Experiment No: 5

Speed Control of 3 Phase Induction Motor

1 Aim

To study the behaviour of inverter fed three phase phase induction motor (IM) and to obtain the performance characteristics (T-N_r) of the motor

2 Theory

In a DC machine, the stator winding is excited by DC current and hence the field produced by this winding is time invariant in nature. In this machine the conversion of energy from electrical to mechanical form or vice versa is possible by one of the following ways:
• rotating the rotor in the field produced by the stator
• feeding external dc current through carbon brushes to the rotor
Now consider three coils A, B and C of N turns each, displaced in space by 120^o degrees and connected to a balanced 3 phase system as shown in Fig.1. (Note that the stator winding of 3 phase IM is distributed in a large number of slots as shown in Fig.2). The expressions for the current drawn by these coils are given by:

$$i_a = I\sin(\omega_s t) \qquad i_b = I\sin(\omega_s t + 120^o) \qquad i_c = I\sin(\omega_s t + 240^o)$$

where $\omega_s = 2\pi F_1$. When this alternating current flows through the coil it produces a pulsating magnetic field whose amplitude and direction depend on the instantaneous value of the current flowing through the coil. Each phase winding produces a similar magnetic field displaced by 120^o degrees in **space** from each other. The steps involved in determining the magnitude and position of the resultant field produced by these coils are as follows:
• Resolve the field produced by individual coil along x and y axes
• Determine $\sum x$ and $\sum y$ components
• Find the magnitude and angle of the resultant magnetic field with respect to the axis of coil-A.

The sum of the x-axis component of the field produced by the three coils is given by:

$$\sum x = Ni_a + Ni_b\cos 120^o + Ni_c\cos 240^o \qquad = Ni_a - (N/2)[i_b + i_c]$$

Since $i_a + i_b + i_c = 0$, the above equation can be written as: $\sum x = (3/2)Ni_a$
Similarly,

$$\sum y = 0 + Ni_b\sin 120^o + Ni_c\sin 240^o \qquad = (\sqrt{3}/2)N[i_b - i_c]$$

The magnitude and angle of the resultant magnetic field are given by:

$$R = \sqrt{(\sum x)^2 + (\sum y)^2} \qquad \& \qquad \theta = tan^{-1}\frac{\sum y}{\sum x}$$

Table-I gives the x and y axis components of the field produced by each coil, $\sum x$ and $\sum y$ components, and the magnitude and angle of the resultant magnetic field for various instantaneous values of the input current. It can be observed that the resultant of the three mmf (magneto-motive force or field) vectors is a vector whose magnitude remains constant (1.5 times the amplitude of mmf produced by the individual phases alone) and its position depends on the instantaneous value of input currents.

$\omega_s t$	i_a	i_b	i_c	$\sum x$	$\sum y$	R	θ
0^o	0	$+(\sqrt{3}/2)I$	$-(\sqrt{3}/2)I$	0	(3/2)NI	(3/2)NI	90^o
30^o	I/2	I/2	-I	(3/4)NI	$(3\sqrt{3}/4)NI$	(3/2)NI	60^o
90^o	I	-I/2	-I/2	(3/2)NI	0	(3/2)NI	0^o
180^o	0	$-(\sqrt{3}/2)I$	$+(\sqrt{3}/2)I$	0	-(3/2)NI	(3/2)NI	180^o

When the instantaneous value of phase-A current is zero (corresponding values of phases B and C are $(\sqrt{3}/2)$I and $-(\sqrt{3}/2)$ I respectively) the resultant field is aligned along the y-axis. When the input cycle completes 90^o the resultant field also rotates by the same amount. In other words, **the result of displacing the three windings by 120^o in space phase and displacing the winding currents by 120^o in time phase is a single positive revolving field of constant magnitude**. Under balanced three phase conditions, the three phase winding produces an air gap mmf wave which rotates at synchronous angular velocity determined by the supply frequency alone. The speed of the rotating magnetic field is

$$\omega_m = \omega_s \tfrac{2}{P} \text{ radians (mechanical)/sec.} \qquad \text{since, } 1^o Elec = (\tfrac{2}{P})^o Mech.$$

If N_s is the speed of the stator magnetic field in 'rpm', then

$$\tfrac{2\pi N_s}{60} = (\tfrac{2}{P}) 2\pi F_1 \qquad N_s = \tfrac{120 F_1}{P}$$

where P is the number of poles.
There are two types of rotor construction, one of them being squirrel cage type. In this type of construction, aluminium bars are embedded in the rotor slots and short- circuited at each end by aluminum end rings. When the rotor is at rest, synchronously rotating stator magnetic field induces a voltage of stator frequency in the rotor. This induced voltage produces rotor currents that interact with the air gap field to produce torque. Since the relative speed between the rotor and the stator field is maximum, the magnitude of the induced voltage in the rotor and hence the current is maximum. Similar to a transformer, for any current flowing in the rotor of an induction motor causes its counterpart to flow in the stator. **Therefore if an induction motor is started at rated voltage and frequency, a high current will be drawn from the source. The magnitude of this current could be approximately 6 times the full load current**. If the rotor is free to rotate, the torque will cause it to rotate in the direction of the rotating field. As the rotor speed increases, the relative speed between the rotor and the stator field reduces. The effect is two fold: (a) induced voltage in the rotor and the hence the current falls, and (b) the frequency of the rotor induced voltage and current falls. The rotor will eventually reach a steady-state speed N_r that is less than the synchronous speed N_s. Rotor cannot by itself achieve synchronous speed because at $N_r = N_s$, the rotor conductors would then be stationary with respect to the stator field; no induced voltage would be induced in the rotor, and hence no torque would be produced. The difference between N_s and N_r is commonly referred to as the **slip speed** and the slip 's' is usually expressed as follows:

$$s = \tfrac{N_s - N_r}{N_s} \qquad N_r = (1-s)N_s$$

In terms of frequency

$$s = \tfrac{F_1 - F_3}{F_1} = \tfrac{\omega_s - \omega_r}{\omega_s} = \tfrac{F_2}{F_1} = \tfrac{\omega_2}{\omega_s} \qquad \text{and} \qquad F_2 = sF_1 \text{ Hz} \qquad \text{or} \qquad \omega_2 = s\omega_s \text{ rad/s}$$

where F_3 is the frequency corresponding to the speed of the rotor, and F_2 is the frequency of the voltage induced in the rotor. Now if the motor is running on no-load at a speed very close to synchronous speed, the induced voltage in the rotor winding will be very small, and so will be the currents thereby developing a torque just sufficient to maintain the rotor in motion. Suppose now that a mechanical load is put on the rotor shaft. The rotor will slow down and in doing so it will increase the slip. The induced

voltage in the rotor winding will now increase both in magnitude and frequency, and will produce more current and therefore more torque. The change in speed or slip required is normally small. The value of s for a medium sized motor may vary from 1 (on no load) to 3% (on full load). e.g. For a 4 pole, 50 Hz induction motor, the variation in speed from no-load to full load could be 1485 to 1455 rpm. The induction motor is therefore a machine of substantially constant speed.
With the rotor revolving in the same direction of rotation as the stator field, the frequency of the rotor currents is sF_1 Hz and they will produce a rotating mmf which will rotate at sN_s rpm with respect to the rotor in the forward direction. Since the rotor itself is rotating at N_r rpm with respect to stator, the speed of the field produced by the rotor currents is given by:

$$sN_s + N_r = sN_s + (1-s)N_s = N_s$$

We see that the field produced by rotor currents rotates at N_s with respect to stator and hence in synchronism with the field produced by the stator currents. Because the rotor and stator fields rotate synchronously, they are stationary with respect to each other and thereby the machine develops a steady torque. Recall the generalized torque equation derived in the manual for expt. no:3, $T \propto F_s F_r \sin\delta$, where, F_s & F_r are stator field and rotor field respectively, and δ is the angle between them. One of the major differences between IM and DC motor is that in the case of a DC motor, δ is always 90^o while in IM it is a function of load. Its value is approximately zero under no-load condition.

2.1 Equivalent Circuit Representation:

The rotor of the induction motor has no electrically conducting connection with the stator supply. The power that it receives and converts to mechanical output at the shaft is transfered inductively - i.e. by transformer action - from stator to rotor by means of mutual flux. Thus, the electrical behaviour of an induction machine is similar to that of a transformer but with the additional feature of frequency transformation (Frequency of rotor current $F_2 = sF_1$). The per phase equivalent circuit of IM looks almost similar to that of a transformer. The steps followed to derive this circuit are almost the same as those in the case of transformer. This circuit is shown in Fig.3 in which
R_s and X_{sl} : stator winding resistance and leakage reactance
$R_r^{'}$ and $X_{rl}^{'}$: referred rotor resistance and leakage reactance
R_c and X_m : the core loss component and magnetizing reactance
$\frac{R_r^{'}(1-s)}{s}$: the electrical analogue of the mechanical load

Referring to this figure, an induction motor can be thought of as a generator feeding a fictitious resistance. It is fictitious because unlike in a transformer it is not an external resistance connected at the load terminals. The mechanical power developed per phase may be regarded as the ohmic loss in a fictitious secondary resistance $\frac{R_r^{'}(1-s)}{s}$ load. Therefore, power developed by the motor is:

$$P_d = (I_r^{'})^2 R_r^{'}(1-s)/s$$

The rotor copper loss is given by: $P_c = (I_r^{'})^2 R_r^{'}$
The air gap power input (or input to rotor) is:

$$P_a = P_d + P_c = (I_r^{'})^2 R_r^{'}/s$$

An important conclusion can be drawn from the fact, out of the power P_a delivered to the rotor, a fraction 's' is lost as heat in the rotor and remaining (1-s) appears as mechanical power including friction, so that

$$P_a : P_c : P_d = 1 : s : (1-s)$$

Hence, the rotor power will always divide itself in this proportion. It is obviously advantageous to run with as small slip as possible. If the mechanical power developed by the motor is P_d at $n_r = (1-s)n_s$ rps, the total developed torque is:

$$T_d = \frac{3P_d}{\omega_r} = \frac{3P_a(1-s)}{2\pi n_s(1-s)} = \frac{3(I_r^{'})^2 R_r^{'}/s}{2\pi n_s}$$

Thus the torque developed is directly proportional to the air-gap power input, regardless of the speed of rotation. Generally, the voltage drops $I_1 R_s$ and $I_1 X_{sl}$ are small. The magnitude of E_1 is approximately equal to V_S. Under this condition, the shunt branch can be connected across the supply terminals (similar to transformer). The expression for equivalent rotor current $I_r^{'}$ is:

$$I_r^{'} = \frac{V_s}{\sqrt{[R_s + R_r^{'}/s]^2 + [x_{sl} + x_{rl}^{'}]^2}}$$

Therefore,

$$T_d = \frac{3{V_s}^2 R_r^{'}/s}{2\pi n_s[(R_s + R_r^{'}/s)^2 + (x_{sl} + x_{rl}^{'})^2]} \tag{1}$$

$$\propto V_s^2 \text{ if } F_1 \text{ is constant.}$$

At normal speeds close to synchronism, 's' is very small. Therefore, $|R_s + R_r^{'}/s| >> |x_{sl} + x_{rl}^{'}|$ and $|R_s| << |R_r^{'}/s|$. An increase in torque is developed by a nearly proportional increase in 's', giving the machine a $T - N_r$ curve nearly linear. Torque is zero when $N_r = N_s$ and increases linearly. The maximum torque that the motor can develop is determined by the condition $\frac{dT}{ds}$ =0. On differentiating the torque expression, it is found that the condition for maximum torque is

$$s = s_{max} = R_r^{'}/(R_s^2 + x^2)^{\frac{1}{2}}, \qquad\qquad x = x_{sl} + x_{rl}^{'}$$

If stator parameters are neglected, $s_{max} = \frac{R_r^{'}}{x_{rl}^{'}}$

At low speeds and at starting, 's' approaches unity. For a normal induction machine, due to the presence of airgap, the leakage flux is quite substantial. The typical value of $\frac{R_r}{x_{rl}}$ = 0.2. Therefore $|R_s + R_r^{'}/s| << |x_{sl} + x_{rl}^{'}|$. Torque is inversely proportional to 's'. The $T - N_r$ curve is a rectangular hyperbola, as shown in Fig. 4. The effect of reducing V_s on torque is also shown in this figure.

Also, at normal speed of operation $|R_r^{'}/s| >> |x_{rl}^{'}|$. The rotor impedance angle $(tan^{-1}\{\frac{x_{rl}^{'}}{R_r^{'}/s}\})$ is approximately zero and therefore the rotor power factor (pf) is ≅ 1 (rotor circuit is almost resistive. This fact can also be argued in the following way: At normal speed of operation, the frequency of rotor current is of the order of 0.5-1.5 Hz. For this very low frequency, $x_{rl} - > 0$ and the circuit becomes resistive. Rotor current is nearly in phase with rotor emf). However, the source has to supply the magnetizing current. Due to the presence of air gap, this current is quite substantial. Therefore, the source pf is always lagging (in case of transformer, the source powerfactor depends on load. It could be unity, lagging or leading). This powerfactor on no-load is very poor (if two-wattmeters are used to measure the input power, one of them would read negative) and improves with load.

2.2 Speed Control:

As mentioned earlier the induction motor is essentially a constant-speed motor. Its speed of rotation is determined by the synchronous speed. Many motor applications, however, require wide variation in motor speed. This can be achieved by varying the stator frequency of the motor thereby varying the synchronous speed. Let us now see the relationship between supply voltage and frequency, and developed torque. The torque equation can also be written as:

$$T_d = 3(\frac{P}{2})\frac{1}{\omega_s}\frac{V_s^2 R_r'/s}{[(R_r'/s+R_s)^2+(x_{sl}+x_{rl}')^2]}$$

Neglecting stator parameters (R_s & x_{sl})

$$T_d = 3(\frac{P}{2})\frac{1}{\omega_s}\frac{V_s^2 s R_r'}{[R_r^2+(s\omega_s)^2 L_{rl}'^2]} \quad \cong 3(\frac{P}{2})(\frac{V_s}{\omega_s})^2\frac{\omega_2}{R_r'}$$

Now, $$I_m = \frac{E_1}{X_m} = \frac{E_1}{2\pi F_1 L_m} \cong [\frac{V_s}{2\pi F_1}]\frac{1}{L_m}$$

Therefore, $$L_m I_m = \phi = \text{Air gap flux linkage} = \frac{V_s}{2\pi F_1}$$

and $$T_d \cong 3(\frac{P}{2})\frac{\phi^2\omega_2}{R_r'}$$

From the above analysis the following observations can be made:

* Developed torque remains constant if ϕ & ω_2 are held constant and is independent of F_1
* Air gap flux will remain constant if $\frac{V_s}{F_1}$ is held constant.
* Generally it is not a good engineering practice to supply a voltage higher than the rated. Therefore air gap flux can be held constant from very low speed to the rated speed.
* $T_d \propto \omega_2$ if air gap flux is held constant. Hence, torque can be controlled by controlling slip speed (ω_2). The shape of $T - N_r$ characteristics remain the same for any frequency below the rated. As F_1 decreases, the value of x-axis intercept decreases while that of y-axis intercept increases. Peak torque developed by the motor remains almost constant.
* Speed above the rated can be increased by keeping V_s at its rated value and increasing F_1. Flux and hence the peak torque capability of the motor reduces (This is also evident from equ.1).

Therefore in order to vary the speed over a wide range, the source should have the following features.
• The magnitude of output voltage should vary with frequency so that $\frac{V}{F}$ remains constant till 50 Hz.
• The magnitude of voltage should remain constant as the frequency is increased above 50 Hz.

$T - N_r$ characteristics of the motor fed from a source having the above mentioned features are shown in Fig. 5. **Since both magnitude and frequency of the source are variable, it is now possible to start the motor at a very low frequency. In that case the speed of the stator field and hence the relative speed between the rotor and the stator field would be low. The machine now draws less current at starting. It could be of the order of full load current and the developed torque of the order of its full load value.**

2.3 Variable Voltage Variable Frequency Source (VVVF)

In the event of a power failure, uninterrupted power supply (UPS) is often used for supplying critical loads such as computers used for controlling important process, etc. (same equipment is also used in residences as a backup in the event of a power failure. This power electronic equipment is also known as **Inverter**). Input power to the UPS (or inveter) comes from the battery bank. In the inverter used for home applications a 12 V Lead acid battery is often used. When the utility power supply is available, power is converted to DC using a rectifier. This dc power is used to charge the battery. In the event of a power failure, stored energy in the battery is used to supply the load. The inverter uses the stored DC power to convert into 50 Hz, 230 V AC. In fact, it is possible to use an inverter to change from dc to any desired frequency, not just 50 Hz.

The block diagram to generate VVVF supply is shown in Fig. 6. The ac power supply is converted to DC and it is filtered using a large capacitor. It maintains a constant voltage at the input of the inverter (similar to a battery) which is converted to AC in such a way that $\frac{V}{F}$ remains constant till F=50 Hz and above this frequency, magnitude of output voltage remains constant.

Note to TAs/RAs: There is a 3 Phase IM which is cut opened. Show the students rotor, rotor bars, end rings, stator coils etc. Also show them stator and rotor laminations.

3 Procedure

A Note down the name plate readings of IM and DC generator. From the name plate readings of the motor determine the net output available at the shaft and number of poles. You may have to justify your answer. **Open** S_1**,** S_2 **and** S_3. These are on the machine stand.

B Connect the circuit as shown in Fig.8 (a) and set the output voltage of the autotransformer to zero and switch on the three phase supply.

This part of the experiment is performed to validate the principle that when the VVVF fed motor is started at low frequency, it develops a much higher torque than that developed by the motor when started with reduced voltage at rated frequency. Go through the following steps (C-E) and then perform the experiment.

C Hold the shaft of the motor firmly and gradually increase the applied voltage to the motor till the rated current is drawn by it.

D Decrease the voltage to zero. Connect the circuit as shown in Fig.8(b).

E Set the inverter output frequency to 8Hz and repeat step-C. Did you experience a higher torque in the second case? In case you are not sure you may repeat the above steps.

This part of the experiment is performed to observe various waveforms of VVVF fed induction motor and to conduct the load test.

F Put off all the lamps and open S. Set the output frequency at 20Hz. Load the separately excited DC generator in steps (in constant flux operation, torque capability and not output power of the motor remains unchanged) and for each load note down the various meter readings and speed. Also observe the following on a digital storage oscilloscope.

 * Line current
 * Line-Line voltage at lower as well as at a higher time base. Make note of the nature of pulses (magnitude, rise and fall time, width etc).

G Repeat the above steps for the inverter output frequency of 40 and 60 Hz (Note that using VVVF source it is possible to increase the speed of rotation above the rated speed).

G Put off all the lamps and open S. Reduce the speed of the motor to zero.

H Interchange any two stator terminals. Put on the supply to the inverter and gradually increase the output frequency of the inverter. Note the direction of rotation.

3.1 Comments on your observations

You might have observed the following:

* Current drawn by the motor fed from a VVVF source is approximately sinusoidal.
* Line-Line voltage waveform is not a sinusoid. It has a large number of pulses of varying width and magnitude ranging from zero to approximately 300 V.
* The variation of magnitude from zero to 300 V and vice versa is very fast.
* The width of the pulses increases with stator frequency.
* Line-Line voltage waveform has a quarter-wave odd symmetry.

The motor is designed for a sinusoidal excitation. When it is fed by a sinusoidal voltage source, it draws a sinusoidal current. The current is still a sinusoid when it is fed from a VVVF source. This can happen only if the Fourier series of the voltage waveform has the following terms:

- Frequency of the first term is same as that of the supply frequency
- Frequency of the next term should be very high compared to the supply frequency (In the inverter provided to you this frequency is of the order of 5 KHz). The motor does not respond to these higher frequency excitation components.

Typical waveform of the line-line voltage and the harmonic spectrum is shown in Fig.7.

3.2 Procedure to determine the torque of the motor

- For each output power of the dc generator, determine the corresponding input power to the dc generator from the given output power vs η plot.
- Assuming 100% coupling efficiency, the above power is the output power of the motor.

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4 Questions to be answered

- You might have observed the intensity of the lamp (either incandescent bulb or fluorescent tube) reducing momentarily when an induction motor of 3-4 HP (or air-conditioner/refrigerator) is switched ON. What could be the reason?
- Why does the direction of rotation reverse when any two stator terminals are interchanged?
- What is the reason for decreasing the speed of the motor to a very low value and then interchanging any two stator terminals in order to reverse the direction of rotation?
- Which type of motor is used in (i) ceiling fan (ii) mixer (iii) vacuum cleaner ?
- What are the advantages of induction motor over separately excited dc motor?
- Why induction motor is also known as asynchronous motor?

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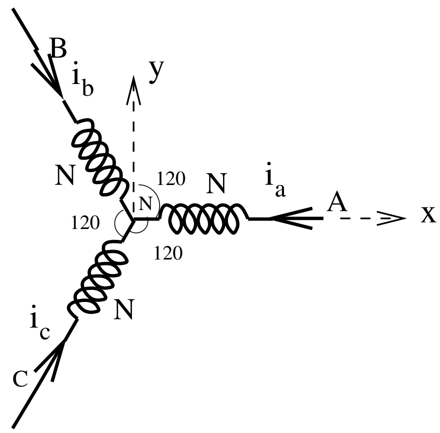


Figure 1: Coil arrangement to produce rotating magnetic field

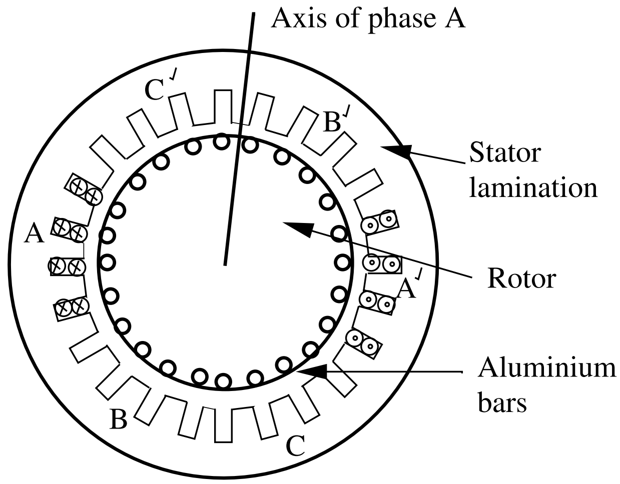


Figure 2: Distributed coil arrangement for 2-pole 3-phase IM

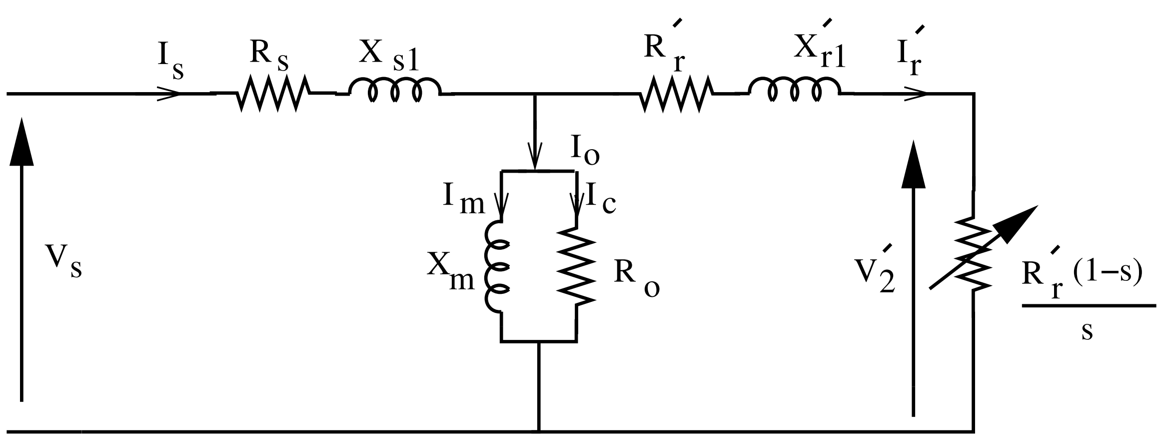


Figure 3: Per phase equivalent circuit of Induction Motor

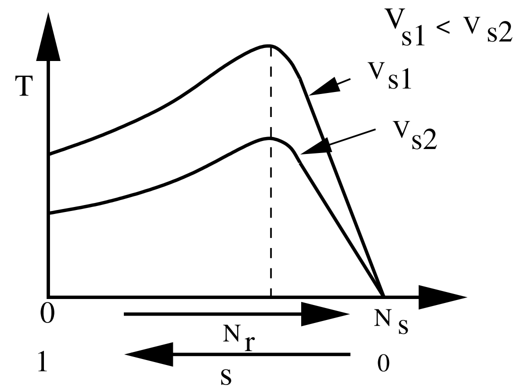


Figure 4: T-Nr characteristic of IM for Variable Voltage Constant Frequency supply

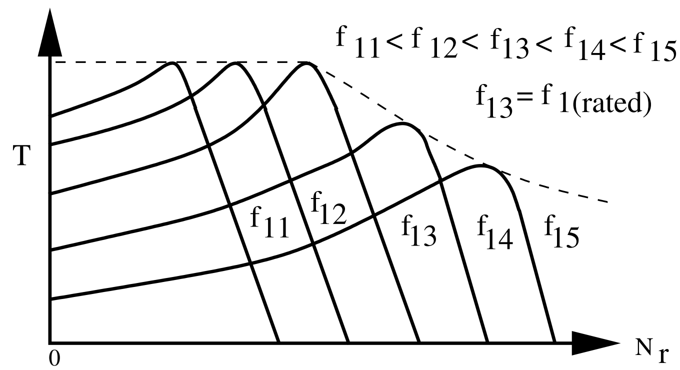


Figure 5: T-Nr characteristic of IM for Variable Voltage Variable Frequency supply

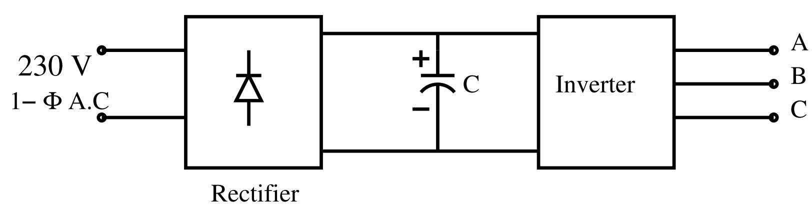


Figure 6: Internal Block Diagram of the VVVF supply (Inverter)

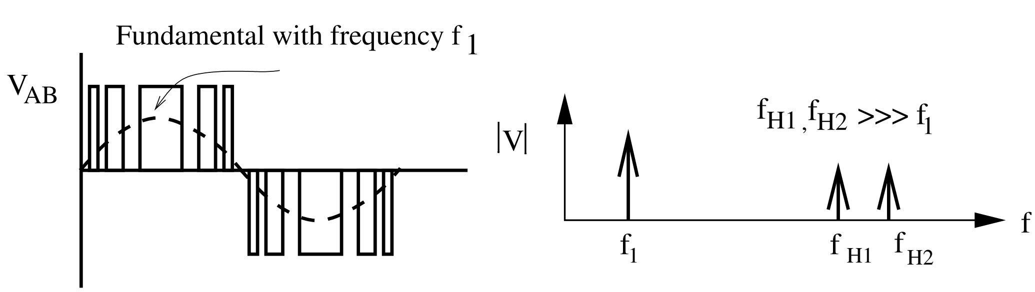
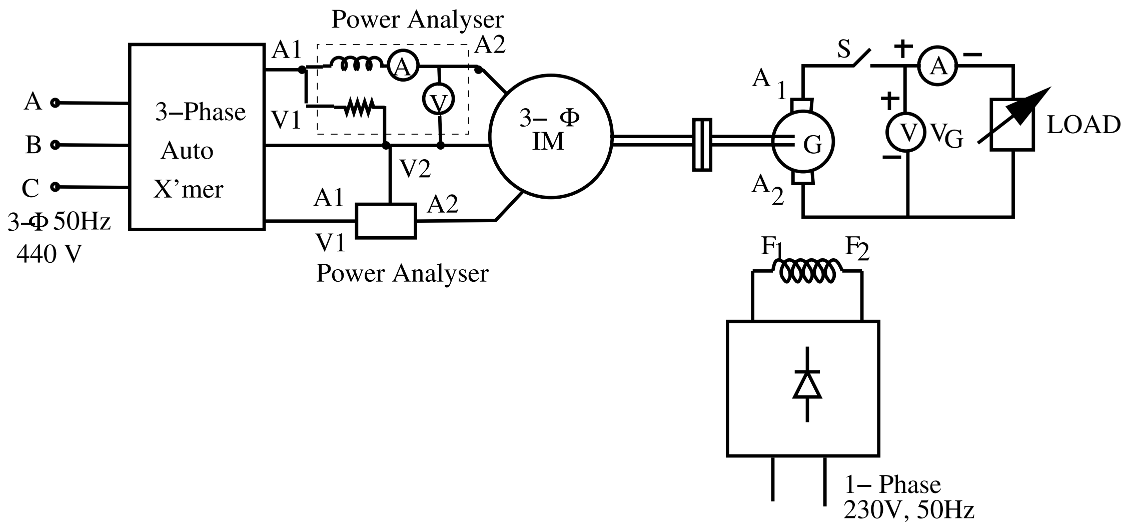
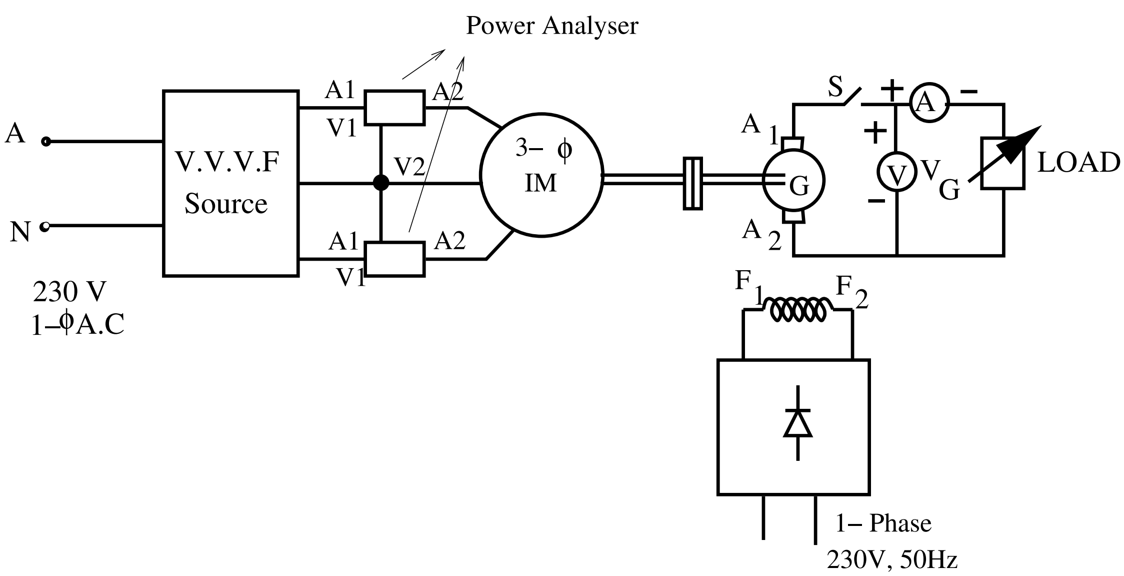


Figure 7: Line-Line voltage waveform and its harmonic spectrum



(a)



(b)

Figure 8: Circuit Diagram to conduct load test on 3 Phase Induction Motor