equation and Terminal Voltage

As it is the case in every motor circuit, it is important to note that in synchronous motor, the direction of current flow into the armature circuit of the motor is in opposite direction to that of generators. While motors receive currents to be excited for operations, generators send out currents from the armature circuit to any receptor that requires power in order to operate.

One important thing to note about all synchronous motors is that, their terminal voltages can be determined by adding the armature voltage drop ($I_A R_A$) to the back E.M.F meanwhile in synchronous generator the terminal voltage measured at the output is determined by subtracting the armature voltage drop ($I_A R_A$) from the E.M.F. The equations for voltage and E.M.F are the same except for the fact that the direction of current flow in generators is in opposition to the direction of current flow in motors and by this the signs between the parameters changes ($V_A = I_A \cdot R_A$) and series field reactance voltage drop ($V_X = I_A \cdot jX_S$) in both generator and motor.

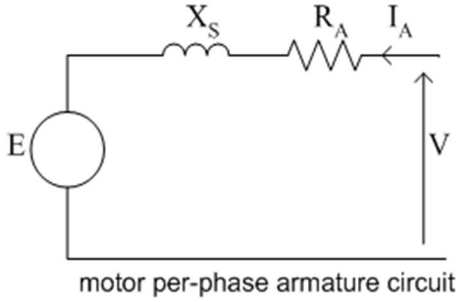


Fig 12. Per Phase Armature Circuit of Synchronous Motor. (Copied from [19]).

$$E = V - (V_A + V_X), \quad \text{or} \quad E = V - (I_A \cdot R_A + I_A \cdot jX_S)$$

$$V = E + (I_A \cdot R_A + I_A \cdot jX_S) \qquad (17)$$

The Circuit on fig 12 above shows clearly the inflow direction of current into the motor circuit, at point R_A and X_S, we measure some voltage drops (V_A and V_X) which when subtracted from the Terminal voltage (V), gives us the electromotive force (E) of the motor. After assembling, both synchronous generator and motor look much more similar to one another and have identical name plate values like frequency, operating speed, etc. In figure (12) above, the current (I_A) flowing from the motor terminal through the armature circuit, is constant since both R_A and X_S are in series to one another but only if the difference V-E, is also constant. [19, 273.]

3.4.3 Comparing Synchronous Motors to Induction Motors

Knowing the differences between synchronous and induction motors, enable subscribers to be able to make demand for each type taking into consideration some important features or aspects associated with the area of application. For example, the desire for a suitable efficiency, speed variation, torque and the nature of load to be driven can influence the choice for the selection of a particular motor to be used wherever need be. In table 3 shown below, the comparisons are analysed in more details.

Table 3. Comparing Synchronous and Induction Motor (Copied from uotechnology.edu.)

Synchronous Motors	Induction Motors
These motors have dc excitation source on the rotor	These motors have wound rotor with slip rings or squirrel cage rotor
Their field currents can be changed to vary the power factor	Their rotor current is AC and is induced by magnetic induction
These motors only run at synchronous speed without slips.	These motors run at less than synchronous speed. Full load slip of about 4%
These motors do not have any inherent starting torque	These motors have inherent starting torque
These motors are started by suitable means then brought to synchronous speed and then synchronized	These motors are self-starting
These motors are used for both constant and variable speed and load drives, where slip is zero	These motors are useful for variable speed and variable load drives where slip is not zero.
These motors generally have high efficiencies	These motors have a slickly less efficiency

In general, one of the major advantages for using a synchronous motor is the ability to control the power factor. Moreover, synchronous motors can be constructed with wider air-gaps than induction motors and by this they are mechanically more stable. However in synchronous motors, electromagnetic power varies linearly with the voltage. Some of the problems associated with synchronous motors are such that the cost per kW output is generally higher than that of induction motors. Also, synchronous motors cannot be started on load since their starting torque is zero. [20, 10.]

3.4.4 Cooling and Enclosure of Synchronous Motor

Depending on the load system to be driven by synchronous motors, special cooling methods and proper enclosures type is used to protect the motor from excess heat that is set up as the motor run over time. Cooling systems play very important role in the whole operating cycles of synchronous motors especially in areas where the torque is relatively high such that the heat production needs to be minimized to safeguard the motor from damages and unwanted noise. One good example is the WEG synchronous motor manufactured in B3, D5 or D6 mounting configurations and with grease lubricated ball or roller bearings or oil lubricated sleeve bearings. Appendix 4, shows a larger synchronous motor totally enclosed for industrial applications.

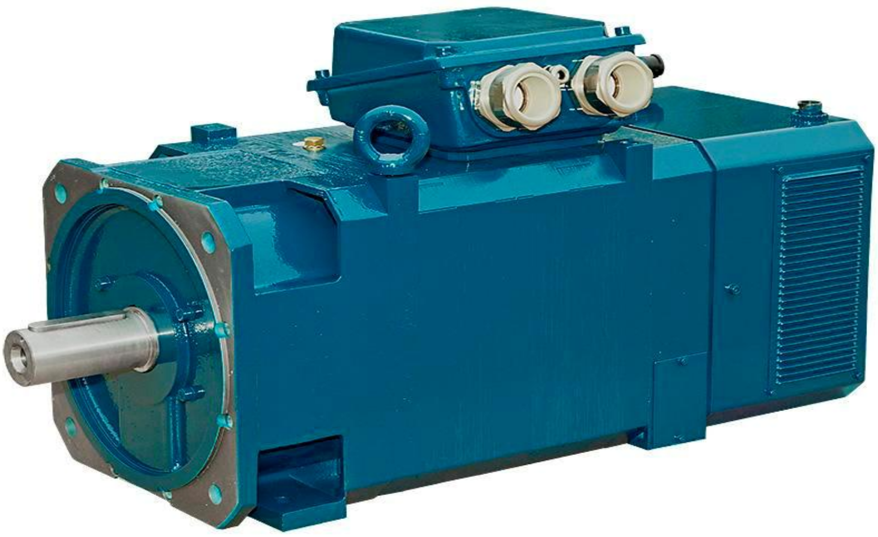


Fig 13. Totally Enclosed (IP54) Air Cooled 3-Phase Synchronous Motor
(Copied from www.directindustry.com)

On figure 13 above, is a totally enclosed synchronous motor with air colled method used. The cooling systems most commonly used are usually open self-ventilated motors, with degree of protection of IP23. Enclosed motors with air-air heat exchanger and degree of protection of IP54 to IPW65. Moreover other methods include enclosed motors with air-water heat exchanger and degree of protection of IP54 to IPW65. Beside all these cooling methods, motors can be supplied with forced ventilation, air inlet and outlet by ducts, and other colling methods always aimed at meeting environment and application characteristics. When specifying synchronous motors, it is also important to consider standard accessories reuired for correct operation and monitoring of the motor unit such as: Vibration detector, water flow thermometer, temperature detectors etc. [21.]

3.5 Protection of Synchronous Motor

Just as different cooling and enclosure types are important measures to ensure the safety of electrical machines like motors and transformers, other protective measures are used to prevent electrical faults such as: Short circuit, Open circuit, and overload faults. In brief, short circuit fault is the contact between two conducting elements with different polarities and can often occur in a motor circuit if the conductors or mechanical parts are not properly insulated or isolated from one another. To prevent short circuit faults in synchronous motors, fuse isolators with accurate calibration are generally used to instantly cut of the power supplying the motor, by this ensuring safety.

Fig 14. Protection of 3-Phase Motor against Measure Faults. (Copied from SELINC)

The SEL-710-5 Motor Protection Relay of figure 14 above, is a device which provides advance protection of synchronous motors against thermal overload, overcurrent, under-current, unbalanced current, differential current, phase loss, ground fault, loss of field, over or under frequency, and much more. The synchronous option also includes, at no additional cost, a voltage divider accessory to interface with the motor excitation system. The relay monitors field voltage and current, and effectively respond to conditions like loss of field, power factor and reactive power issues related to synchronous motors.

The device calculates the percent of thermal capacity used in the motor to determine maximum safe start times with full motor protection. It uses the eight programmable push buttons and 16 configurable tricolored LEDS on the front panel for control and indication with default start and stop functions. Can be installed in extreme environments with the industry's widest ambient temperature operating rage of –40° to +85°C (–40° to +185°F). Generally protects synchronous motors supported by VFDs and creates an integrated control system with a variety of I/O and communications options. [22.]

3 Measurement and Results.

Table 4 below shows values for an already assembled synchronous motor with similar features that can be liken to that of the motor designed during this thesis. The protection type of IP55 as seen on the table below, is closely related to that of the motor designed for this project with protection type of IP54. One very important feature to consider is the number of phases which in this example is also three. The power factor and efficiency mentioned on table 1 of page 16, are only assumed to be of values 0.8 and 92% respectively. With an AC voltage range of 380-400V for existing motor, we conclude that the motor designed for this thesis is operating within a define voltage range of 380-415V.

Table 4. Similar Parameters of an Existing Motor. (Copied from Alibaba.com).

Brand Name (OEM)	Small Electric Motors
Type	PM Synchronous Motor
Power	0.18kw - 22kw
Voltage	380V, 400V
Frequency	30-70Hz
Pole	4pole
Protection Class	IP 55
Cooling type	IC0141
Efficiency	92 %
Amb Temperature	-15 ~ 40^0 C
Protection feature	Totally Enclosed
Insulation Class	B, F

The existing synchronous motor whose values are represented on table 4 above has relatively higher efficiency as that of the motor design for this thesis. Starting can as well be done by using VFD (Variable Frequency Drive) which varies the source frequency to an appropriate value needed to run the motor at the synchronous speed. The motor specified on table 4 above is suitable for application where higher efficiency is required and other advantages are; it is easy to install, reliable in resisting environmental hazards, electricity saving and most application for this special motor include textile machinery, food processing, wood work etc.[23.]

5 Conclusion and Discussion

The thesis subject explains in details, the operating principle of a 3-phase PM synchronous motor, the nature of the supply to the motor using the variable frequency drive unit (VFD) to achieve a steady synchronous speed when the frequency is set to a fixed value at which the motor is synchronized. With the objective to achieve a constant speed and to produce the torque-speed characteristics of the motor, one of the very important points observed in the thesis was the ability to use synchronous motors under leading, lagging or unity power factors. By comparing synchronous motors to induction motors, one very big advantage was the possibility to achieve higher efficiency with synchronous motors than with induction motors.

The most fundamental starting point for the project was the calculation of main parameters such as the rotor diameter, number of N-loops, magnetic flux, phase voltage using MATHCAD program which enabled the choice of selection of the stator and rotor models for this motor taking into consideration the diameter, length and cross-sectional areas of the rotor and stator. With all the required formulas available, calculating the different values using MATHCAD was successful though at some points became very challenging to realize a suitable rotor diameter until when some values from the data were modified, which then facilitated the achievement of a preferred rotor size in metres. This machine has a variety of application such as in; Compressors, Fans, power factor improvement units, pumps, blowers, paper mills etc, due to their effective and highly efficient mode of operation

It was equally very important to come out with a constructive table of values as shown in table 1 of this project. From the table, all the values, symbols, and SI units for each parameter used in the calculations are mentioned making understanding easier. Also special notes were given to figures used in the texts to show details of the subject at each point and mentioning the sources from which pictured texts are extracted for used in this thesis. Considering that the datasheet for this motor in study matches with the standard, quality and functional principle of already existing motors with identical or as much similar properties, one could conclude that this 3-Phase PM Synchronous motor was designed according to the required specifications.

1 Fitzgerald, A. E.; Charles Kingsley, Jr.; Alexander Kusko (1971). "Chapter 6, Synchronous machines, steady state". Electric Machinery, 3rd Ed. USA: McGraw-Hill. pp. 283–330. Library of Congress Catalog No. 70-137126. [Online]. Available:https://en.wikipedia.org/wiki/Synchronous_motor. [Accessed 18 August 2015].

2 TMEIC, Synchronous Motor Enclosure Type. [Online]. https://www.tmeic.com. [Accessed 18 August 2015].

3 The Invention of Electric Motors. [Online]. https://www.eti.kit.edu/english/1376.php. [Accessed August 27 2015].

4 Synchronous Motor Working Principle. [Online]. http://www.electrical4u.com/ synchronous motor. Online Electrical Engineering. [Accessed 28 August 2015].

5 Pia Salminen (2004), Motor Slot, Slot angle and Airgap. Lappeenranta University of Technology. [Online]. https://www.doria.fi/bitstream/handle/10024/31164/TMP. [Accessed 02 September 2015].

6 Kai Lindgren (2015), Synchronous Reluctance, Slot Area and N-loops. Metropolia University of Applied Sciences Finland [Accessed from lecture materials].

7 Construction of Synchronous Motor, Operating Principle and Motor Internal Structure. [Online]. http://www.electrical4u.com/. Online Electrical Engineering. [Accessed 28 August 2015].

8 Operation of Synchronous Motor with DC Excitation. [Online]. http://www.electrical-knowhow.com/2012/05/classification-of-electric-motors-part_22.html. [Accessed 20 August 2015].

9 Stephen J. Chapman, Electric Machinery Fundamentals, 5th Ed, p. 285. McGraw-Hill (2012), BAE System Australia. Power Factor Improvement.

10 B. M. Weedy, Electric Power Systems 2nd Ed, John Wiley and Sons, London, 1972, page 149. Synchronous Motor and Power Factor Correction. [Online]. https://en.wikipedia.org/wiki/Synchronous_condenser. [Accessed 17 September 2015].

11 Synchronous Motor V Curve with Variable Excitation for Power Factor Correction [Online]. http://www.electrical4u.com/synchronous-motor-excitation. [Accessed 06 October 2015].

12 Starting Methods for Synchronous Motor. [Online]. http://www.mytechinfo.com/2015/02/ .html. Accessed 28 August 2015].

13 Stephen J. Chapman, Electric Machinery Fundamentals, 5th Ed. McGraw-Hill (2012), BAE System Australia. Motor Torque Equation.

14 Torque-Speed Characteristic of Synchronous Motor. [Online]. https://en.wikipedia.org/wiki/Adjustable speed drive. [Accessed 25 September 2015].

15 Campbell, Sylvester J. (1987). Solid-State AC Motor Controls. New York: Marcel Dekker, Inc. pp. 79–189. Variable Frequency. [Online].https://upload.wikimedia.org/wikipedia/commons/e/e5/VFD_System.png. [Accessed 06 October 2015].

16 VFD Operator Interface. [Online]. http://efvjiwo.en.hisupplier.com/product-1891229-three-phase-inverter-variable-frequency-inverter.html [Accessed 16 October 2015].

17 Power Flow Diagram and Losses. [Online]. http://people.ucalgary.ca/~aknigh/electrical_machines/fundamentals/f_ac_losses.html. [Accessed 10 October 2015].

18 Application of Synchronous Motors. [Online]. http://electricalquestionsguide.blogspot.fi/2012/09/applications-synchronous-motors.html. [Accessed 20 October 2015]

19 Stephen J. Chapman, Electric Machinery Fundamentals, 5th Ed, p. 273. McGraw-Hill (2012), BAE System Australia. E.M.F Equation and Terminal Voltage, Per Phase Armature Circuit of Synchronous Motor.

20 DR Suad Ibrahim Shahl. [Online]. http://uotechnology.edu.iq/dep-eee/lectures/3rd/Electrical/Machines%202/III_SM.pdf Difference between Synchronous and Induction Motors. [Accessed 22 October 2015].

21 Synchronous Motor Enclosure [Online]. http://ecatalog.weg.net/files/wegnet/WEG-synchronous-motors-technical-article-english.PDF. [Accessed 26 October 2015].

22 Synchronous Motor Protection [Online]. https://www.selinc.com/SEL-710-5/ [Accessed 27October 2015].

23 Existing Synchronous Motor with Similar Parameters. [Online].http://www.alibaba.com/product-detail/MSEJ-three-phase-synchronous-brake-motor. [Accessed 27 October 2015].

Calculation of Motor’s Parameters Using Mathcad Programme

$m0 := 3$ $n := 500$ $kw := 0.9$ $Am := 25$ $Dr := 1$

$Pshaft := 100$ $\varepsilon 0 := 1$ $cosfii := 0.8$ $Bm := 0.7$ $lst := 0.4$

$VDC := 32$ $P := 4$ $\eta := 0.9$

a)

$$Va := \frac{VDC}{\sqrt{6}} = 132.681$$

$$Ia := \frac{Pshaft}{m0 \cdot Va \cdot \eta \cdot cosfii} = 3.139 \qquad Ef := Va = 132.681$$

b)

$$nsec := \frac{n}{60}$$

$$Dr2lst := \varepsilon 0 \cdot \frac{Pshaft}{\frac{\pi^2}{2} \cdot kw \cdot nsec \cdot Bm \cdot Am \cdot \eta \cdot cosfii} = 0.018$$

$$Dr := \sqrt{\frac{Dr2lst}{lst}} = 0.213$$

c)

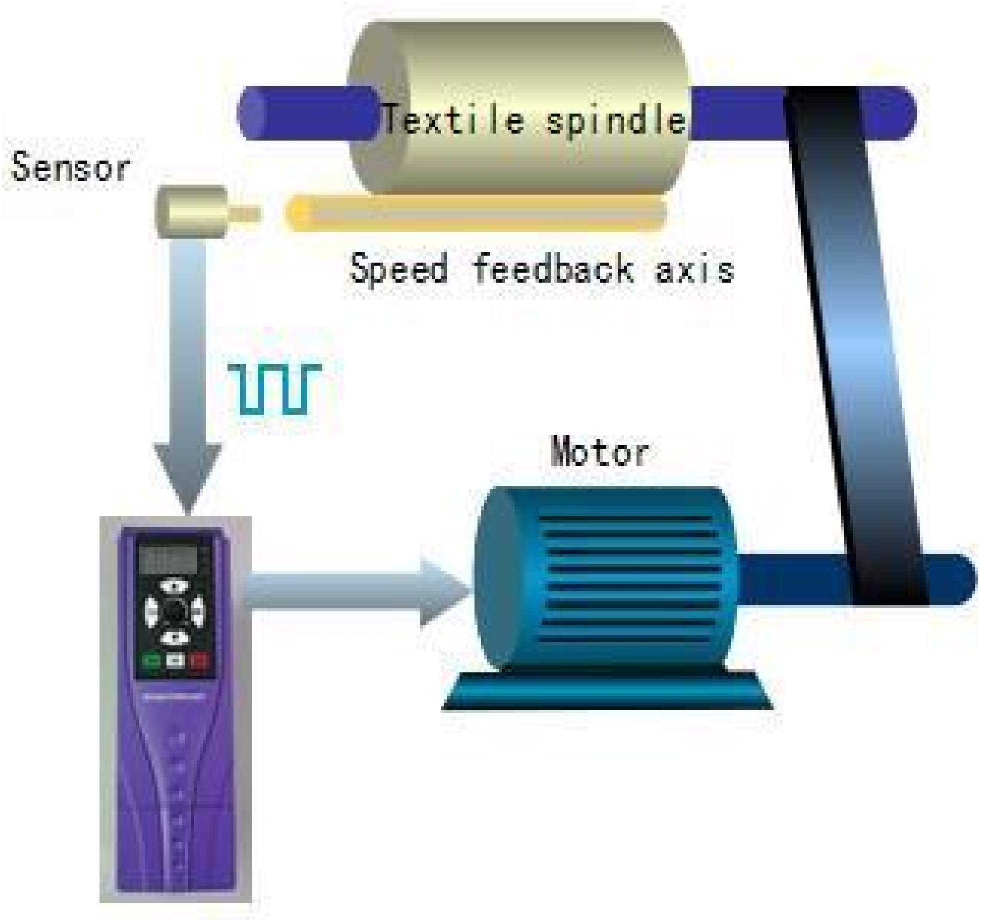
$$\tau p := \pi \cdot \frac{Dr}{P} = 0.167$$

$$\Phi f := \frac{2}{\pi} \cdot Bm \cdot \tau p \cdot lst = 0.03$$

d)

$$Nc := \frac{Ef}{\sqrt{2} \cdot \pi \cdot nsec \cdot \frac{P}{2} \cdot kw \cdot \Phi f} = 6.27 \qquad Nc2 := \frac{Am}{2 \cdot m0 \cdot Ia \cdot \sqrt{2}} \cdot 2 \cdot \pi \cdot \left(\frac{Dr}{2}\right) = 6.27$$

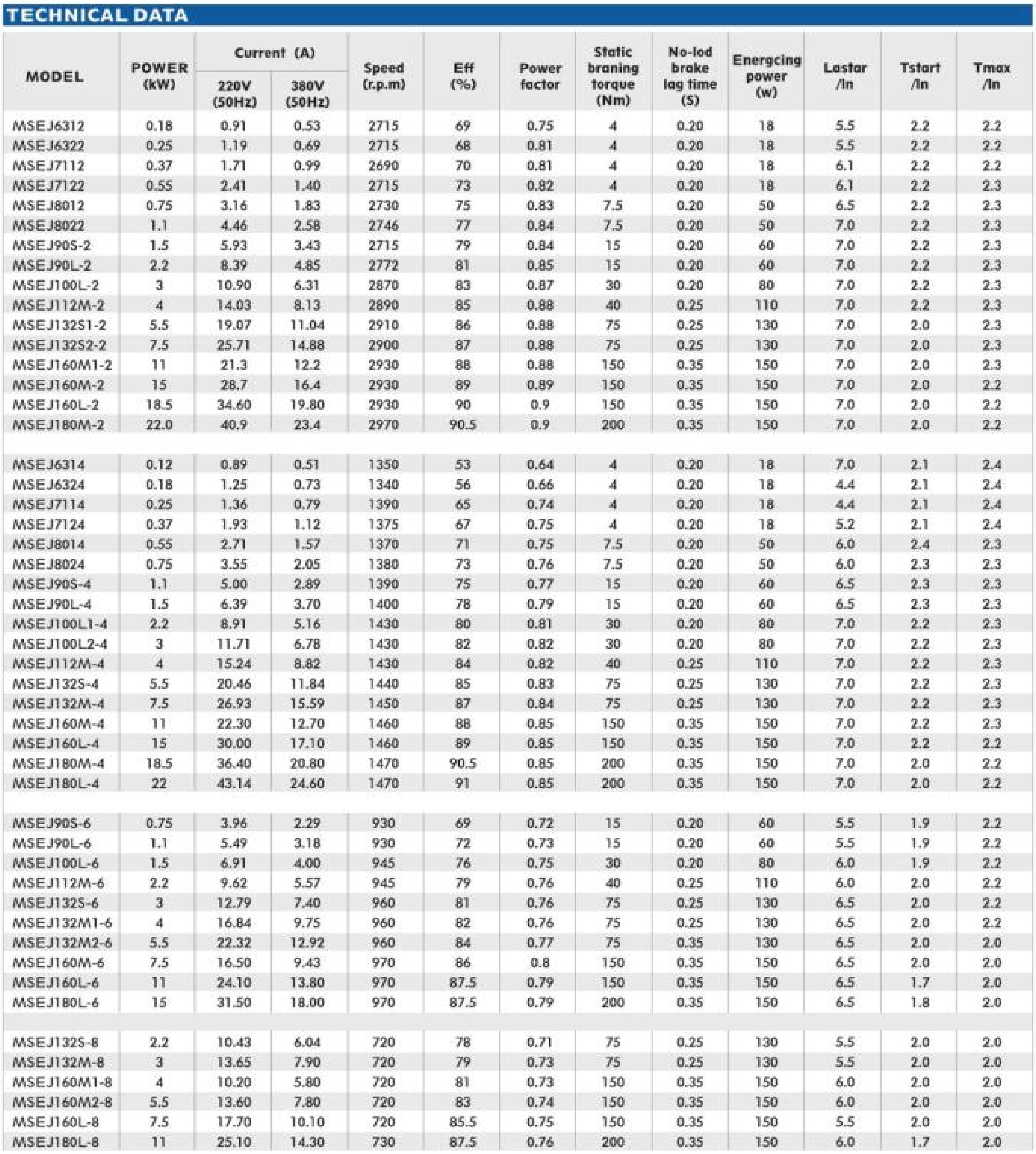
Setup for Varying Frequency of Motor Using VFD.



VFD

Appendix 3

Catalogue of Existing PM Synchronous Motor.



TECHNICAL DATA

MODEL	POWER (kW)	Current (A)		Speed (r.p.m)	Eff (%)	Power factor	Static braning torque (Nm)	No-lod brake lag time (S)	Energcing power (w)	Lastar /In	Tstart /In	Tmax /In
		220V (50Hz)	380V (50Hz)									
MSEJ6312	0.18	0.91	0.53	2715	69	0.75	4	0.20	18	5.5	2.2	2.2
MSEJ6322	0.25	1.19	0.69	2715	68	0.81	4	0.20	18	5.5	2.2	2.2
MSEJ7112	0.37	1.71	0.99	2690	70	0.81	4	0.20	18	6.1	2.2	2.2
MSEJ7122	0.55	2.41	1.40	2715	73	0.82	4	0.20	18	6.1	2.2	2.3
MSEJ8012	0.75	3.16	1.83	2730	75	0.83	7.5	0.20	50	6.5	2.2	2.3
MSEJ8022	1.1	4.46	2.58	2746	77	0.84	7.5	0.20	50	7.0	2.2	2.3
MSEJ90S-2	1.5	5.93	3.43	2715	79	0.84	15	0.20	60	7.0	2.2	2.3
MSEJ90L-2	2.2	8.39	4.85	2772	81	0.85	15	0.20	60	7.0	2.2	2.3
MSEJ100L-2	3	10.90	6.31	2870	83	0.87	30	0.20	80	7.0	2.2	2.3
MSEJ112M-2	4	14.03	8.13	2890	85	0.88	40	0.25	110	7.0	2.2	2.3
MSEJ132S1-2	5.5	19.07	11.04	2910	86	0.88	75	0.25	130	7.0	2.0	2.3
MSEJ132S2-2	7.5	25.71	14.88	2900	87	0.88	75	0.25	130	7.0	2.0	2.3
MSEJ160M1-2	11	21.3	12.2	2930	88	0.88	150	0.35	150	7.0	2.0	2.3
MSEJ160M-2	15	28.7	16.4	2930	89	0.89	150	0.35	150	7.0	2.0	2.2
MSEJ160L-2	18.5	34.60	19.80	2930	90	0.9	150	0.35	150	7.0	2.0	2.2
MSEJ180M-2	22.0	40.9	23.4	2970	90.5	0.9	200	0.35	150	7.0	2.0	2.2
MSEJ6314	0.12	0.89	0.51	1350	53	0.64	4	0.20	18	7.0	2.1	2.4
MSEJ6324	0.18	1.25	0.73	1340	56	0.66	4	0.20	18	4.4	2.1	2.4
MSEJ7114	0.25	1.36	0.79	1390	65	0.74	4	0.20	18	4.4	2.1	2.4
MSEJ7124	0.37	1.93	1.12	1375	67	0.75	4	0.20	18	5.2	2.1	2.4
MSEJ8014	0.55	2.71	1.57	1370	71	0.75	7.5	0.20	50	6.0	2.4	2.3
MSEJ8024	0.75	3.55	2.05	1380	73	0.76	7.5	0.20	50	6.0	2.3	2.3
MSEJ90S-4	1.1	5.00	2.89	1390	75	0.77	15	0.20	60	6.5	2.3	2.3
MSEJ90L-4	1.5	6.39	3.70	1400	78	0.79	15	0.20	60	6.5	2.3	2.3
MSEJ100L1-4	2.2	8.91	5.16	1430	80	0.81	30	0.20	80	7.0	2.2	2.3
MSEJ100L2-4	3	11.71	6.78	1430	82	0.82	30	0.20	80	7.0	2.2	2.3
MSEJ112M-4	4	15.24	8.82	1430	84	0.82	40	0.25	110	7.0	2.2	2.3
MSEJ132S-4	5.5	20.46	11.84	1440	85	0.83	75	0.25	130	7.0	2.2	2.3
MSEJ132M-4	7.5	26.93	15.59	1450	87	0.84	75	0.25	130	7.0	2.2	2.3
MSEJ160M-4	11	22.30	12.70	1460	88	0.85	150	0.35	150	7.0	2.2	2.3
MSEJ160L-4	15	30.00	17.10	1460	89	0.85	150	0.35	150	7.0	2.2	2.2
MSEJ180M-4	18.5	36.40	20.80	1470	90.5	0.85	200	0.35	150	7.0	2.0	2.2
MSEJ180L-4	22	43.14	24.60	1470	91	0.85	200	0.35	150	7.0	2.0	2.2
MSEJ90S-6	0.75	3.96	2.29	930	69	0.72	15	0.20	60	5.5	1.9	2.2
MSEJ90L-6	1.1	5.49	3.18	930	72	0.73	15	0.20	60	5.5	1.9	2.2
MSEJ100L-6	1.5	6.91	4.00	945	76	0.75	30	0.20	80	6.0	1.9	2.2
MSEJ112M-6	2.2	9.62	5.57	945	79	0.76	40	0.25	110	6.0	2.0	2.2
MSEJ132S-6	3	12.79	7.40	960	81	0.76	75	0.25	130	6.5	2.0	2.2
MSEJ132M1-6	4	16.84	9.75	960	82	0.76	75	0.25	130	6.5	2.0	2.2
MSEJ132M2-6	5.5	22.32	12.92	960	84	0.77	75	0.35	130	6.5	2.0	2.0
MSEJ160M-6	7.5	16.50	9.43	970	86	0.8	150	0.35	150	6.5	2.0	2.0
MSEJ160L-6	11	24.10	13.80	970	87.5	0.79	150	0.35	150	6.5	1.7	2.0
MSEJ180L-6	15	31.50	18.00	970	87.5	0.79	200	0.35	150	6.5	1.8	2.0
MSEJ132S-8	2.2	10.43	6.04	720	78	0.71	75	0.25	130	5.5	2.0	2.0
MSEJ132M-8	3	13.65	7.90	720	79	0.73	75	0.25	130	5.5	2.0	2.0
MSEJ160M1-8	4	10.20	5.80	720	81	0.73	150	0.35	150	6.0	2.0	2.0
MSEJ160M2-8	5.5	13.60	7.80	720	83	0.74	150	0.35	150	6.0	2.0	2.0
MSEJ160L-8	7.5	17.70	10.10	720	85.5	0.75	150	0.35	150	5.5	2.0	2.0
MSEJ180L-8	11	25.10	14.30	730	87.5	0.76	200	0.35	150	6.0	1.7	2.0

Appendix 4

Totally Enclosed Large Synchronous Motor.

Basic Structure of a PM Synchronous Motor.