ANALYSIS OF PEAK POWER TRACKER FOR GRID CONNECTED VSCF POWER CONVERSION SCHEME

A DISSERTATION

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By

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CANDIDATE'S DECLARATION

This is to certify that the report which is being presented in this dissertation entitled **"ANALYSIS OF PEAK POWER TRACKER FOR GRID CONNECTED VSCF POWER CONVERSION SCHEME"** in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in Alternate Hydro Energy Systems, submitted in the Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee is an authentic record of my own work carried out during a period from July 2003 to June, 2004 under the Supervision of **Shri. S.N.Singh**, "Senior Scientific Officer", Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

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ABSTRACT

Variable speed wind turbines generators provide the opportunity to capture more power than fixed speed turbines. However the variable speed machine output can be variable voltage and variable frequency for fluctuating wind speeds. The quality of power output can be improved if adequate controls are incorporated in the systems. The fluctuating wind generator output needs to be controlled. To this effect, one needs to study the dynamic characteristics of the generator system under variable speed. Based on the dynamic performance of the system, better controls can be designed. The variable speed generators can create voltage and frequency fluctuations and power surges in a weak network. The effect of the commonly used control techniques like converter/inverters and its control on the quality electricity obtained with reduced harmonics are discussed in this dissertation. The fabrication of the grid connected variable speed constant frequency (VSCF) power conversion scheme has been done to obtain the fixed output voltage and frequency irrespective of the input. An algorithm of tracking the peak power in a wind energy in a wind energy conversion system has been discussed which is independent of the turbine parameters and air density. The algorithm searches for the peak power by varying the speed in the desired direction. The peak power points in the P-ω Curve corresponds to $dp/d\omega = 0$. This fact is made use of in the optimum point search algorithm.

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NOMENCLATURE

Symbols	Description	Unit
μ	Overlap angle	Deg.
θ	Angle by which d-axis leads the magnetic axis of phase a winding	Rad
α	Firing delay angle	Deg
a.c.	Alternating current	
d.c.	Direct current	
n	Synchronous speed	rpm
f	Frequency	Hz
p_f	No of field poles	
γ_s	Stator's angular coordinate	Deg.
K	Constant	
ω_r	Rotor angular velocity	Rad/s
fd	Field winding	
Kd	d-Axis circuit damper	
Kq	q-Axis circuit damper	
e_a, e_c, e_b	Instantaneous stator phase to neutral voltages	Volt
i_a, i_b, i_c	Instantaneous stator currents in phase a,b,c	Amp
e_{fd}	Field voltage	Volt
i_{fd}, i_{kd}, i_{kq}	Field and damper circuit currents	Amp
R_{fd}, R_{kd}, R_{kq}	Rotor circuit resistances	Ohm

L_{aa}, L_{bb}, L_{cc}	Self-inductances between stator windings	Henry
L_{ab}, L_{bc}, L_{ca}	Mutual inductances between stator windings	Henry
L_{afd}, L_{akd}, L_{akq}	Mutual inductances between stator and rotor windings	Henry
L_{ffd}, L_{kkd}, L_{kkq}	Self-inductances of rotor circuits	Henry
R_a	Armature resistance per phase	Ohm
p	Differential operator d/dt	
ψ	Flux linkage	Amp Turn
T	Transformation matrix	
Z_{base}	Base impedance	Ohm
λ	Tip speed ratio	
r	Radius of the wind turbine	m
ω_m	Wind turbine shaft angular speed	rad/s
V_w	Wind speed	m/s
C_p	Power coefficient or energy efficiency coefficient	
C_r	Blade design constant	
β	Blade pitch angle	
ρ_w	Wind turbine output power	W
ρ	Air density	
A	Area swept	m^2
K_t	Proportional constant	
Δp	Change in active power	
$\Delta\omega$	Change in angular velocity	
Vc	Carrier wave	

Vr	Reference wave
p_{cr}	Carrier ratio
MI	Modulation index
VSCF	Variable speed constant frequency
UPS	Uninterrupted power supply
HVDC	High voltage DC
MOSFET	Metal oxide field effect semiconductor transistor
IGBT	Insulated gate bipolar transistor
GTO	Gate turn off transistor
THD	Total harmonic distortion

INTRODUCTION AND LITERATURE SURVEY

1.1 GENERAL

The increasing rate of depletion of conventional energy resource has given a rise to increased emphasis on renewable energy sources such as wind, small hydro heads in hilly region tidal power plant river flow and natural gases such as biogas, geothermal etc. Wind energy is a very good resource and can supply us electric power at a cheaper rate if realized properly. The main problem with wind energy generation is that wind speed varies randomly. So if we can find out a suitable generation scheme which gives us power with a constant frequency even if the speed of the prime mover varies, then that type of generation will be very much useful for converting the wind energy to electric energy.

Synchronous generator is most commonly used for generation of 3-phase ac power. The speed of the generator must remain constant to generate power at constant frequency. If we use it incases where speed fluctuation is common, it will generate power at a variable frequency varying in proportion with the speed. The speed fluctuation is wide in case of wind turbines and naval on board ship gas turbines. In these cases constant frequency power generation is required against prime mover speed fluctuation so in such cases the synchronous generator should he provided with additional power conversion circuitry to supply power at Constant Frequency in spite of prime mover speed fluctuation. This type of power generation is called variable speed constant frequency generation. The generator with additional circuitry is called variable speed constant frequency (VSCF) generator. This type of power generation will find a wide application in many fields such as in large windmills, aircraft and naval on-board ship power systems.

1.2 VARIABLE SPEED CONSTANT FREQUENCY GENERATOR

Variable speed Constant frequency power generator is mainly used where the speed variation is wide and unpredictable such as Wind power generation Wind is an excellent source of power and it is inexhaustible. But the main problem is that the frequency variation will be there if speed varies.

So to make generation of power versatile, power generation at Constant frequency is required in spite of variation in generator speed. The speed variation results in voltage magnitude and frequency change of the synchronous generator. Such problems could be overcome by constant gear train mechanism and excitation control of synchronous generator. The constant gear train mechanism can be conveniently eliminated if a direct power conversion link is introduced. This idea gives rise to variable speed Constant frequency generation schemes. The VSCF generation is possible by using three types of machines configuration.

(i) By induction generator

(ii) By synchronous generator

(iii) By synchronous generator with permanent magnets.

All the three possible types are discussed as below;

1.2.1 VSCF Scheme using Induction Generator

The induction machine may be utilized as a self excited induction generator by connecting a suitable capacitor bank across the machines terminals [1]. Due to the presence of residual magnetism in the rotor, a small emf is induced at the machine terminals. As the speed increases, the capacitor impedance decreases, the excitation increases and therefore the terminal voltage of the machine increases. But this rise of voltage is limited due to the saturation of magnetic circuit of the machine. The terminal voltage of the generator depends on the value of capacitor, speed and load. Moreover, in general an induction motor operating as an induction generator will have poorer efficiency due to high losses as it \s performance depends upon the machine parameters. However an induction machine with low winding resistances and leakage reactance should have a better performance in terms of high efficiency and power factor when operated as induction generator.

The main advantages of an induction generator are.

i. Requirement of a separate dc source is eliminated in case of self-excited induction generator, which is necessarily required for excitation in case of synchronous generator. Also maintenance requirements like brush maintenance are removed.

ii. Automatic protection against external short circuit, which causes the excitation to collapse and consequently no voltage, is generated.

The self-excited induction generators have some disadvantages such as less efficiency, poor power factor, more heating in the rotor and Possibility of distortion of terminal voltage waveform because of the need to stabilize the excitation for saturated conditions.

Self-excited induction generators can be used to supply power to grid, where sources such as wind, small waterfalls are available. Converting the output of induction generator to dc and inverting the dc at grid frequency can achieve it. This type of scheme gives the variable speed constant frequency generation because the output frequency remains constant in spite of variation of speed of the induction generator.

1.2.2 VSCF Doubly Fed Induction Generator

The variable speed constant frequency double output induction generator VSCF-DFIG is a wound rotor induction machine with dc-link converter in the rotor circuit as shown in fig. 1.1[2]. The generator is assumed to be connected to an infinite bus and runs at constant dc current by changing the inverter-firing angle. This kind of a generator can be used in a wind energy conversion system. Because of the presence of the leakage inductance in each phase of the induction machine, the currents cannot vary at an infinite rate, and therefore the process of transferring the current from one phase to the other does not occur instantaneously but over a period. The duration of this period is called overlap angle (μ). It is also called the commutation interval, or the commutation time. In the normal mode of operation, the overlap angle (μ) is less than 60 degrees. Hence, during the commutation interval only three diodes are conducting simultaneously. One from the common anode group and two from the common cathode group or vice versa.

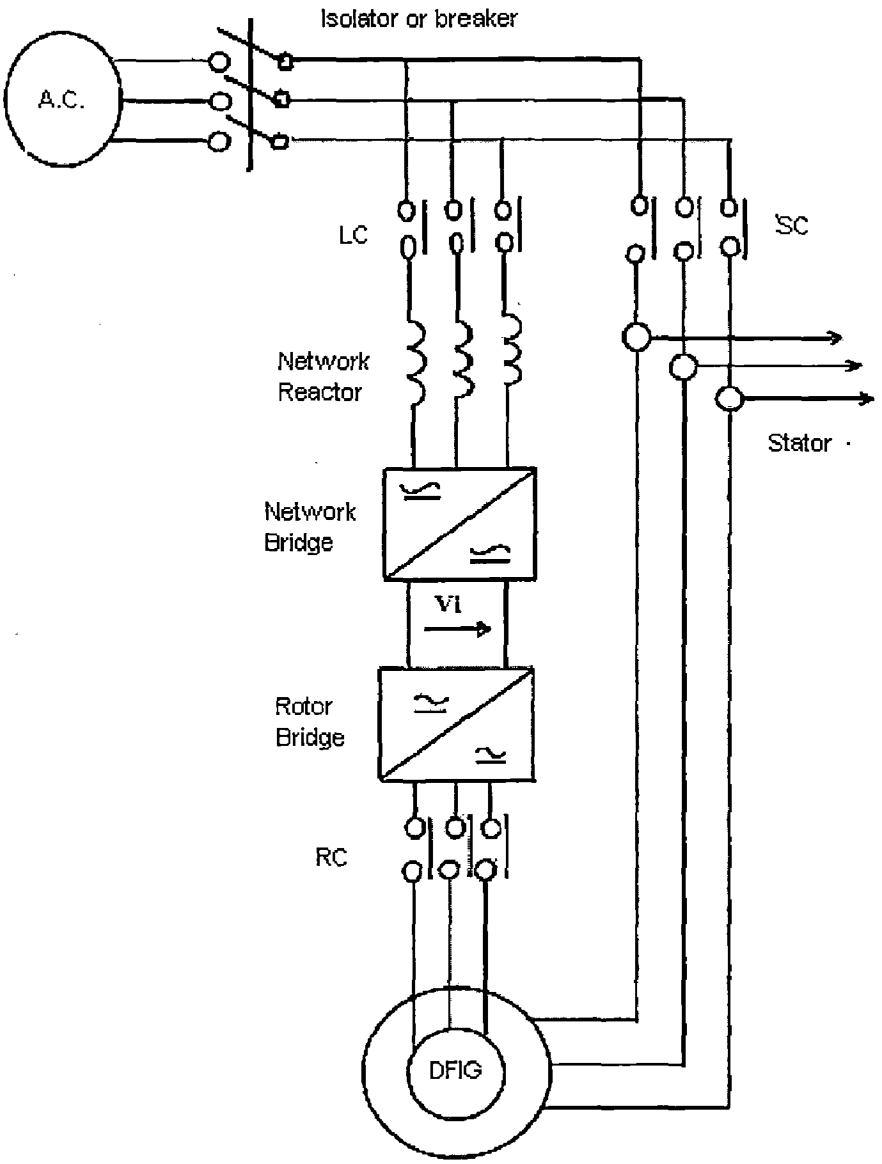


Fig 1.1: Doubly Fed Induction Generator

The commutation interval is followed by the interlude interval which is defined as the interval in which only two diodes, one from each group are conducting simultaneously. The interlude interval starts at tile instant the commutation interval ends and lasts for a period of (60^{o}-μ) degree since there is a commutation every 60 degrees. In the normal mode of operation and in one fundamental cycle of power line frequency, the electrical phenomenon during which a commutation interval is followed by an interlude interval repeats, itself six times.

Therefore, it is sufficient to analyze the system for one sixth of a cycle, a commutation interval followed by an interlude interval. In converting the ac power to dc power, a converter efficiently breaks or chops the ac current waveform by allowing the current to flow during only a portion of the cycle. This results in the generation of harmonic voltage and currents on both ac and dc sides.

For a six pulse converter the harmonics are principally of the order $k = 6n$ on the dc side and $K = 6n + 1$ on the ac side where n is any integer. In general converter is likely to produce harmonics of all orders. In this type of configuration of induction generator as discussed above, part of the power from the turbine is fed into file network through the stator and part of it through the rotor, the latter being proportional to the slip. The nominal speed of operation is, above synchronous speed. By choosing to work at a higher slip, (Higher speed) more of the power can be transmitted through the rotor thereby reducing the overall size of the generator. Typically, the nominal speed could be 1.6 times the synchronous speed. This gives a possible speed range, below nominal, or more than 30 percent, a range considered sufficient for maximizing the energy capture. The range above nominal speed can be freely chosen in keeping with the requirements of the mechanical design of the rotor.

The generator is connected to 50 Hz network. The synchronous speed is therefore relatively high and use of gears is unavoidable. The start can be smooth as desirable since tile machine can be accelerated at any predetermined ramp rate. Once the cut-in speed is reached, the turbine takes over, accelerates the generator under wind power when run by wind, and takes it upto the operating range. There is a small speed range around he synchronous speed during which the static frequency changer. Control cannot function due to too low a rotor voltage and without tile benefit of any damping control.

1.2.3 VSCF Scheme with Synchronous Generators

The synchronous generator used for variable speed constant frequency power conversion may be of two types. [3].

(i) Conventional synchronous generator with dc supply to rotor.

(ii) Synchronous generator with permanent magnet rotor.

The second type may further divided into two types depending on the nature of waveform induced. If the induced emf has sinusoidal waveform is called permanent magnet synchronous generator (PMSG) and if the induced emf has a trapezoidal waveform. It is called Permanent magnet dc (PMDC) brush less generator. PMDC brush less generator has a 15% higher power density compared to the former, and the rectified voltage will have lower harmonic ripples compared with its counterpart.

1.2.4 Sinusoidal PM brush less generator

The sine wave generator differs from the square (or trapezoidal) brush less generator in the following ways.

(i) Sinusoidal or quasi-sinusoidal distribution of magnet flux in air gap.

(ii) Sinusoidal or quasi-sinusoidal current waveforms.

(iii) Quasi-sinusoidal distribution of stator conductors' i.e. short pitched and distributed or concentric stator windings.

The quasi-sinusoidal distribution of magnet flux around the air gap is achieved by tapering the magnet thickness at the pole edges and by using a shorter magnet pole are typically 120°. The use of short pitched, distributed or concentric windings are exactly the same is in a.c. generator. Indeed the sine wave generator is a simple synchronous generator with permanent magnet in the rotor.

1.2.5 Electromagnetic excitation

With permanent magnet in the rotor, the geometrical size is decreased the geometrical size is decreased the cross-sectional area available for copper conductors decrease with the square of linear dimension, but the need for mmf decreases only with the linear dimension being primarily determined by the length of the air gap. As the motor size is further decreased, the air gap length reaches as minimum manufacturability value past this point the mmf requirement decreases only slightly decreases only slightly. The per unit copper losses increases faster and efficiency decreases rapidly. The loss free excitation provided by the permanent magnets therefore increases in relative value, as the size is decreases. In larger generators, the volume of magnets with adequate properties increases with motor size to the point where permanent magnet excitation is just too expensive. It is therefore rare to find PM machines rated much larger than a few kW [3].

1.3 INDUCTION GENERATOR VS SYNCHRONOUS GENERATOR FOR VSCF GENERATION

The main advantages of induction generators for VSCF generation are less maintenance, requirement of a separate d.c supply is eliminated and automatic protection against external short circuit is not required.

The chief disadvantages of induction generators in VSCF generation are less efficiency, poor power factor, more heating in the rotor and possible distortion of terminal voltage waveform due to harmonics.

The advantages of permanent magnet synchronous generator in VSCF generation are high efficiency, compactness allow simple controllability of the system by introducing permanent magnetic rotor. If the rating of the generator is increased, the volume of magnet in rotor increases and after certain limit it becomes expensive. Hence, for higher rating machine use of electromagnetic excitation instead of permanent magnet excitation is inevitable.

From the discussion in this chapter, it is worth to note that synchronous generator is superior to induction generators in certain respects. The electromagnetic excitation of the generator is economical for higher rating machine. Therefore, VSCF generation with a synchronous generator and software control gives an added advantage to this type of systems.

1.4 OPERATING PRINCIPLE

In the variable speed constant frequency, using a diode or thyristor bridge as discussed above, the output voltage of the generator first rectifies power generation, using a synchronous generator of any type of configuration. The d.c voltage thus obtained is inverted to ac at the nominal system frequency. An inductor is connected between the diode bridge and inverter to smoothen the current.

The firing pulses of the thyristors of Inverter Bridge may be generated by any convenient method. The system can also he made to operate in close loop by voltage and current feed back of the dc link. The voltage and current of the dc link can be controlled and hence the power output to the supply. The thyristor of the inverter may be line commutated for simplicity. The proposed scheme is shown in Fig 1.2[4]

1.5 INVERTERS

Inverters are used to convert a d.c voltage/current to a.c voltage/current. The inverters are mainly classified into two categories i.e. forced commutated inverters and line-commutated inverters. The advantages of line-commutated inverters over forced commutated inverters are as follows:

i. Converter grade thyristors can be used in line-commutated inverters, as the switching frequency is less.

ii. No extra commutating circuitry is needed for the commutation. The line voltage themselves commutate the outgoing thyristors when the incoming thyristor is fired.

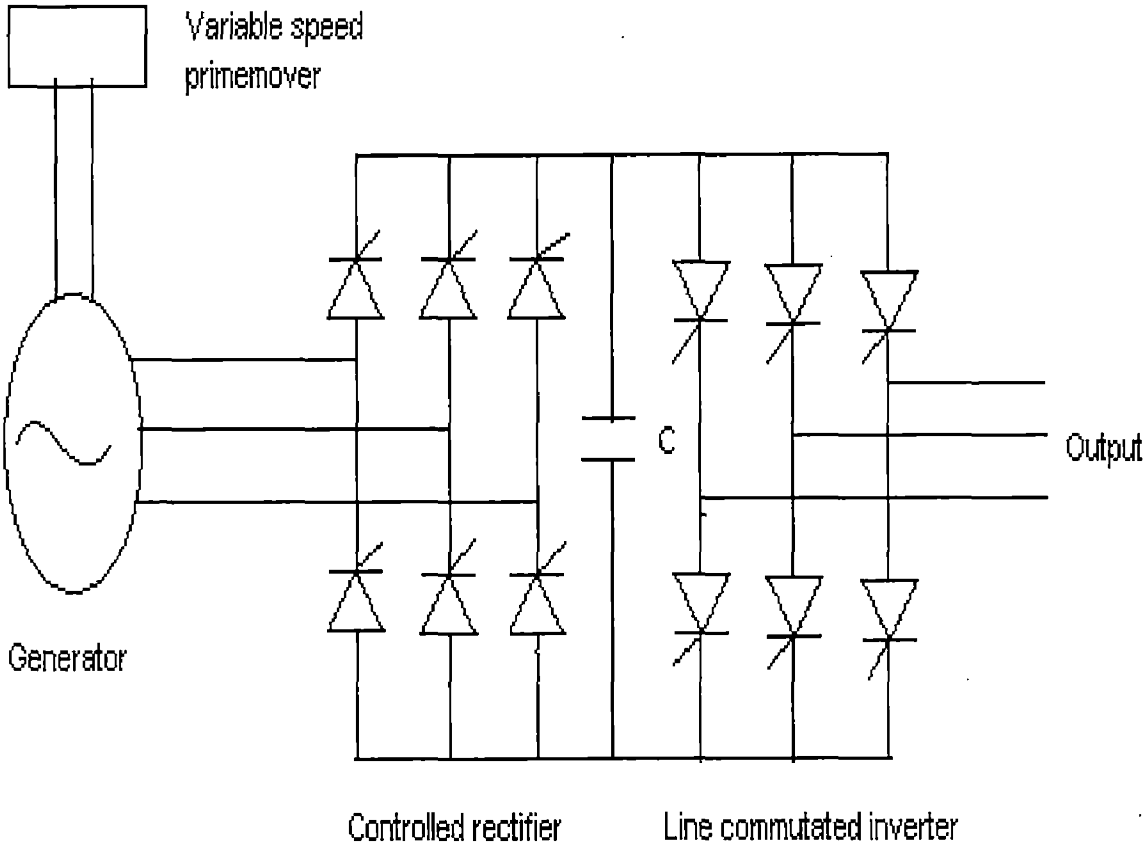


Fig 1.2: Variable speed constant frequency system

iii. Due to use of converter grade thyristors, which are cheaper than inverter grade thyristor, and absence of extra commutating circuitry, they are cheaper.

The basic principle of operation of a line-commutated inverter is to control the point in time at which the conduction in each thyristor is allowed to commence during each a.c cycle. By this it means, it is possible to choose the time segments of the a.c voltage waves, which appear at the d.c terminals. Since in case of line-commutated inverters the firing angle is kept greater than 90^o, the average voltage at the d.c terminals is negative. However the direction of current remains same as in case of converter due to unidirectional nature of devices, so power flow is from d.c to a.c side. [5]

1.6 LITERATURE REVIEW

A lot of work has been done in this area in the last decade and in present decade. Various schemes are proposed and analyzed by different authors, Schemes of easy control strategies are also developed and comparisons between various schemes are done. In recent times most of the works has been done on microprocessor and computer applications in this field. Some papers with work relating to this field are given below.

Z. Chen, and E. Spooner in their paper [6] “Grid power quality with variable speed wind turbines” have described the VSCF generation with PM generator modeling and simulation techniques of a wind power converter and connected power system, harmonics distribution and a case study is also given.

Eduard Muljadi et al. in their paper [7] “Zero sequence method for energy recovery from a variable speed wind turbine generator” have described a method of convert energy from a variable frequency induction generator based wind energy system to fixed frequency form. The simulation of proposed system and also an experimental verification on a small system is also present.

R. Krishnan and Geun-Hei Rim in their paper [4] have described the variable speed constant frequency power conversion scheme with PM synchronous generator. It describes the VSCF power conversion scheme with trapezoidal permanent magnet blushless generator modeling of subsystems in the scheme in steady state, derivation of its performance equations, harmonics and their magnitude and finally an experimental verification of the scheme will full wave line commutated converter.

R. Jones in his paper “Power electronic converter for variable speed wind turbine” [8] presents the maximum power transfer from wind at reduced noise level and high efficiency at low speed of wind is presented.

A.S. Nens et al. in their paper [9] presents a VSCF generator scheme that supplied the power to ac system. In this, they present control strategy of the system to increase the system efficiency in accordance with control of active and reactive power. A simulation and its results are also described.

Byong-Kuklee and Mehrdad Ehsani in his paper [10] give the idea for VSI inverter using switching concept Voltage doublers rectifier and PWM ac – dc – ac converted and their implementation is also presented.

Hari Sharma, et al. in their paper [10] "Power Quality Simulation of a Variable Speed Wind Generator Connected to a Week Grid" presents the concept of VSCF generator with PM synchronous generator and simulation of the system is presented.

1.7 SCOPE OF PRESENT WORK

In present work, hardware for VSCF power conversion scheme using synchronous generator has been developed. A synchronous generator is used as a voltage source with the control circuit to make the output voltage at constant voltage and frequency. A dc motor with excitation control is used as a prime mover to the synchronous generator. This model can be used to track the peak power available in the wind by using peak power tracking algorithm explained.

MODELLING OF SYNCHRONOUS GENERATOR

2.1 DESCRIPTION OF SYNCHRONOUS GENERATOR

Synchronous generator is the principal source of electric energy on power system. In this thesis we study the detail mathematical model of a synchronous machine and study its steady state operation.

The schematic of the cross–section of a three phase synchronous machine with one pair of field poles is shown in Fig 2.1. [3] The machine consists of two essential elements: the field and the armature. The field winding carries direct current and produces a magnetic field, which induces alternating voltage in the armature windings.

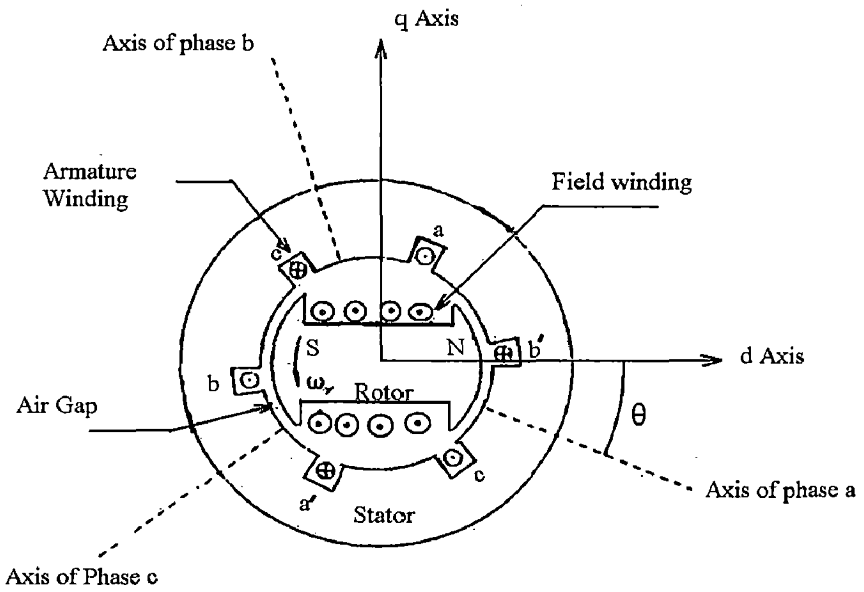


Fig 2.1 Schematic diagram of a three-phase Synchronous machine

The armature windings usually operate at a voltage that is considerably higher than that of the field and thus they require more space for isolation. They are also subject to high transient currents and must have adequate mechanical strength. So normally the armature is on stator. The three phase windings of the armature are distributed in 120^{0} phase displaced so that, with uniform rotation of the magnetic field, voltage displaced by 120^{0} in time phase will be produced in the windings. The armature is subjected to varying magnetic flux; so the stator iron is built up of thin laminations to reduce eddy current losses.

When carrying balanced three phase currents, the armature will produce a magnetic filed in the air gap rotating at synchronous speed. The filed produces by the direct current in the rotor winding. On the other hand, revolves with the rotor. For production of a steady torque, the filed of stator and rotor must rotate at the same speed.

The namable of filed poles are determined by the speed of the rotor and frequency of the armature currents. Thus, synchronous speed is given by;

$$n = \frac{120 f}{p_f} \tag{2.1}$$

Where,

n_s is the synchronous speed of machine,

f is frequency in Hz,

p_f is number of field poles.

2.2 MODEL DEVELOPMENT

2.2.1 Assumptions for Model Development

A three phase, wound-field synchronous generator has three identical armature windings symmetrically distributed around the air-gap, and one field winding. One or more damper windings can also be present and, for our convenience in this section, we will assume that one damper winding is present in each machine's axis. Normally, armature windings are placed on the stator, and field and damper windings on the rotor. However, there are cases, such as the exciter in Fig. 2.1, when armature windings are placed on the rotor and field winding on the stator (the exciter has nor damper windings). This does not affect the machine modeling approach at all, since only relative motion between the stator and rotor windings is important. Therefore, throughout this text, when we refer to 'rotor windings', we will always imply the field (and damper, if existent) winding placed at the opposite side of the air gap with respect to the three-phase armature windings.

Several assumptions are needed in order to simplify the actual synchronous machine and make the model development less tedious [11].

(i) It is assumed that every winding present in the machine produces a sinusoidal MMF along the air gap, which, for phase a, can be expressed as

$$MMF_a = Ki_a \sin(p_f n_s \gamma_s /2) \tag{2.2}$$

Where p_f represents the machine's number of poles, and γ_s stands for the stator's angular coordinate.

(ii). Iron permeability in the machine is assumed infinite. This is equivalent to neglecting all effects due to magnetic saturation, and flux fringing;

(iii). Rotor construction is assumed the only factor contributing to magnetic asymmetry in the machine. Effects of the stator or rotor or rotor slots can be taken into account by Carter's factor. This assumption results in approximating the magnetic conductivity function as where depend on the geometry of the air gap.

(iv) Local value of magnetic flux density B is obtained by multiplying local values of MMF and magnetic conductivity. The third harmonic of the magnetic flux density resulting from this multiplication is neglected, in accordance with assumption 1.

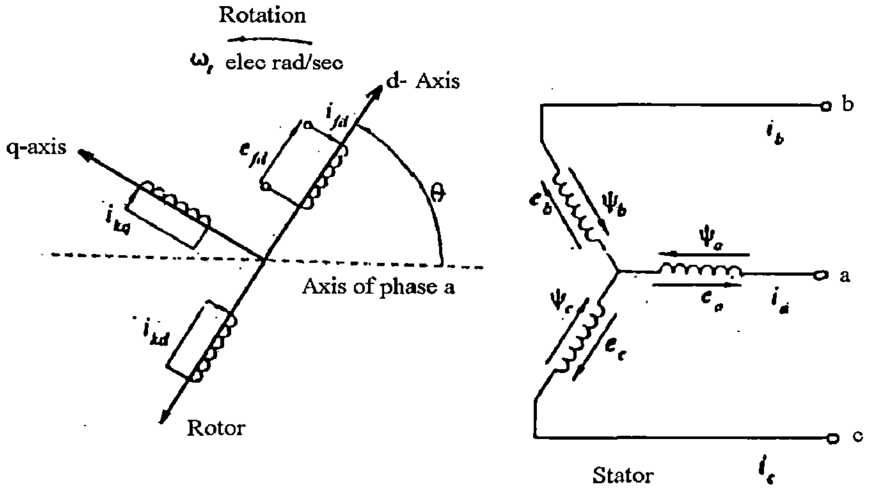
Errors introduced by these assumptions are normally small enough to be negligible, particularly from the point of view of the machine's dynamic performance.

2.2.2 Development of the Model's Equations and Equivalent Circuit

A synchronous machine can be described by a system of n + 1 equation, n of which are electrical and one of which is mechanical. The number n of electrical equations is equal to the number of independent electrical variables necessary to describe the machine. These variables can either be currents or flux linkages. Currents are chosen to be the independent variables [11].

Electrical equations are obtained by writing Kirchoff's voltage law for every winding i.e. by equating the voltage at the winding's terminal to the sum of resistive and inductive voltage drops across the windings. Note that damper windings, if present, are always short-circuited. Therefore, their terminal voltage is equal to zero. The machine equations will be developed, by assuming linear flux-current relationships.

The circuit involved in the analysis of a synchronous machine is shown as in Fig 2.2



fd : field winding

Kd : d-Axis circuit damper

Kq : q-Axis circuit damper

θ : Angle by which d-axis leads the magnetic Axis of phase a winding, electrical rad

ωr : Rotor angular velocity, electrical rad/s

Fig 2.2: Stator and rotor circuits of a synchronous machine

The stator circuits consist of three phase armature windings carrying alternating currents. The rotor circuits comprise field and damper windings. The damper field winding is connected to a source of direct current. For purpose of analysis, the currents in the (solid rotor and/or damper winding) may be assumed to flow in two sets of closed circuits: one set whose flux is in line with that of the field along the d – axis and the other set whose flux is at right angles to the field axis or along the q – axis.

θ is defined as the angle by which d –axis leads the centerline of phase a winding in the direction of rotation as shown in Fig 2.2. Since the rotor is rotating with respect to the stator, angle θ is continuously increasing related to the rotor angular velocity ω_r and time t as follows;

$$\theta = \omega_r t \tag{2.3}$$

Writing equations of the coupled circuits identified in Fig. 2.2 before we attempt to do this can develop the electrical performance equations of a synchronous machine; it is useful to review how the equations of simple circuits may be written. The positive direction of field and damper currents is assumed to be into the machine [11].

We will use the following notation in writing the equations for the stator and rotor circuits:

e_a, e_c, e_b = instantaneous stator phase to neutral voltages

i_a, i_b, i_c = instantaneous stator currents in phase a,b,c

e_{fd} = field voltage

i_{fd}, i_{kd}, i_{kq} = field and damper circuit currents

R_{fd}, R_{kd}, R_{kq} = rotor circuit resistances

L_{aa}, L_{bb}, L_{cc} = self-inductances between stator windings

L_{ab}, L_{bc}, L_{ca} = mutual inductances between stator windings

L_{afd}, L_{akd}, L_{akq} = mutual inductances between stator and rotor windings

L_{ffd}, L_{kkd}, L_{kkq} = self-inductances of rotor circuits

R_a = armature resistance per phase

p = Differential operator d/dt

2.2.3 Stator Circuit Equations

The voltage equations of the three phases are [11];

$$e_a = \frac{d\psi_a}{dt} = R_a i_a = p\psi_a - R_a i_a \tag{2.4}$$

$$e_b = p\psi_b - R_a i_a \tag{2.5}$$

$$e_c = p\psi_c - R_a i_c \tag{2.6}$$

The flux linkage in the phase a winding at any instant is given by;

$$\psi_a = L_{aa}\, i_a - L_{ac}\, i_c + L_{afd}\, i_{fd} + L_{akd}\, i_{kd} + L_{akq}\, i_{kq} \tag{2.7}$$

Similar expressions apply to flux linkages of windings b and c. the units used are Webers, henrys, and amperes. The negative sign associated with the stator winding currents is due to their assumed direction.

Now L_{aa} self-inductance is varying due to rotation of rotor, which can be written as;

$$L_{aa} = L_{aa0} + L_{aa2} \cos 2\theta \tag{2.8}$$

So that the flux equation is expressed as below:

2.2.4 *Flux equation*

$$\psi_a = -i_a\left[L_{aa0} + L_{aa2}\cos 2\theta\right] + \left[L_{ab0} + L_{aa2}\cos\left(2\theta + \frac{\pi}{3}\right)\right]$$

$$+ i_c\left[L_{ab0} + L_{aa2}\cos\left(2\theta - \frac{\pi}{3}\right)\right] + i_{fd}\, L_{afd}\cos\theta$$

$$+ i_{kd}\, L_{akd}\cos\theta - i L_{adq}\sin\theta \tag{2.9}$$

Similarly;

$$\psi_b = -i_a\left[L_{ab0} + L_{aa2}\cos\left(2\theta + \frac{\pi}{3}\right)\right] + i_b\left[L_{aa0} + L_{aa2}\cos\left(2\theta - \frac{\pi}{3}\right)\right]$$

$$+ i_c\left[L_{ab0} + L_{aa2}\cos(2\theta - \pi)\right] + i_{fd}\, L_{afd}\cos\left(\theta - \frac{2\pi}{3}\right)$$

$$+ i_{kd}\, L_{akd}\cos\left(\theta - \frac{2\pi}{3}\right) - i L_{adq}\sin\left(\theta + \frac{2\pi}{3}\right) \tag{2.10}$$

and

$$\psi_c = -i_a\left[L_{ab0} + L_{aa2}\cos\left(2\theta - \frac{\pi}{3}\right)\right] + i_b\left[L_{ab0} + L_{aa2}\cos(2\theta - \pi)\right]$$

$$- i_c\left[L_{aa0} + L_{aa2}\cos 2\left(\theta - \frac{2\pi}{4}\right)\right] + i_{fd}\, L_{afd}\cos\left(\theta + \frac{2\pi}{3}\right)$$

$$- i_{kd}\, L_{akd}\cos\left(\theta + \frac{2\pi}{3}\right) - i_{kq}\, L_{akq}\sin\left(\theta + \frac{2\pi}{3}\right) \tag{2.11}$$

2.2.5 Rotor circuit equations

The rotor circuit equations

$$e_{fd} = p\psi_{fd} + R_{fd}\, i_{fd} \tag{2.12}$$

$$o = p\psi_{fd} + R_{fd}\, i_{fd} \qquad (2.13)$$

$$o = p\psi_{fd} + R_{fd}\, i_{fd} \qquad (2.14)$$

The rotor circuits see constant permeance because of the cylindrical structure of the stator. Therefore, the self-inductances of rotor circuits and mutual inductances each other do not vary with rotor position.

The rotor circuit flux linkages may be expressed as follows

$$\psi_{fd} = L_{kfd}\, i_{fd} + L_{lkd}\, i_{kd} - L_{afd}\left[i_a \cos\theta + i_b \cos\left(0 - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \qquad (2.15)$$

$$\psi_{fd} = L_{kd}\, i_{fd} + L_{kkd}\, i_{kd} - L_{akd}\left[i_a \cos\theta + i_b \cos\left(0 - \frac{2\pi}{3}\right) + i_c \cos\left(\theta + \frac{2\pi}{3}\right)\right] \qquad (2.16)$$

$$\psi_{kq} = L_{kkq}\, i_{kq} + L_{akq}\, i_{akq}\left[i_a \sin\theta + i_b \sin\left(0 - \frac{2\pi}{3}\right) + i_c \sin\left(\theta + \frac{2\pi}{3}\right)\right] \qquad (2.17)$$

2.3 SYNCHRONOUS GENERATOR MODEL IN ROTOR REFERENCE FRAME

The mmf wave due to the currents in the three armature phases travels along the periphery of the stator at a velocity of ω_s rad/s. This is also the velocity of the rotor. Therefore, for balanced synchronous operation, the armature mmf wave appears stationary with respect to the rotor and has a sinusoidal space distribution. Since a sine function can be expressed as a sum of two sine functions, the mmf due to stator windings can be resolved into two sinusoidal distributed mmf waves stationary with respect to the rotor, so that one has its peak over the d-axis and the other has its peak over the q-axis. Therefore, i_d may be interpreted as the instantaneous current in a fictitious armature winding which rotates at the same speed as the rotor, and remains in such a position that its axis always coincides with the d-axis. The value of the current in this winding is such that it results in the same mmf on the d-axis as do actual phase currents flowing in the armature windings. A similar interpretation applies to i_q, except that it acts on the q-axis instead of the d-axis.

The dq0 transformation may be viewed as a means of referring the stator quantities to the rotor side. This is analogous to referring secondary side quantities in a transfer to the primary side by means of the turn's ratio. The inverse transformation can similarly be viewed as referring the rotor quantities to the stator side.

The analysis of synchronous machine equations in terms of dq0 variable is considerably simpler than in terms of phase quantities, for the following reasons [11]:

(i) The dynamic performance equations have constant inductances.

(ii) For balance conditions, zero sequence quantities disappear.

(iii) For balanced steady-state operation, the stator quantities have constant values. For other modes of operation, they vary with time. Stability studies involve slow variations having frequencies below 2 to 3 Hz.

(iv) The parameters associated with d and q-axis may be directly measured from terminal tests.

Under balanced steady-state conditions, the dq0 transformation is equivalent to the use of phasors to represent alternating stator phase quantities. In many ways, the advantages of using d, q variable are similar to those of using phasors (instead of directly with time varying sinusoidal quantities) for steady-state analysis of ac circuits.

The following transformation matrix gives transformation from the abc to the dq0 reference frame.

$$T = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (2.18)$$

Inverse transformation (from the dq0 to the abc reference frame) is then given by

$$T_{inv} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \qquad (2.19)$$

With the use of this transformation dq0 currents are:

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (2.20)$$

2.3.1 Stator Flux Linkages in dq0 Components

Using the expressions for ψ_a, ψ_b and ψ_c given by transforming the flux linkages and currents into dq0 components and with the suitable reduction of terms involving trigonometric terms, we obtain the expressions which are given below:

$$\psi_d = -\left(L_{aa0} + L_{ab0} + \frac{3}{2}L_{aa2}\right) i_d + L_{afd}\, i_{fd} + L_{akd}\, i_{kd} \tag{2.21}$$

$$\psi_q = -\left(L_{aa0} + L_{ab0} - \frac{3}{2}L_{aa2}\right) i_q + L_{akq}\, i_{kq} \tag{2.22}$$

$$\psi_0 = -\left(L_{aa0} + 2L_{ab0}\right) \tag{2.23}$$

Defining the following new inductances:

$$L_d = L_{aa0} + L_{ab0} + \frac{3}{2}L_{aa2} \tag{2.24}$$

$$L_d = L_{ca0} + L_{ab0} + \frac{3}{2}L_{aa2} \tag{2.25}$$

$$L_o = L_{aa0} + L_{ab0} \tag{2.26}$$

The flux linkage equations become:

$$\psi_d = -L_d\, i_d + L_{afd}\, i_{fd} - L_{akd}\, i_{kd} \tag{2.27}$$

$$\psi_q = -L_q\, i_q + L_{akq}\, i_{kq} \tag{2.28}$$

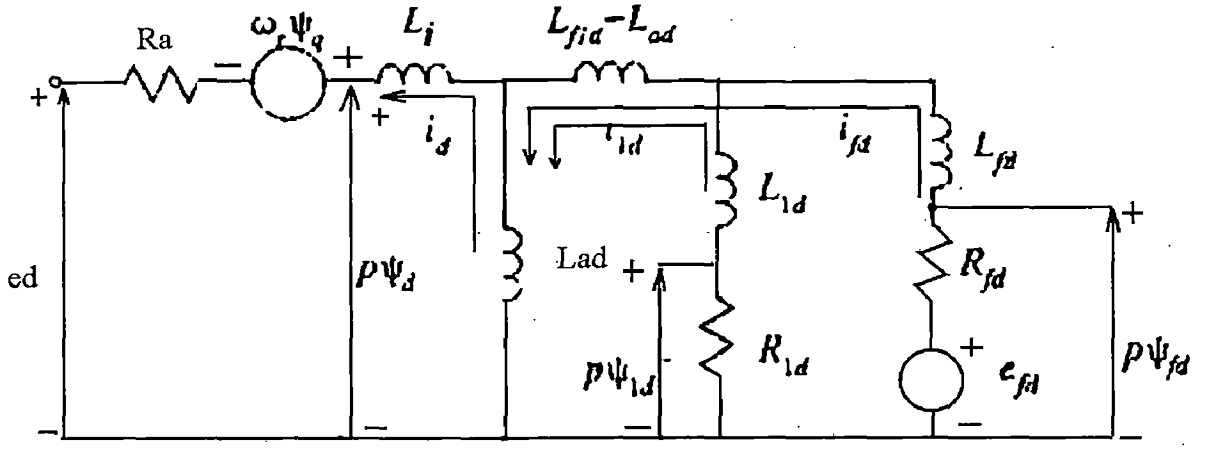
$$\psi_o = -L_o\, i_o \tag{2.29}$$

The dq0 components of stator flux linkages are seen to be related to the components of stator and rotor currents through constant inductances.[11]

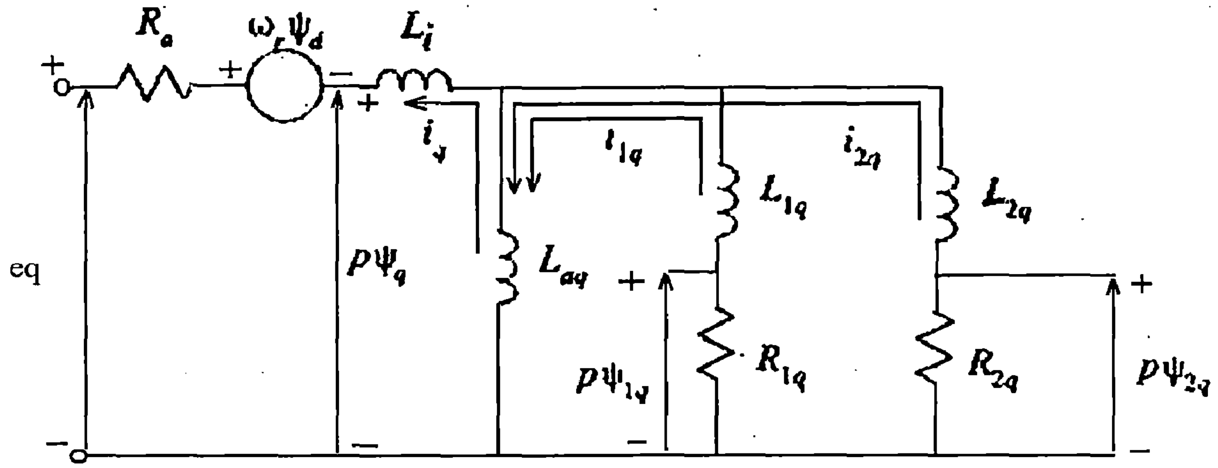
2.3.2 Rotor Flux Linkages

Substitution of the expressions for i_d, i_q in equation 2.15 to 2.17 gives the following

$$\psi_{fd} = -L_{ffd}\, i_{fd} + L_{fkd}\, i_{kd}\, \frac{3}{2} L_{afd}\, i_d \tag{2.30}$$



(a) d-Axis equivalent circuit



(b) q-Axis equivalent circuit

Fig 2.3 Equivalent circuit of Synchronous generator

$$\psi_{kd} = -L_{fkd}\, i_{fd} + L_{kkd}\, i_{kd}\, \frac{3}{2} L_{akd}\, i_d \qquad (2.31)$$

$$\psi_{kq} = -L_{kkq}\, i_{kq} - \frac{3}{2} L_{akq}\, i_q \qquad (2.32)$$

2.3.3 Stator Voltage Equation in dq0 Component

Basic equations for phase voltages in terms of phase linkages and currents are given by the equations 2.4 to 2.6. By applying the dq0 transformation of these equations the following expressions in terms of transformed component of voltages, flux linkages and currents result:

$$e_d = p\psi_d - \psi_q\, p\theta - R_a\, i_d \qquad (2.33)$$

$$e_q = p\psi_q - \psi_d\, p\theta - R_a\, i_q \qquad (2.34)$$

$$e_o = p\psi_o - R_a\, i_o \qquad (2.35)$$

Equations (2.4)-(2.17) describe the synchronous generator's equivalent circuit in the rotor reference frame shown in Fig. 2.3.[11]

Several comments can be made regarding this equivalent circuit:

- d and q axis equivalent circuits are similar to a transformer equivalent circuit in each of them, several windings, each characterized by some resistance and leakage inductance, are coupled through a mutual coupling inductance. The difference, compared to the transformer case, is that, while a transformer equivalent circuit is an ac circuit, here, when the generator is operating in sinusoidal steady state, all voltages, currents and flux linkages are dc.

- Even though armature windings are now represented in the rotor reference frame, and there are no time-variant inductances, the fact that armature windings are magnetically coupled is taken into account by presence of cross-coupling terms in the d-axis and q-axis's equivalent circuit's armature branch. For each axis, that term is equal to the product of rotor speed and total flux linked with armature winding of the other axis.
- If a machine (such as the exciter) has not damper windings, the equivalent circuit can be easily adapted by removing from it the branches representing damper windings. The rest of the circuit remains unchanged.
- All rotor parameters are reflected to armature. Therefore, when this circuit is used for simulation, and actual values of rotor variables are of interest, the turns ratio between the rotor and armature needs to be taken into account.

This equivalent circuit describes a synchronous generator electrically. The mechanical variable is represented by rotor speed, and the mechanical equation of the system is needed in order to complete the model.

This equation relates the external torque applied to the generator's shaft to the electromagnetic torque that the machine developers internally. However, for the purpose of this work, the mechanical equation of the system is not considered, i.e. rotor speed is assumed to be known. The reason for that is the fact that our interest consists primarily in describing electrical behavior of the generator loaded with a diode rectifier and converter load. To do that, it is legitimate to assume constant speed since electrical transients in the machine can be considered much faster than mechanical transients.

With the above considerations, rotor speed is not a variable, but a parameter of the system. That causes (2.15)-(2.17) to be a set of linear differential equations.

2.4 MODEL IMPLEMENTATION IN PER UNIT SYSTEM

In power system analysis, it is usually convenient to use a per unit system to normalize system variables. Compared to the use of physical units (amperes, volts, ohms, webers, henrys, etc.), the per unit system offers computational simplicity by eliminating units and expressing system quantities as dimensionless ratios. Thus,

$$\text{Quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

A well chosen per nit system can minimize computational effort, simplify evaluation and facilitate understanding of system characteristics. Some base quantities may be chosen independently and quite arbitrarily, while others follow automatically depending on fundamental relationships between system variables. Normally, the base values are chosen so that the principal variables will be equal to one per unit under rated condition].

In the case of a synchronous machine, the per unit system may be used to remove arbitrary constants and simplify mathematical equations so that they may be expressed in terms of equivalent circuits. The basis for selection of the per unit system for the stator is straightforward, whereas it requires careful consideration for the rotor. Several alternatives per unit systems have been proposed in the literature for the selection of base rotor quantities [11].

2.4.1 Base Quantities

(i) Stator base quantities

3-phase VA_{base} = volt-ampere rating of machine, VA

$e_{s\,base}$ = peak phase-to-neutral rated voltage, V

f_{base} = rated frequency, Hz

$i_{s\,base}$ = peak line current, A

$$\frac{3-\text{phase}\,VA_{base}}{(3/2)e_{base}}$$

$$Z_{s\,base} = \frac{e_{s\,base}}{i_{s\,base}}\Omega$$

$$\omega_{base} = 2\pi f_{base} \text{ elec. rad/s}$$

$$\omega_{m\,base} = \omega_{base}\frac{2}{P_r}\text{mech. rad/s}$$

$$L_{s\,base} = \frac{Z_{s\,base}}{\omega_{base}}, H$$

$$\psi_{s\,base} = L_{s\,base}\, i_{s\,base}, \text{ Wb} - \text{turns}$$

(ii) Rotor base quantities

$$i_{fd\,base} = \frac{L_{ad}}{L_{afd}} i_{s\,base}, A$$

$$i_{kd\,base} = \frac{L_{ad}}{L_{akd}} i_{s\,base}, A$$

$$i_{kq\,base} = \frac{L_{ad}}{L_{akq}} i_{s\,base}\,, A$$

$$e_{fd\,base} = \frac{3-\text{phase VA}_{base}}{i_{fd\,base}}, V$$

$$Z_{fd\,base} = \frac{e_{fd\,base}}{i_{fd\,base}}, \Omega$$

$$= \frac{3-\text{phase VA}_{base}}{i^2_{fd\,base}}$$

$$Z_{kd\,base} = \frac{3-\text{phase VA}_{base}}{i^2_{kd\,base}}, \Omega$$

$$Z_{kq\,base} = \frac{3-\text{phase VA}_{base}}{i^2_{kq\,base}}, \Omega$$

$$L_{fd\,base} = \frac{Z_{fd\,base}}{\omega_{base}}, H$$

$$L_{kd\,base} = \frac{Z_{kd\,base}}{\omega_{base}}, H$$

$$L_{kq\,base} = \frac{Z_{kqbase}}{\omega_{base}}, H$$

$$t_{base} = \frac{1}{\omega_{base}}, s$$

$$T_{base} = \frac{3-\text{phase VA}_{base}}{\omega_{m\,base}}, Nm$$

* **Per unit stator voltage equations**

$$e_d = p\psi_d - R_a\, i_a \qquad (2.36)$$

$$e_q = p\psi_q - R_a\, i_a \qquad (2.37)$$

$$e_0 = p\psi_0 - R_a\, i_0 \tag{2.38}$$

* **Per unit rotor voltage equations**

$$e_{fd} = p\psi_{fd} - R_{fa}\, i_{fd} \tag{2.39}$$

$$0 = p\psi_{td} - R_{ta}\, i_{td} \tag{2.40}$$

$$0 = p\psi_{tq} - R_{tq}\, i_{tq} \tag{2.41}$$

* **Per unit stator flux linkage equations**

$$\psi_d = -\,(L_{ad} + L_p) + L_{ad}\, i_{fd} + L_{ad}\, i_{td} \tag{2.42}$$

$$\psi_d = -\,(L_{aq} + L_p) + L_{aq}\, i_{1qd} + L_{aq}\, i_{2d} \tag{2.43}$$

$$\psi_0 = -\,L_o\, i_o \tag{2.44}$$

* **Per unit rotor flux linkage equations**

$$\psi_q = L_{ffd}\, i_{fd} + L_{fld}\, i_{ld} - L_{ad}\, i_d \tag{2.45}$$

$$\psi_{td} = L_{f1d}\, i_{fd} + L_{1ld}\, i_{1d} - L_{ad}\, i_d \tag{2.46}$$

$$\psi_{tq} = L_{11d}\, i_{1q} + L_{aq}\, i_{2d} - L_{aq}\, i_q \tag{2.47}$$

* **Per unit air-gap torque**

$$T_e = \psi_d\, i_d - \psi_q\, i_q \tag{2.48}$$

For power system stability analysis, the machine equations are normally solved with all quantities expressed in per unit (pu), with the exception of time.

CHAPTER –3

PEAK POWER TRACKING ALGORITHM

3.1 WIND POWER AND WIND TURBINE CHARACTERISTICS

In the continuous search of clean, safe and renewable energy sources, wind power is certainly one of the most attractive solutions. Wind power was used earlier for several centuries for propelling ships, driving windmills, pumping water, irrigating fields and numerous other purposes. The exploitation of plenty of cheap fossil fuels and development of internal combination engines have led to the wind power being gradually replaced by other energy sources during the first half of 20th century. Wind energy is considered to be very clean, cheap important renewable energy source particularly for rural areas, farms, remote on-shore and offshore installation away from main electrical grid.

The wind turbine is characterized by the non-dimensional curves of coefficient of performance as function of tip speed ratio λ. Tip speed ratio λ is the ratio of linear speed of the tip of blades to the rotational speed of wind turbine. It can be expressed, as follows and details are available in nomenclature:

$$\lambda = \frac{r\omega_m}{V_w} \tag{3.1}$$

$$C_p = 0.5\left[\frac{rC_f}{\lambda} - 0.022\beta - 2\right]e^{-0.255\frac{rC_f}{\lambda}} \tag{3.2}$$

$$\rho_w = 0.5\rho A V_w^3 C_p \tag{3.3}$$

Where λ = Tip speed ratio

r = Radius of the wind turbine (m)

ω_m = Wind turbine shaft angular speed (rad/s)

V_w = Wind speed (m/s)

C_p = Power coefficient or energy efficiency coefficient

C_r = Blade design constant

β = Blade pitch angle

ρ_w = Wind turbine output power (W)

ρ = Air density

A = Area swept

$=\pi r^2 \ (m^2)$

The cage rotor induction machine is the most frequently used generator for grid-connected wind energy conversion system. When connected to the constant frequency network, the induction generator runs at near-synchronous speed, drawing the magnetizing current from the mains, thereby resulting in constant speed constant frequency (CSCF) operation. However, if there is flexibility in varying the shaft speed, the energy capture due to fluctuating wind velocities can be substantially improved.

3.2 ALGORITHM

The requirement for variable-speed constant frequency (VSCF) operation led to several developments in the generator control of wind energy conversion system. Irrespective of the generator used for a variable-speed wind energy conversion system (WECS), the output energy depends on the method of tracking the peak power points on the turbine characteristics due to fluctuating wind conditions.

The proposed algorithm is explained with the help of Fig.3.1, where the P-ω curves corresponding to three wind velocities are shown. Let the present wind velocity being v1. The generator is run in the speed control mode with a speed reference of $\omega 1$, which corresponds to the optimum operating point P1 for velocity v1. The generator output power and speed are sampled at regular intervals of time. If the wind velocity is steady at v1, the difference between successive samples of active power P (i.e. ΔP,) will be very small and no action is taken.

Now, let there be a step jump in wind velocity from v1 to v2. Since the turbine shaft speed cannot change instantaneously (the reference for the speed Controller is not yet changed and the inertia of the system is extremely high), this would result in a change of operating point from P1 to P2. Therefore, ΔP would be large and positive Corresponding to this change in ΔP, a positive change in speed reference is commanded.

The change in speed reference is $\Delta\omega*$ is made proportional to ΔP. This shifts the operating point from P2 to P3, resulting in a smaller positive change in ΔP. Since this change in is due to a positive change in $\Delta\omega*$, it implies that the peak power point is further to the right-hand side on the curve.

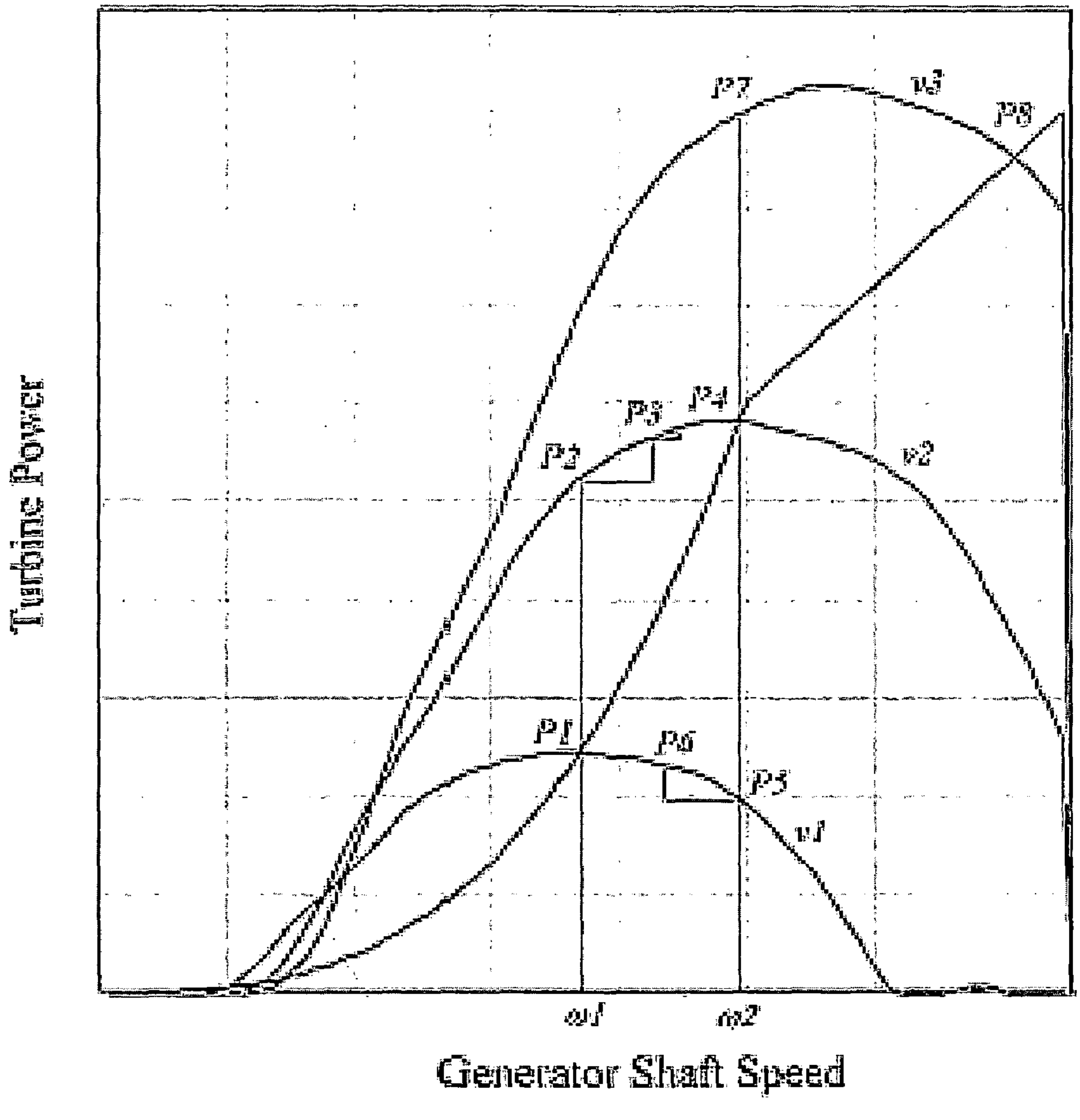


Fig 3.1 Shift of operating points in the proposed peak power tracking algorithm

Thus, a further positive change in $\Delta\omega*$ is commanded in proportion to ΔP. In this process, when becomes very small (within some defined band), no further change in speed command is given and the system keeps operating at P4.

Now if the wind velocity again changes from v2 to v1, the operating point shifts to P5, resulting in a large negative change in ΔP. Thus, a negative change in speed reference in proportion to ΔP is applied. However, this results in a positive change in ΔP as the operating point shifts to P6. Since the positive change is due is to the left of P6. Therefore, the speed reference is further reduced.

The algorithm continues until ΔP is within the predefined band and the operating point again slides back close to P1. The algorithm is implemented in the following manner. The active power is sampled at a particular rate and the incremental change is computed as

$$\Delta P\ (k) = P\ (k) - P\ (k-1) \qquad (3.4)$$

The magnitude of $\Delta\omega*$ (k) is given by

$$|\Delta\omega*\ (K)| = |\Delta P\ (k) \cdot K_t| \qquad (3.5)$$

Where

K t : Proportional Constant

However the sign of $\Delta\omega*$ (K) has to be properly assigned. If $\Delta\omega*$ (K –1) is zero (i.e. the speed reference was not changed in the previous sample), then the sign of ΔP (k) alone decides the sign of $\Delta\omega*$ (K).

If $\Delta\omega*$ (K-1) is non-zero, the product of the signs of $\Delta\omega*$ (K-1) and ΔP (k) determines the sign of $\Delta\omega*$ (K).

This can be formulated as follows:

```
If $(\Delta\omega^* (K-1) ) == 0 )$
    $S = Sign\ [\ \Delta P\ (K)\ ],$
else
    $S = Sign\ (\Delta P\ (K)) \cdot Sign\ ((\Delta\omega^*\ (K-1)\ )$
$\Delta\omega^*\ (K) = S.\ /\Delta P\ (k) \bullet K\ t\ /$
```

The reference signal is sampled at the same frequency as the active power. If the magnitude of ΔP (k) is within some small-defined band P*band*, then the reference speed is not changed; otherwise it is changed by $\Delta\omega^*$ (K). [12]

```
If $(/\Delta P\ (k)\ / <= P_{band})$
    $\omega^*\ (K) = \omega^*\ (K-1),$
else
    $\omega^*\ (K) = \omega^*\ (K-1) + \Delta\omega^*\ (K).$
```

With this reference the machine is operated in speed control mode.

3.3 SELECTION OF PROPORTIONAL CONSTANT Kt

Proportional constant Kt determines the change in speed reference for a given change in power p. There it depends on the slope of the p-ω characteristics. To choose a value of Kt, an approximate idea of the turbine characteristics is needed. The p-ω characteristics in the region of operation of the peak power-tracking algorithm are considered.

The approximate changes in $\Delta\omega$ for successive change in wind velocities, and hence Δp is also shown. It is obvious that the $\Delta\omega/\Delta p$ more for lower wind velocities and vice-versa.

If Kt is set to the maximum value of $\Delta\omega/\Delta p$ in the operating range then, for changes in wind velocities during high wind conditions, the increment in speed reference would be more than desired. This would result in overshooting of the optimum operating point .the system would oscillate about the peak point before it settles down.

Therefore the maximum value of kt is limited by the lowest value of $\Delta\omega/\Delta p$. a large value of Kt will also result in a large transient in generator torque, which is not desirable. However the value of Kt selected is substantially lower than the limit imposed by the minimum value of $\Delta\omega/\Delta p$.

CHAPTER – 4

SWITCHING MODEL OF CONVERTERS AND INVERTERS

4.1 RECTIFIERS

A rectifier converts ac power to dc. A simple diode bridge rectifier is uncontrolled while the thyristor rectifiers are controlled and capable to control the output voltage as required. The power conversion in these circuits is from a.c. mains voltage to a variable d.c voltage. Rectifiers are widely used in d.c drives, UPS, and HVDC systems.[13]

4.1.1 Three Phase Bridge Converter

A circuit arrangement that is commonly used with thyristor is the three-phase bridge circuit shown in Fig. 4.1. This is a relatively simple circuit using six thyristor. If there is no delay, the thyristor with the most positive anode conducts and produces a positive output voltage at P relative to the neutral. The lower half wave group has a common anode connection, and the thyristor with the most negative cathode conducts to make terminal N negative with respect to the normal. Assuming negligible over lap, the potential of terminal P therefore follows the upper envelope of the alternating of input voltage, while the potential of terminal N follows the lower envelope. The output voltage between P and N terminal is equal to the vertical distance between the upper and lower envelope in Fig 4.2 and therefore it is formed by segments of the three phase line-to-line voltages and has a six pulse ripple as shown.[14]

The average output voltage of six-pulse converter with zero firing delay.

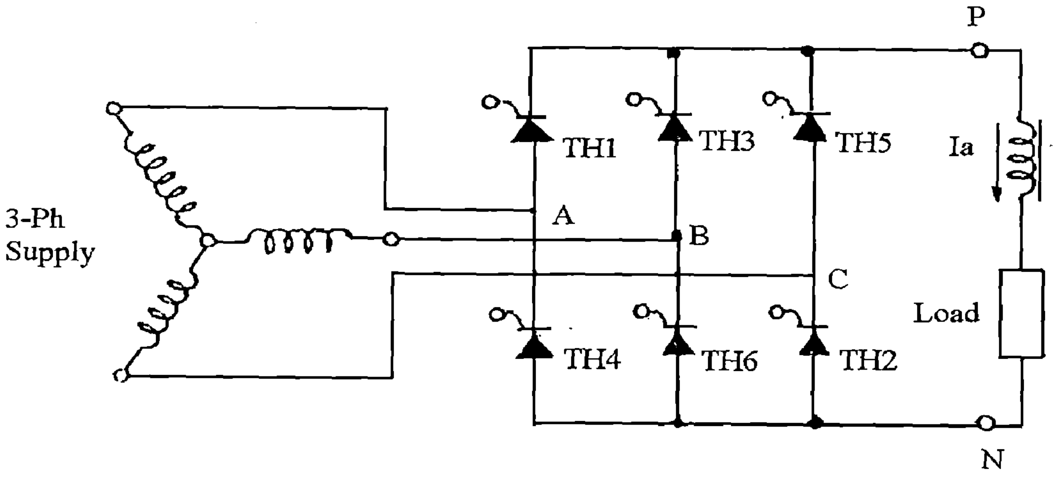


Fig 4.1 Three-phase bridge rectifier

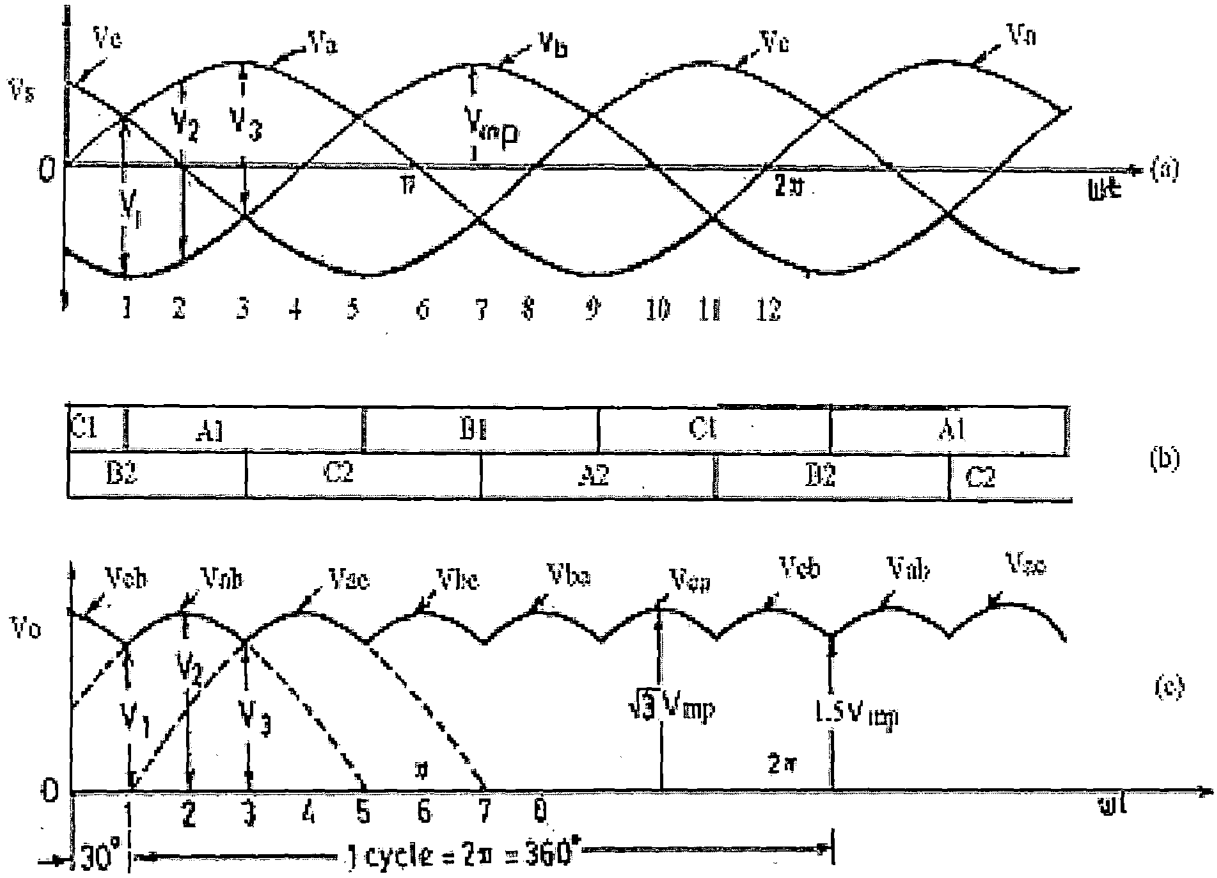


Fig 4.2 Three-phase input voltage and rectified voltage

$$V_{dm}\ \frac{3\sqrt{2}}{\pi}V_l = \frac{3\sqrt{2}}{\pi}V_p h = 2.34\ V_{ph}$$

With firing delay angle α ($0^0 \leq \alpha \leq 30^0$) the voltage waveform is modified and the average output is given by

$$Vd = vdm \cos\alpha$$

If $30^0 \leq \alpha \leq 90^\circ$

$$Vd = \frac{Vdm}{2}(1+\cos\alpha)$$

4.1.2 Harmonic Distortion Due to Power Converter Circuits

The ac line current of a phase-controlled converter is non-sinusoidal, and therefore, the circuit acts as a generator of harmonic currents. These harmonic currents develop harmonic voltage drops across the network source impedance, causing distortion of the supply voltage delivered to the converter itself and to other consumers in the area [15].

In general, the harmonic currents on the ac side of the converter are of order $k = np \pm 1$, where p is the pulse number of the converter and n is an integer; the pulse number is the number diodes or thyristor which successively begin to conduct during one cycle of the supply frequency. The six-phase half-wave circuit is therefore classified as a six-pulse system, as also is the three-phase bridge circuit. The lowest order harmonics generated by these circuits are the fifth and the seventh. A 12-pulse converter is obtained if two six-pulse groups, with a 30-degreephase displacement form a 24-pulse system. Increasing the pulse number reduces the total harmonic content by eliminating low-order harmonics, but correct balance between converter groups is essential.

Theoretically, the amplitude of the kth harmonic current is given by $I\sqrt{k}$, where I_1 is the fundamental amplitude. However, this relationship assumes infinite dc circuit inductance and instantaneous commutation. In practice, commutation overlap reduces the amplitude of the harmonic current below this theoretical value. Delayed firing reduces the overlap angle and so tends to increase the harmonic amplitude [15].

Distortion of the ac supply voltage waveform is objectionable, as it may cause overheating of power-factor-correcting capacitors due to large harmonic currents. At the harmonic frequencies, undesirable resonance may also occur between the power-factor-correcting capacitance and the system inductance. A certain amount of telephone interference is also possible. In order to avoid these difficulties, supply authorities specify that the total converter rating must not form an excessive part of the load on the power system. Engineering Recommendation G.5/3 of the Electricity Council of Great Britain is a typical utility specification on the connection of converter equipment to the power system. This document states that smaller times of converter equipment, which are in general use, are acceptable for connection to the ac supply without any detailed consideration of the system itself. Thus, three-pulse and six-pulse converters can be connected to the three-phase, 415 V, ac supply provided their ratings are not greater than 8 kVA and 12 kVA, respectively. Larger kVA ratings are permissible at higher system voltages. If the equipment size exceeds these limits, then it must be judged against a table of maximum permitted values of harmonic current that a consumer may feed into the system, assuming that the existing harmonic levels on the system are within specified limits. If the converter is intended for connection to the 415 V distribution system, the permissible harmonic current levels are 56 A for the fifth harmonic, 40 A for the seventh harmonic, 19 A for the eleventh harmonic, and 16 A for the thirteenth harmonic. In order to satisfy these limits, the rating of a diode converter should be less than 150 kVA for a six-pulse circuit and less than 300 kVA for a 12-pulse system. Again, larger ratings are permitted at higher system voltages [15].

At higher power levels, the pulse number of the converter installation may have to be increased in order to reduce the harmonic content to an acceptable value. Transformers are required to produce the correct phase displacement between converter groups, which increases the cost of the installation. Harmonic filters are also used to suppress specific low impedance paths for particular harmonic currents.

Power converter circuits also cause system voltage distortion known as lien notching. During the brief commutation overlap period, two phases of the ac supply are short-circuited, as explained earlier. This produces a notch in the ac line voltage waveform for the duration of the overlap angle, u. Thus, a three-phase bridge circuit produces six notches per cycle of the line voltage, and these notches are rich in high frequencies, which are readily propagated through the power system.

Power converters may also generate radio-frequency interference (RFI) or electromagnetic interference (EMI) due to the sudden changes of current, which occur in diode and thyristor circuits. This interference is partly radiated directly but is mainly propagated in the supply lines and may cause interference to broadcast reception or malfunction of thyristor equipment. In general, distortion of the ac system voltage due to a converter load may cause interaction between converter installations by coupling transient emfs into sensitive trigger circuits or by producing excessive dv/dt transients in thyristor anode circuits, or by the introduction of spurious zero crossings in the lien voltage waveform. The danger of interaction may usually be eliminated by good circuit design and layout, by shielding sensitive control circuits and by fitting dv/dt suppression circuits [15].

4.2 INVERTERS

In an inverter circuit, dc power is converted to ac power at desired output voltage and frequency. The main industrial application of inverters is for adjustable speed ac drives, induction heating, stand by aircraft power supplies, UPS (uninterruptible power supplies) for computer, HVDC transmission lines and VSCF wind energy conversion system [14]. The dc power input the inverter is obtained from rectifier. The configuration of ac to dc converter and dc to ac converter is called a dc link converter. Semiconductor devices with controlled turn off capability, such as transistors, MOSFETs, IGBTs, and GTO, can be used when these devices are available with the required voltage and current ratings. The inverters are mainly classified into two categories i.e. forced commutated inverters and line-commutated inverters.

i. Converter grade thyristors can be used in line-commutated inverters, as the switching frequency is less.

ii. No extra commutating circuitry is needed for the commutation. The line voltage themselves commutate the outgoing thyristors when the incoming thyristor is fired.

iii. Due to use of converter grade thyristors, which are cheaper than inverter grade thyristor, and absence of extra commutating circuitry, they are cheaper.

The basic principle of operation of a line-commutated inverter is to control the point in time at which the conduction in each thyristor is allowed to commence during each ac cycle. By this it means, it is possible to choose the time segments of the ac voltage waves, which appear at the dc terminals. Since in case of line-commutated inverters the firing angle is kept greater than 90^o, the average voltage at the dc terminals is negative. However the direction of current remains same as in case of converter due to unidirectional nature of devices, so power flow is from dc to ac side.

The output frequency of the static inverter is determined by the rate at which the semiconductor devices are switched on and off by inverter control circuitry, consequently and adjustable frequency ac output is readily provided. However, the basic switching action of the inverter normally results in non-sinusoidal output voltage and current waveforms that may adversely affect output performance.

The flittering of harmonics is not feasible when the output frequency varies over a wide range, and the generation of ac waveforms with low harmonic content is important. When the inverter feeds a transformer or ac motor, the output voltage must be varied in conjunction with frequency to maintain the proper magnetic conditions. Output voltage control is therefore an essential feature of an adjustable frequency system, and various techniques for achieving voltage control are studied.

There are broadly two inverter, voltage source inverter and current source inverter. The voltage fed, or voltage source inverter (VSI) is powered from a still, or low impedance do voltage source such as battery or rectifier. The output voltage of which is smoothed by an LC filter. The larger filter capacitor across the inverter input terminals contain a constant dc link voltage. The inverter is therefore an adjustable frequency voltage source. The output voltage of which is essentially independent of load current. On the other hand, the current fed or current source inverter is supplied with a controlled current from a dc source of high impedance Typically a phase controlled rectifier feeds the inverter with regulated current through a large services inductor. Thus load current rather than load voltage is controlled and the inverter output voltage is independent upon the load impedance.

4.2.1 PWM Inverter

PWM (Pulse Width Modulation) techniques are characterized by constant amplitude pulses. The width of these pulses is however modulated to obtain inverter output. Voltage control and to reduce its harmonic content and it may be used to minimize objectionable harmonic effects on load.

Various PWM techniques are used in the inverter. The choice of a particular PWM control depends on the permissible harmonic content in the inverter output voltage.

The commonly used techniques are

(i). Single pulse width modulation

(ii). Multiple pulse width modulation

(iii). Sinusoidal pulse width modulation

(iv). Modified sinusoidal pulse width production

(v). Phase angle control.

Out of the above control strategies sinusoidal pulse width modulation is the most commonly used one in industrial applications. [13]

4.2.2 Sinusoidal Pulse Width Modulation (SPWM)

Sinusoidal PWM is approximated by use of an inverter control circuit in which a high frequency triangular carrier wave, V_c is compared with a sinusoidal reference wave V_r, of desired frequency, and the crossover points are used to determine the inverter switching instants. In Fig. 4.3 an asymmetrical triangular wave is mixed with a sine wave reference to produce a PWM waveform in which the width of each plus in defined by the interval between successive intersections. Consequently, the pulse width is approximately proportional to the mean sine wave ordinary in a pulse interval. When the frequency of the triangular wave is much greater than that of the sine wave, the variation in sine wave magnitude is insignificant between adjacent intersections, and the resulting PWM

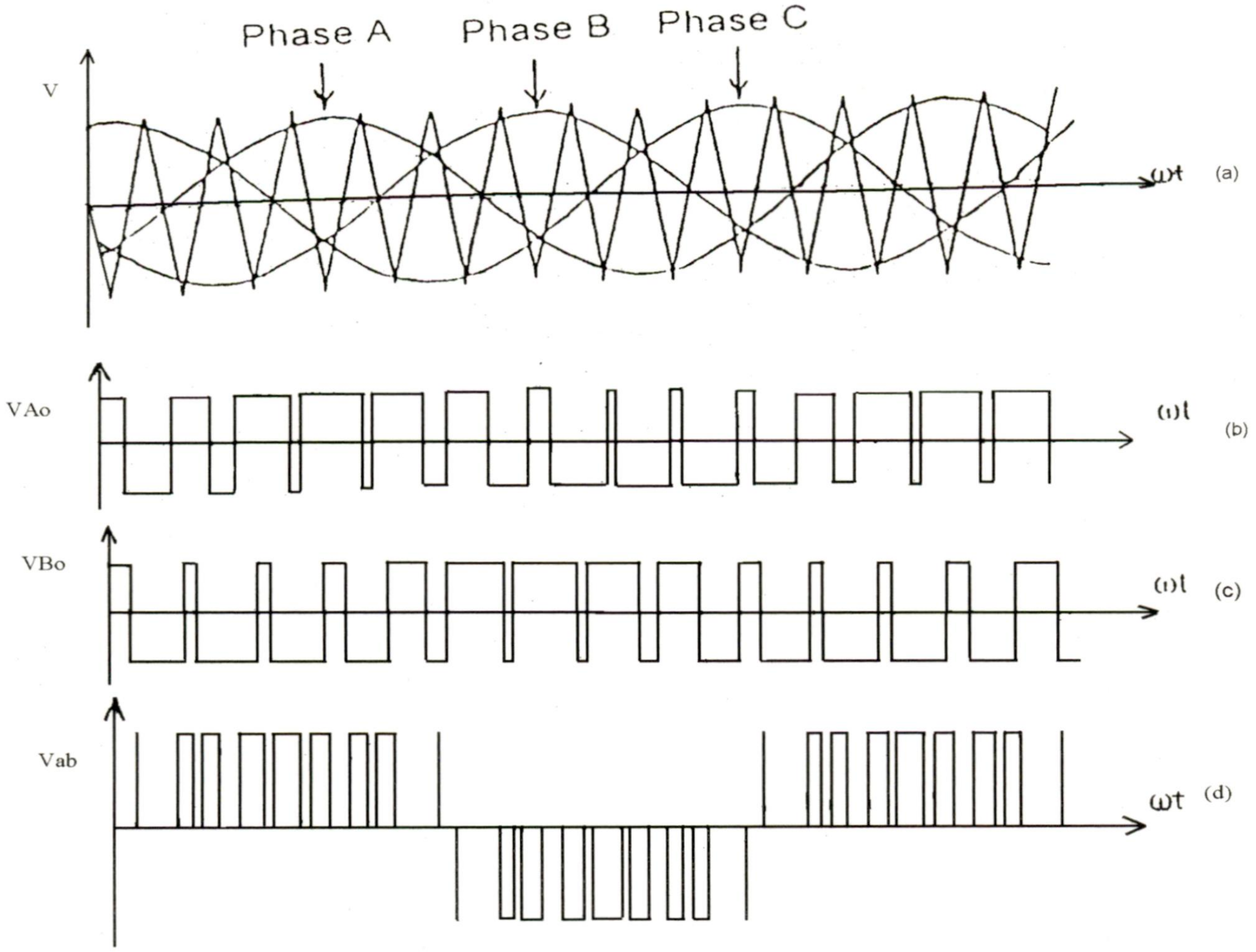


Fig 4.3 Voltage waveform for a three-phase sinusoidal pulse width modulation inverter:

(a) Reference sine wave and triangular carrier wave;

(b) Pole voltage of phase A;

(c) Pole voltage of phase B;

(d) Line voltage Vab (Vab = Va -Vb)

waveform approaches closely the ideal waveform in which pulse width is a sinusoidal function of angular position [14].

Fig. 4.3 shows the voltage waveform for a three phase sinusoidal PWM inverter in which carrier ratio is nine and the modulation index is almost unity. The pole voltage V_{AO}, V_{BO}, V_{CO} and the resultant line-to-line voltage, V_B are shown. The modulation index ($MI = V_r/V_c$) V_r reference voltage amplitude, V_c = carrier wave amplitude, controls the fundamental output voltage of the inverter. The carrier ratio ($p_{cr} = f_c/f_r$) controls the dominant harmonics of the inverter output voltage. For the carriers ratio of p_{cr} the harmonic of order ($2p_{cr} \pm 1$) are dominant over most of the range of MI, but harmonics of order ($p_{cr} \pm 2$) are also significant. In general, the lowest harmonic of appreciable magnitude is or order ($p_{cr} - 2$). The harmonic content involve in SPWM inverter is given in Fig. 4.3 [14].

In SPWM inverter, for a dc link voltage, Vd and unity modulation index, the amplitude of the fundamental line-to-neutral voltage for star-connected load is Vd/2, For a six-step line-to-neutral voltage waveform, the fundamental amplitude is 2 V d/π or 0.636 Vd. The corresponding fundamental rms line-to-line voltages are 0.612 Vd for sinusoidal PWM and 0.78 Vd for a six-step waveform. Thus for a given dc link voltage, the sine wave PWM inverter has a fundamental voltage capability which is only 0.612/0.780 = 0.785 or 78 percent of that for a six–step inverter.

In sinusoidal pulse-width modulation method the widths of the pulses that are nearer to the peak of the wave do not change significantly with the variation of modulation index. This is due to the characteristics of a sine wave. A new modified sinusoidal pulse width modulation method can be used to improve the performance [14].

4.2.3 Modified Sinusoidal Pulse-Width Modulation (MSPWM)

In modified sinusoidal pulse-width modulation, method (MSPWM) the carrier wave is applied during the first and last 60° intervals per half-cycle (0 to 60° and 120° to 180°) as shown in Fig. 4.4 the fundamental component is increases and their harmonic characteristics are improved.

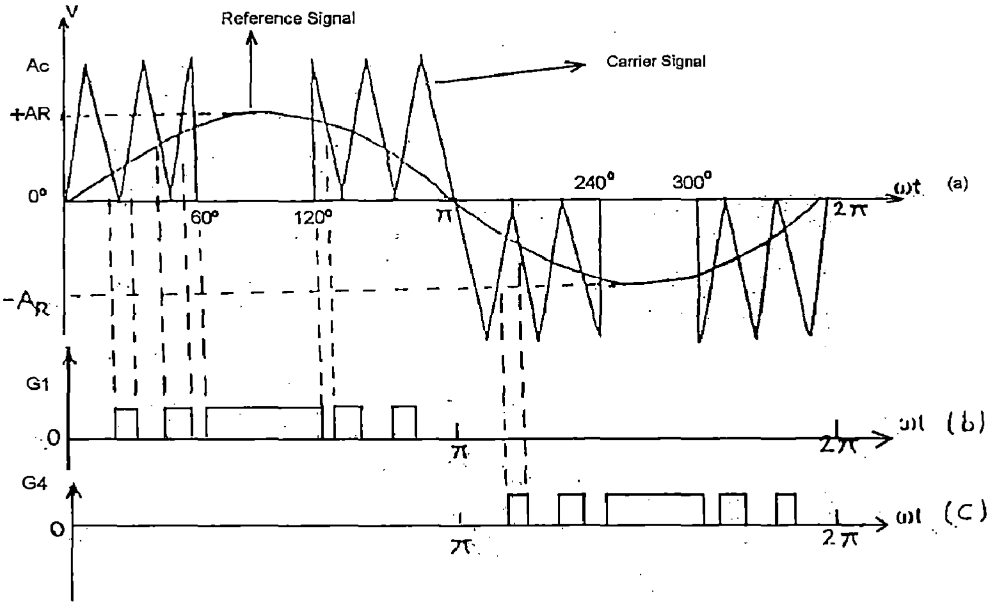


Fig 4.4 Modified Sinusoidal Pulse Width Modulation; (a) Reference Sine Wave

(b) Gate Signal G1 (b) Gate Signal G4

It reduces the number of switching of power devices and also suffers from drawbacks of low fundamental output voltage. Some advanced modulation techniques can be used to improve the performance of the drive system. The commonly used techniques are;

(i). Trapezoidal modulation,

(ii). Staircase modulation,

(iii). Stepped modulation,

(iv). Harmonic injection modulation,

(v) Delta modulation.

These control techniques permit improved utilization of the available dc link-voltage.

4.2.4 Advance Modulation Techniques

(i) Trapezoidal modulation

In trapezoidal modulation comparing a triangular carrier wave with a modulating trapezoidal wave as shown in Fig. 4.5 generates the gating signals. This type of modulation increases the peak fundamental output voltage upto 1.05 Vs. but the output contains low order harmonics [14].

(ii) Staircase modulation

The modulating signal in the case of staircase wave is shown in Fig. 4.6. the levels of stairs are calculated to eliminate specific harmonics. The number of steps is chosen to obtain the desired quality of output voltage. This is an optimized PWM and is not recommended for fewer than 15 pulses in one cycle.

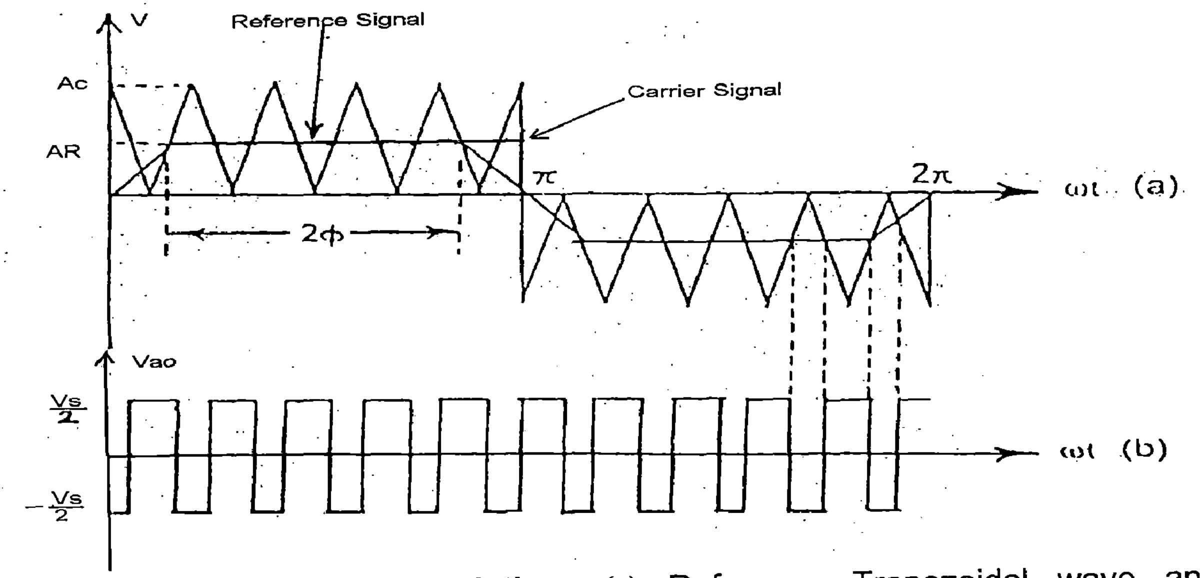


Fig 4.5 Trapezoidal Modulation; (a) Reference Trapezoidal wave and Triangular Carrier wave; (b) Pole voltage of phase A

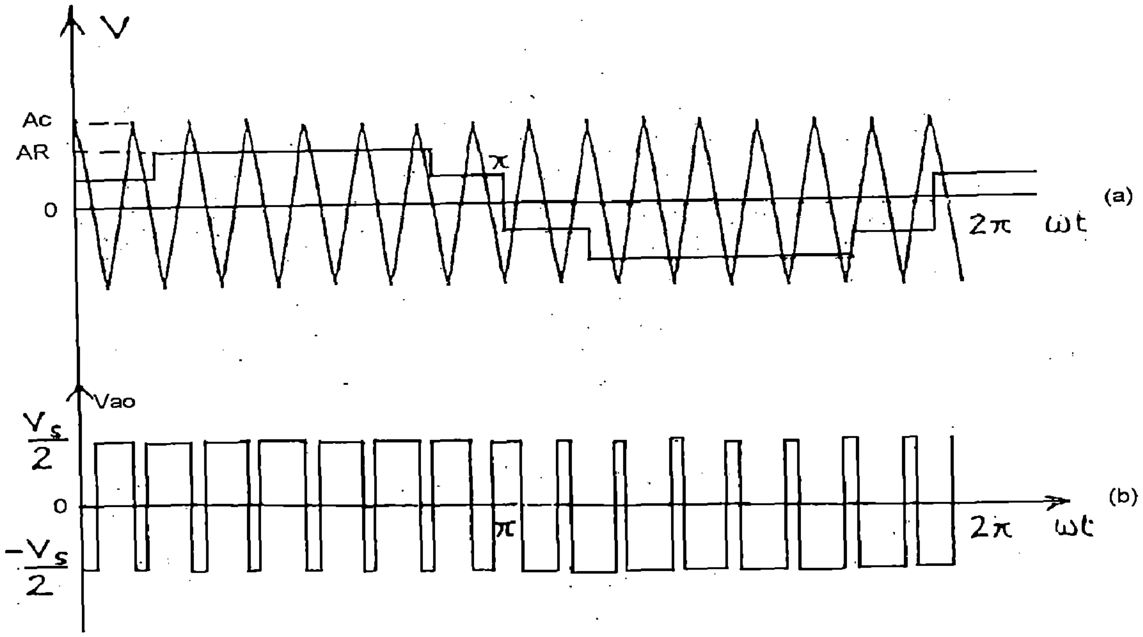


Fig 4.6 Staircase Modulation; (a) Reference staircase wave and triangular carrier wave; (b) Pole voltage of phase A

This type of control provides a high-quality output voltage with a fundamental value of upto 0.94 Vs [13].

(iii) Stepped modulation

The modulating signal is a stepped wave, which is shown in Fig. 4.7. It is divided into specified intervals, say 20°, with each interval being controlled individually to control the magnitude of the fundamental c harmonics. This type of control gives low distortion, but higher fundamental amplitude compared to that of normal PWM control [14].

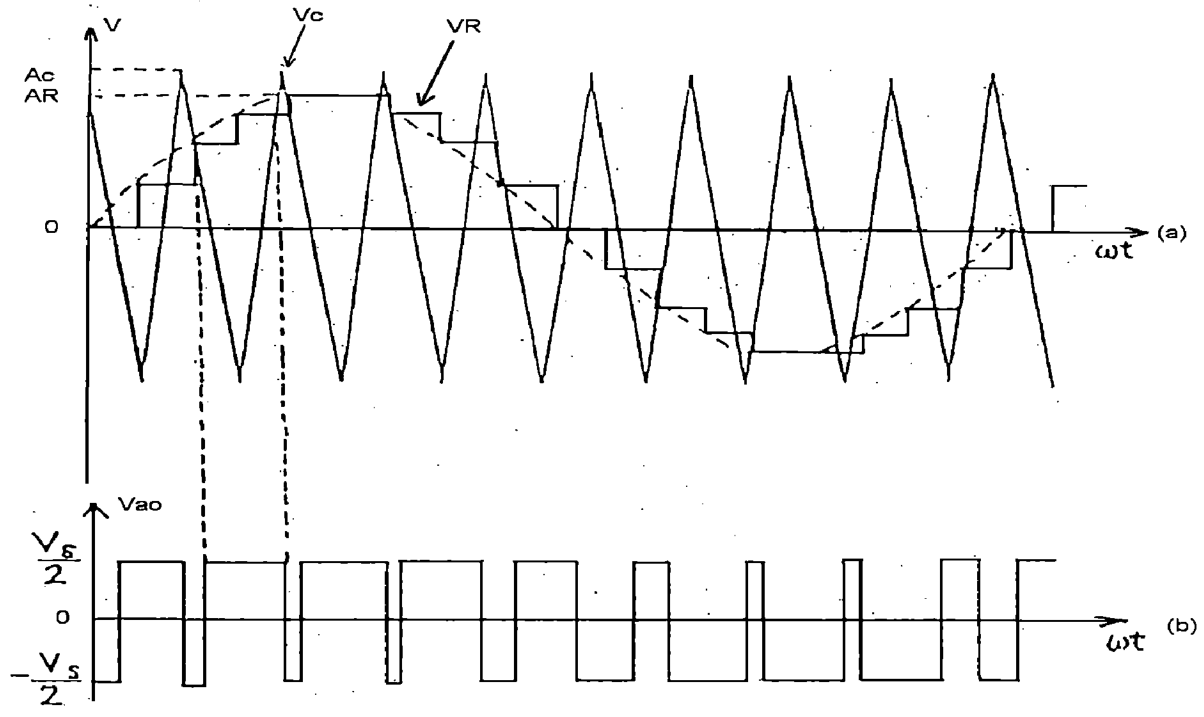


Fig 4.7 Stepped Modulation (a) Reference Stepped wave and Triangular Carrier wave; (b) Pole voltage of phase A

(iv) Harmonic injected modulation

The modulating signal is generated by injecting harmonics to the sine wave. This results in flat-topped waveform and reduces the amount of over modulation. It provides a higher fundamental amplitude and low distortion of the output voltage. The modulating signal is generally composed of third and ninth harmonics as shown in Fig. 4.8 the injection of 3rd harmonics will not affect the quality of the output voltage, because the output of a three-phase inverter does not contain triplet harmonics.

If only third harmonic is injected then modulating signal can be generated from 2/3 segments of a sine wave as shown in Fig 4.9. This is same as injecting 3rd harmonics to a sine wave. He line-to-line voltage is sinusoidal PWM and the amplitude of the fundamental component is approximately 15% more than that of a normal sinusoidal PWM. Since each arm is switched off for one-third of the period, the heating of the switching devices is reduced.

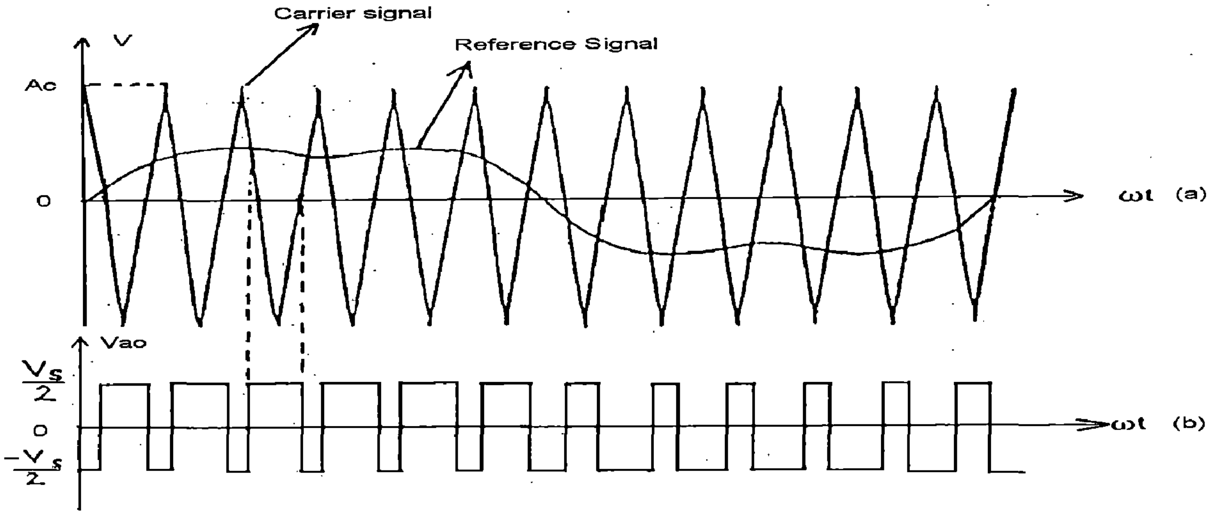


Fig 4.8 Selected harmonic injected modulation; (a) Third and ninth harmonic injected reference modulating signal; (b) Pole voltage of phase A

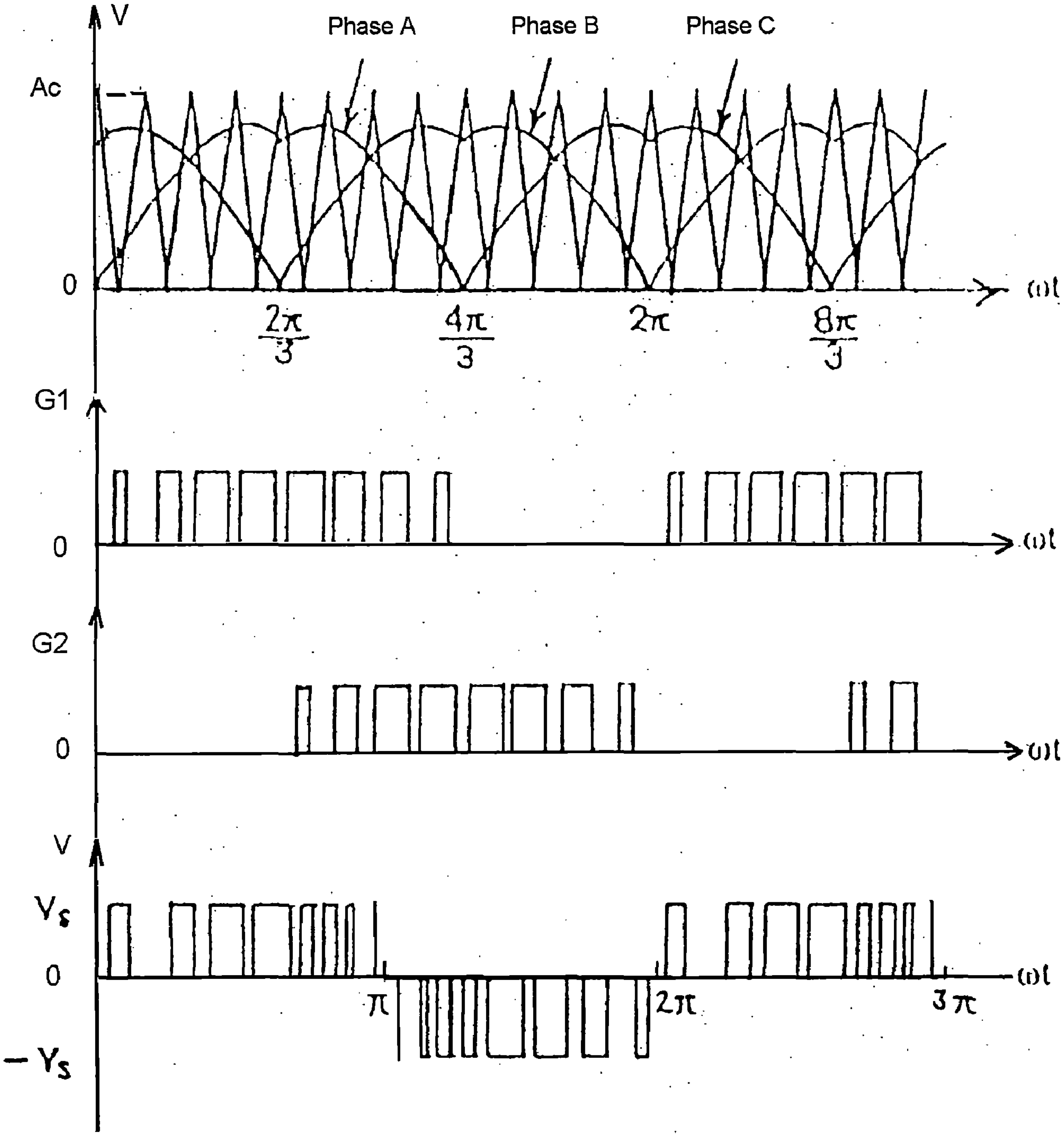


Fig 4.9 Third harmonic injection Modulation

(v) Delta modulation

In delta modulation, a triangular wave is allowed to oscillate within a defined window AV above and below the reference sine wave V, as shown in Fig 4.10. It is also known as hysteresis modulation. The fundamental output voltage can be upto Vs and dependent on the peak amplitude and frequency f_r, of the reference voltage. The delta modulation can control the ratio of voltage to frequency, which is a desirable feature in ac motor control. [14]

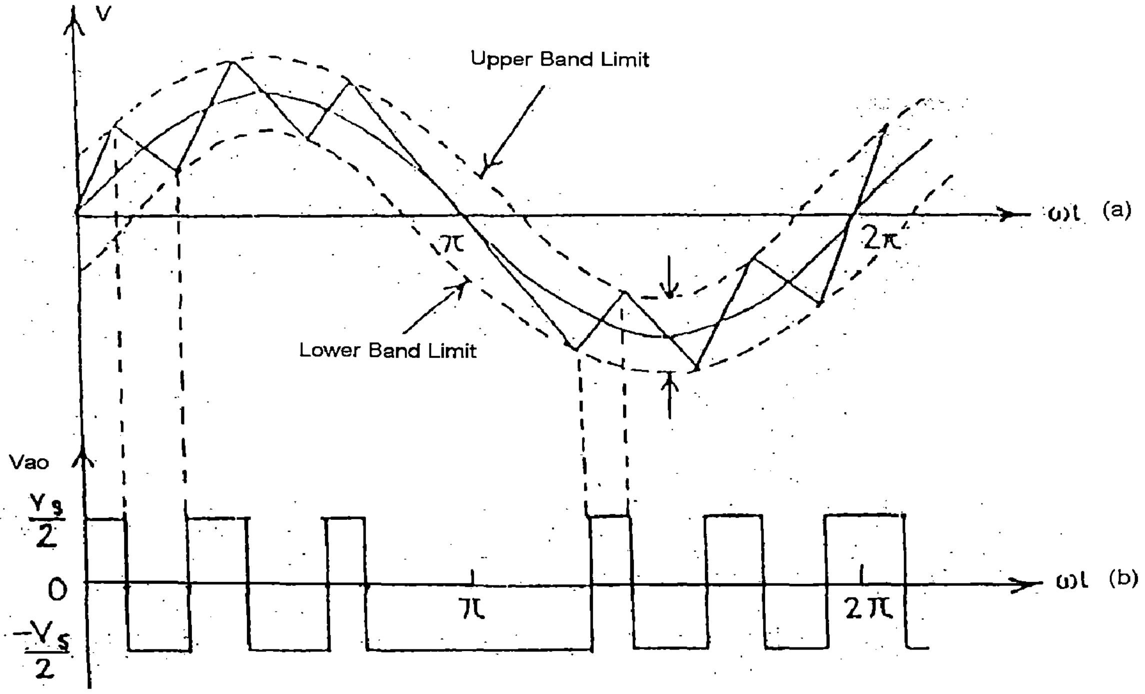


Fig 4.10 Delta Modulation; (a) Triangular in defined window Δ V; (b) Pole voltage of phase A

4.3 COMMENTS ON PWM SCHEME

- It is desirable to push carrier ratio 'p' to as large as possible.
- The main impetus for that when p is high, then the harmonics will be at higher frequencies because frequencies of harmonics are related to f=kp(fm), where fm is the frequency of the modulating signal.
- Although the voltage THD improvement is not significant, but the current THD improves greatly because the load normally has some current filtering effect.
- In any case, if a low pass filter is to be fitted at the inverter output to improve the voltage THD, higher harmonic frequencies is desirable because it makes smaller filter component.

4.4 REDUCTION OF HARMONICS

There are several industrial applications, which may allow a harmonic content of 5% of its fundamental component of input voltage when inverters are used. Actually, the inverter output voltage may have harmonic content much higher than 5% of its fundamental component. In order to bring this harmonic content to a reasonable limit of 5% one method is to insert fillers between the load and inverter. If the inverter output voltage contains high frequency harmonic, these can be reduced by a low size filter. For the attenuation of low frequency harmonics, however the size of filter components increases. This makes the filter circuit costly, bulky and weightily and in addition, the transient response of the system becomes sluggish. This shows that lower order harmonics from the inverter output voltage should be reduced by some means other than the filter.

Subsequent to this high frequency component form voltage can easily be attenuated by a low size, low cost filter [14]. The harmonic content of the sinusoidal PWM converter is shown in Fig. 4.11 [13].

Harmonics reduction methods are;

i. By PWM

ii. By transformer connection

iii. By stepped wave inverter

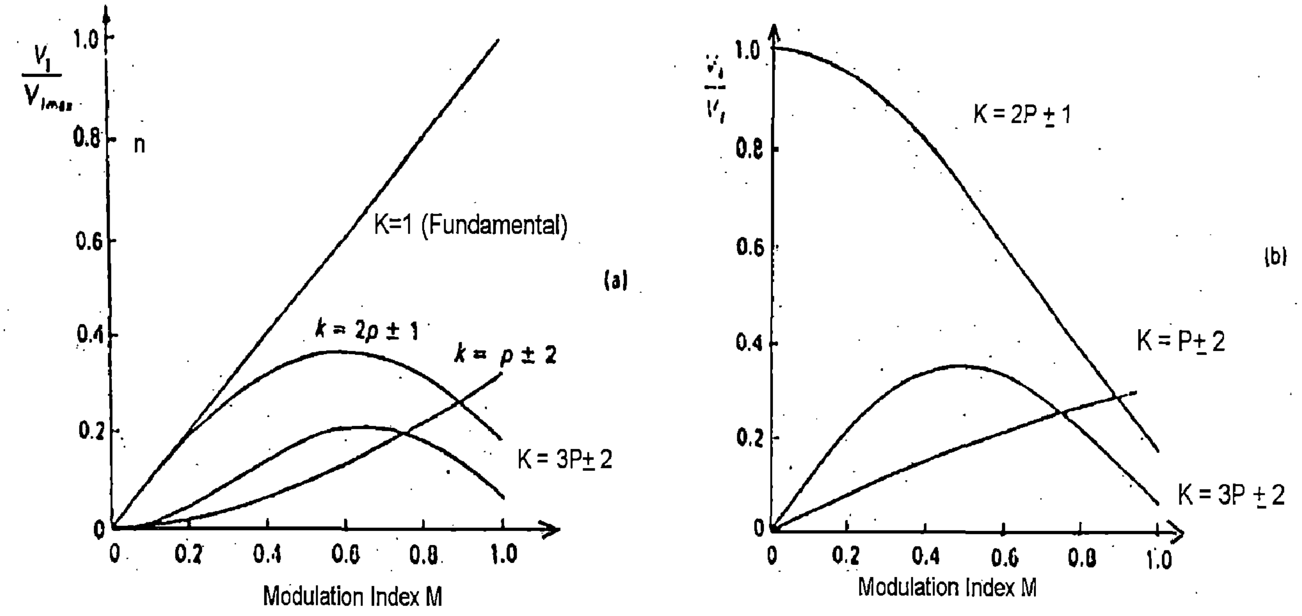


Fig 4.11 Harmonic content of the SPWM voltage as a function of Modulation Index;

(a) Harmonic amplitude Relative to maximum fundamental amplitude;

(b) Harmonic amplitude relative to actual fundamental amplitude

HARDWARE FOR VSCF POWER CONVERSION SCHEME

5.1 GENERATOR MODEL

Generator model is developed by the use of equations as described in CHAPTER-2. This model realization is in per unit terms so it is a small signal model. A simple model of generator is shown. The results of the simulation have been shown in Fig. 5.12 to Fig. 5.20.

Since this model is a small signal model, its limit is to not realize with the switching model for conversion in fixed frequency and voltage whether the speed variation at input is allowed.

5.2 VSCF SYSTEM CONFIGURATION

The simplified diagram of three-phase VSCF conversion system, in which a controlled rectifier and voltage source inverter, with sinusoidal PWM technique feeding a three-phase load is shown in Fig. 5.1.

In this scheme three-phase voltage source use as input, this ac supply is convert into dc with a bridge rectifier, the output voltage of controlled rectifier is make constant by connecting a large capacitor at the input terminal of inverter. This capacitor makes the input dc voltage constant and also suppresses harmonic feed three parallel arms each arm having two thyristors using line-commutated inverter.

Each inverter phase of half bridge has a comparator, which is fed with the reference voltage for that phase and triangular carrier wave which is common to all the three-phase. The ratio of carrier to reference frequency or carrier ratio, p,

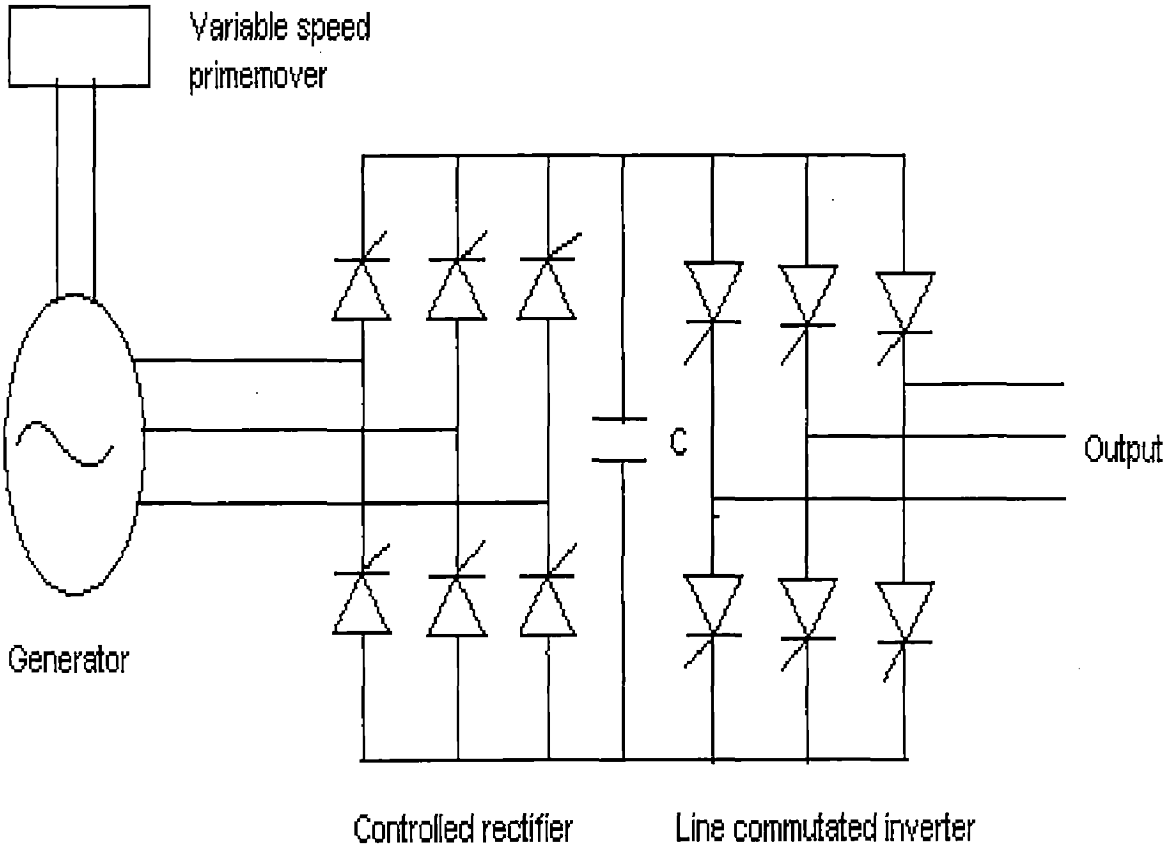


Fig 5.1 VSCF Power conversion scheme

is taken to be multiple of three to ensure identical phase voltage waveforms in a three-phase system. The triangular carrier wave has fixed amplitude. The ratio of sine wave amplitude to carrier amplitude is termed as modulation index (MI). Output voltage control is achieved by variation of the modulation index and thereby the sine wave amplitude. This variation alters the pulse widths in the output voltage waveform but preserves the sinusoidal modulation pattern. The VSCF model has been fabricated and results under different conditions have been recorded.

The system model has been fabricated whose components are:

(i) Three-phase power supply,
(ii) Single-phase controlled bridge rectifier,
(iii) SPWM inverter (power circuit),
(iv) Pulse generator (control circuit),
(v) Snubber circuit
(vi) Capacitor,
(vii) Oscilloscopes

The various subsystem blocks have been developed as discussed below;

5.2.1 Three – Phase Power Supply

The subsystem for the three-phase balanced ac source is shown in Fig. 5.1. The peak value of a, b and c phases is 254.03 V.

$V_{am} = V_{bm} = V_{cm} = 254.03$ V

The line voltage of the three-phase system is;

V_l (rms) = 440 V.

5.2.2 Single-Phase Bridge Rectifier

The subsystem for the single-phase diode bridge rectifier is used. Here diode bridge rectifier has been used for the conversion of single-phase ac into dc.

The average dc output voltage from single-phase diode bridge rectifier is [14];

$$V_{dc} = \frac{2\sqrt{2}}{\pi} V_m$$

5.2.3 SPWM Inverter Power Circuit

The power circuit of a SPWM inverter has been shown in Fig 5.1. The power circuit consists of six Inverters. The switching devices are numbered in the sequence in which they are triggered to obtain voltage V_{ab}, V_{bc}, and V_{ca} at the output terminal of the inverter.

5.2.4 Pulse Generator Control Circuit

The control circuit of the SPWM inverter is shown as in Fig 5.2. Here each inverter phase has a comparator, which is fed with the reference wave for that phase and carrier wave, which is common to all the three phases. The carrier and reference waves are mixed in a comparator. When reference wave has magnitude higher than carrier wave, the comparator output is high otherwise it is low. The comparator output is processed in a trigger pulse generator in such a manner that the output voltage wave of the inverter has a pulse width in agreement with the comparator output pulse width. There are numerous approaches of designing gate pulses at the required delay angle.

Following are some of the schemes of generating gating pulses.

(i) Cosine wave crossing control

(ii) Ramp comparator approach

(iii) Equidistant pulse firing scheme

(iv) Digital firing scheme.

5.2.5 Snubber Circuit

Snubber circuits are used to protect the thyristors against voltage transients and over currents. For this purpose, a resistor is connected in series with a capacitor and this is put across the thyristors. The series connection of R-C is also called a snubber circuit

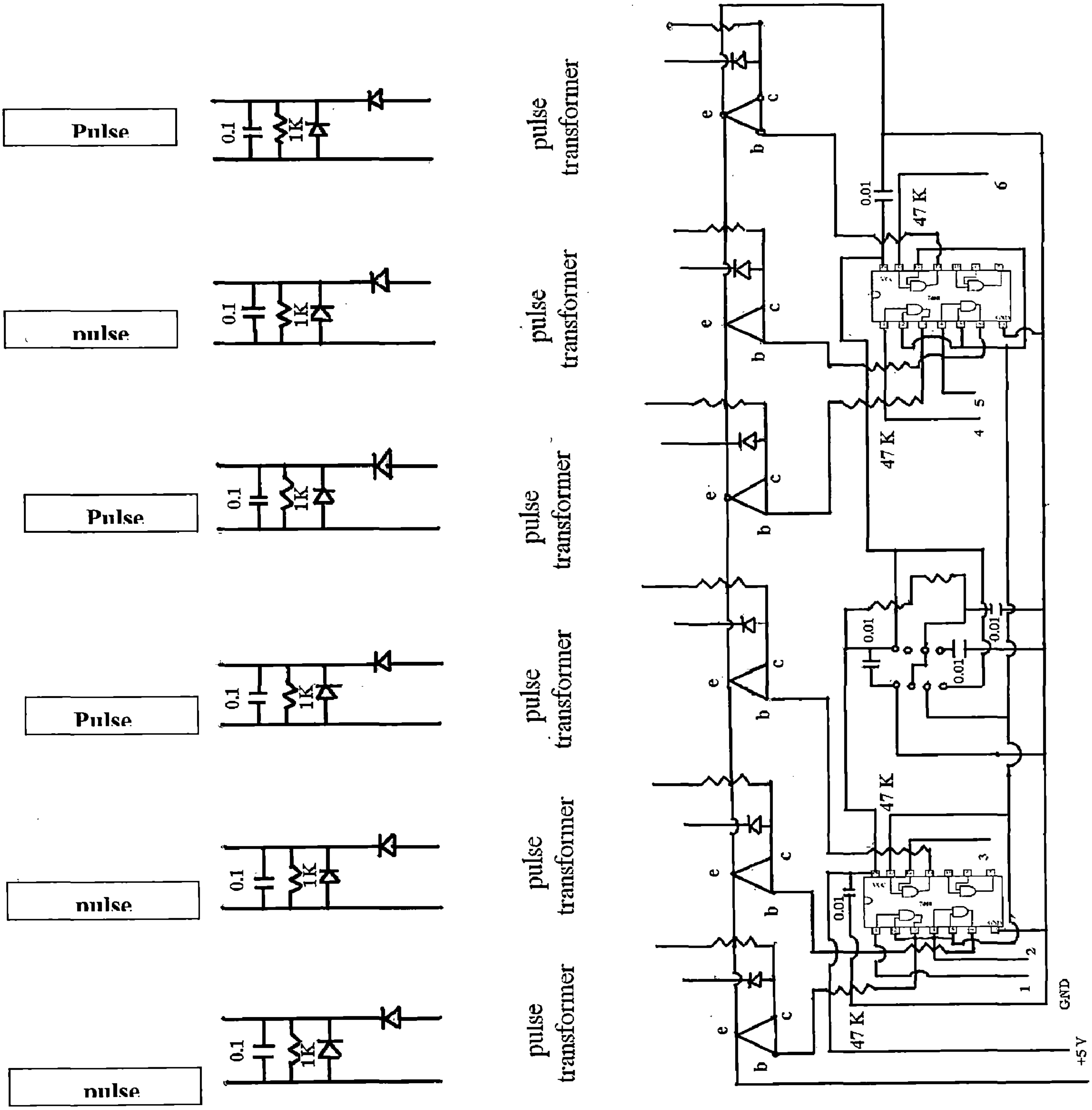


Fig 5.2 Firing Circuit of Thyristors

5.2.6 Capacitor

A large capacitor is connected across the output terminal of the bridge rectifier for smoothing of dc output voltage of the rectifier. This capacitor also suppresses the harmonic feed back to ac source.

5.2.7 Oscilloscopes

For obtaining the nature of current and voltage scopes are employed.. These scopes have also facility of storing data into workspace, which come through simulation. Various curves can be plotted on the scope. Also the firing pulses can be checked through cathode ray oscilloscope (CRO).

5.3 LIST OF ICs USED IN PULSE GENERATOR CONTROL CIRCUIT SCHEME

(i) DM 7400

(ii) DM7408

(iii) DM74121

(iv) LM339

(v) IC 555 Timer

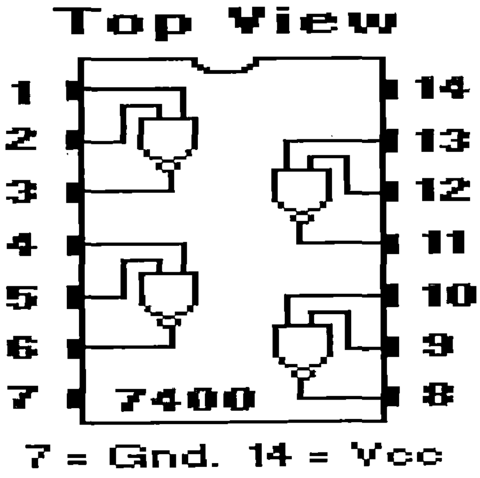


Fig 5.3: Pin Configuration of IC7400

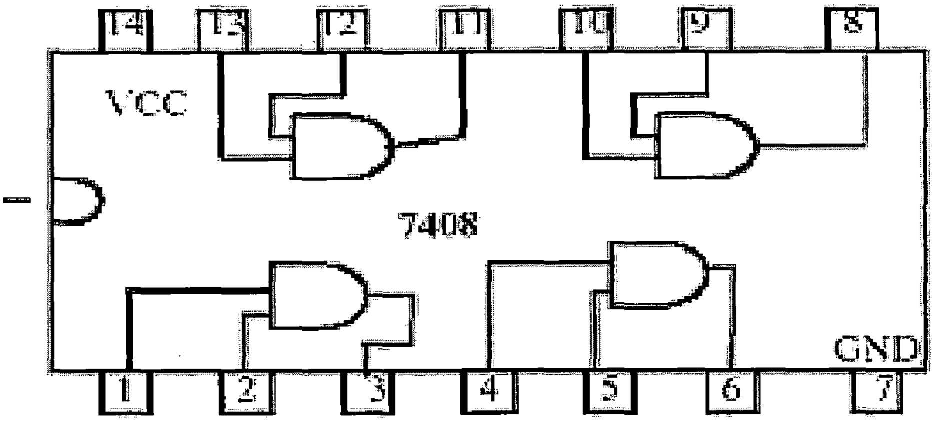


Fig 5.4: Pin configuration of IC 7408

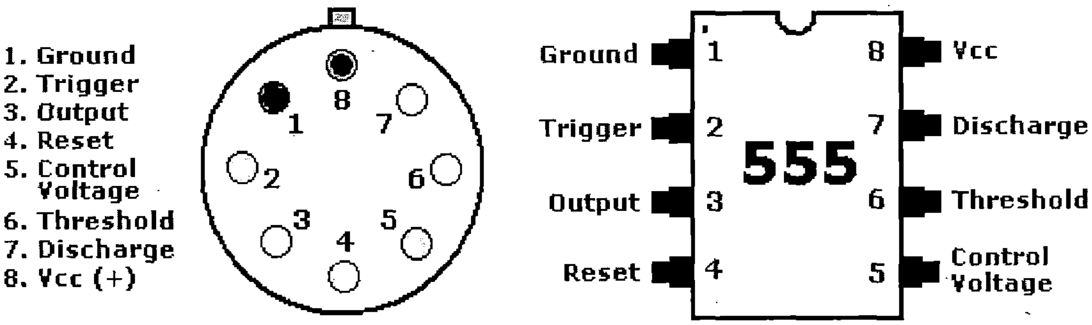


fig. 1. 8-pin T package

fig. 2. 8-pin V package

Fig 5.5: pin configuration of IC 555 Timer

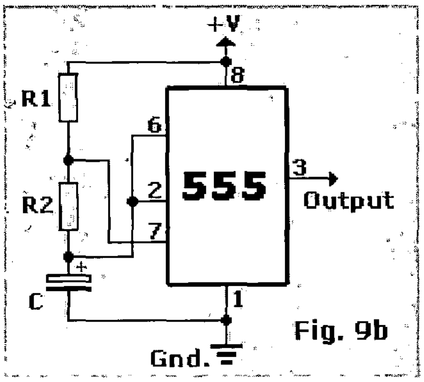


Fig 5.6 Internal configuration of IC 555 Timer

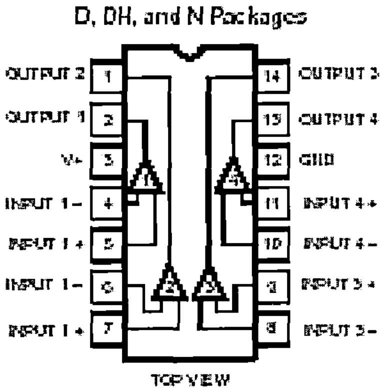


Fig 5.7 Pin configuration of IC LM 339

5.4 SYSTEM MODEL AND ITS SIMULATION

Using MATLAB has simulated the VSCF model and results under different conditions have been recorded. The system model has been developed in SIMULINK/POWER SYSTEM block set whose components are:

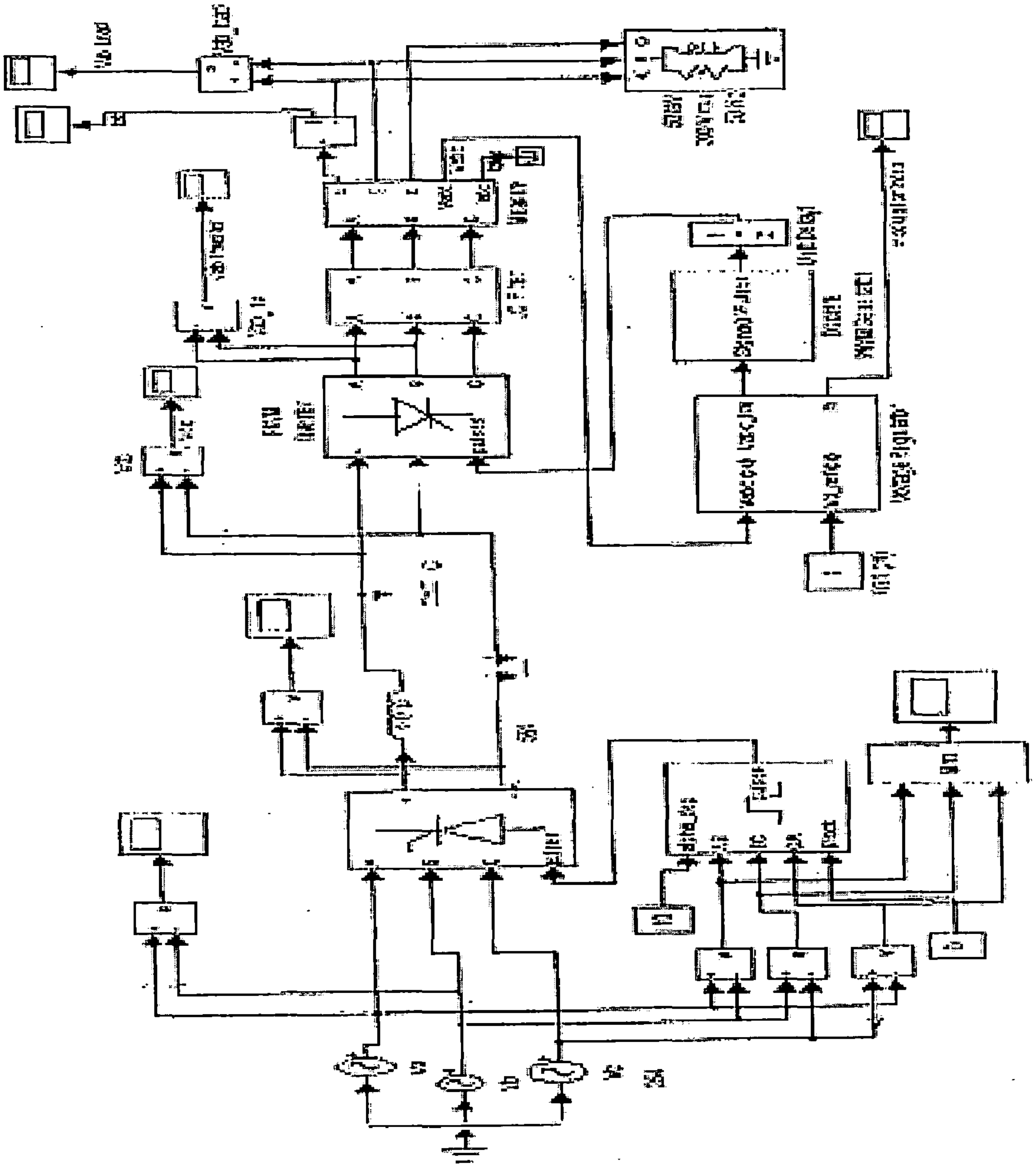


Fig 5.8 Simulation of VSCF power conversion scheme

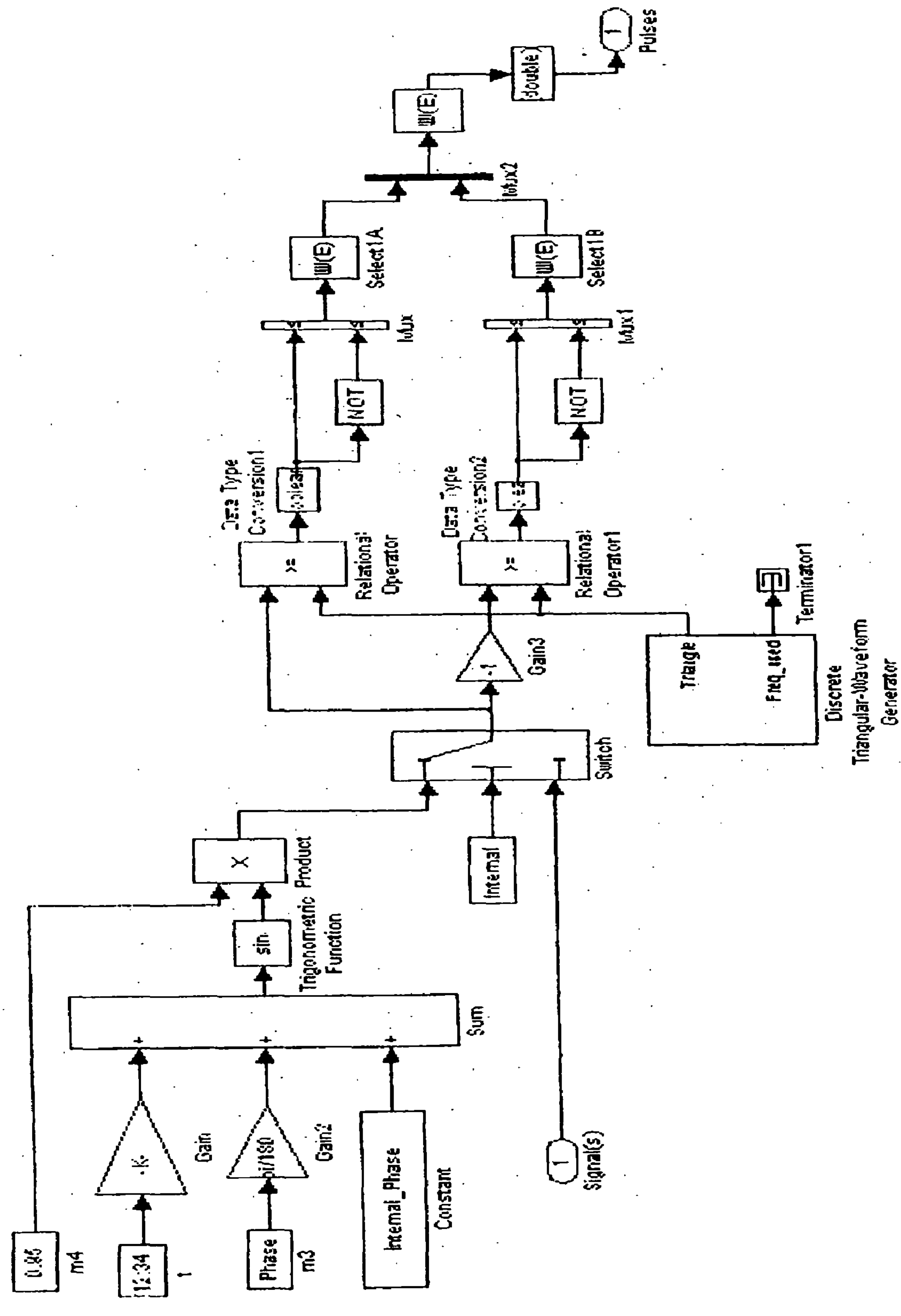


Fig 5.9: PWM pulse generator

5.5 RESULTS

Modeling of the synchronous generator has been carried out and results obtained from simulation have been attached. The VSCF system in which converter to convert ac voltage into dc at constant voltage and inverter to give a.c voltage at constant frequency and result obtained has been shown in Figure 5.12 to 5.20.

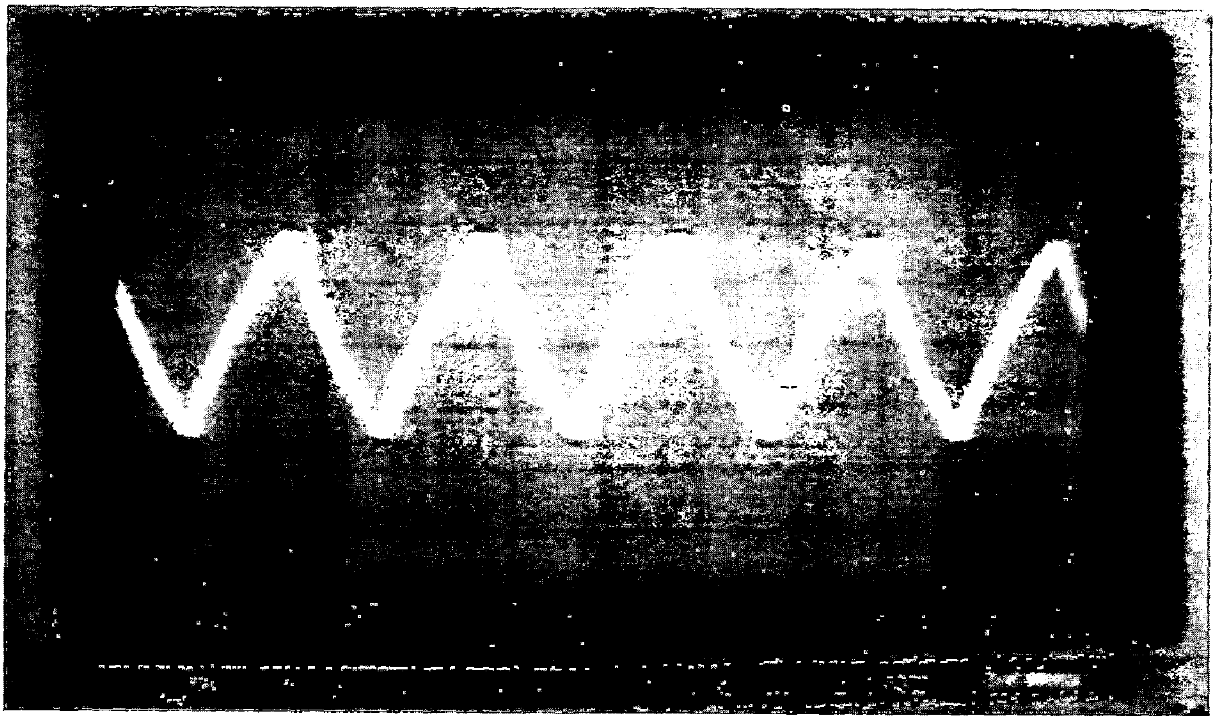


Fig 5.10: Voltage across capacitor of IC 555

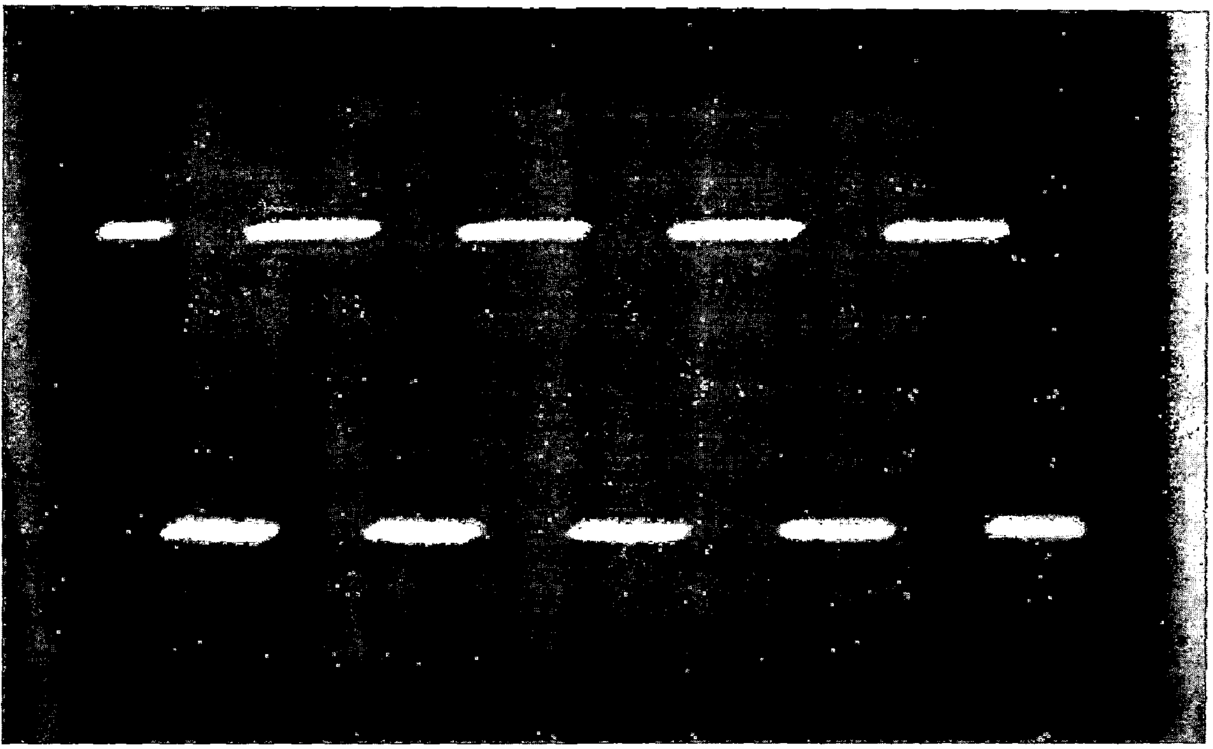


Fig 5.11: Input rectangular pulse to IC 7408

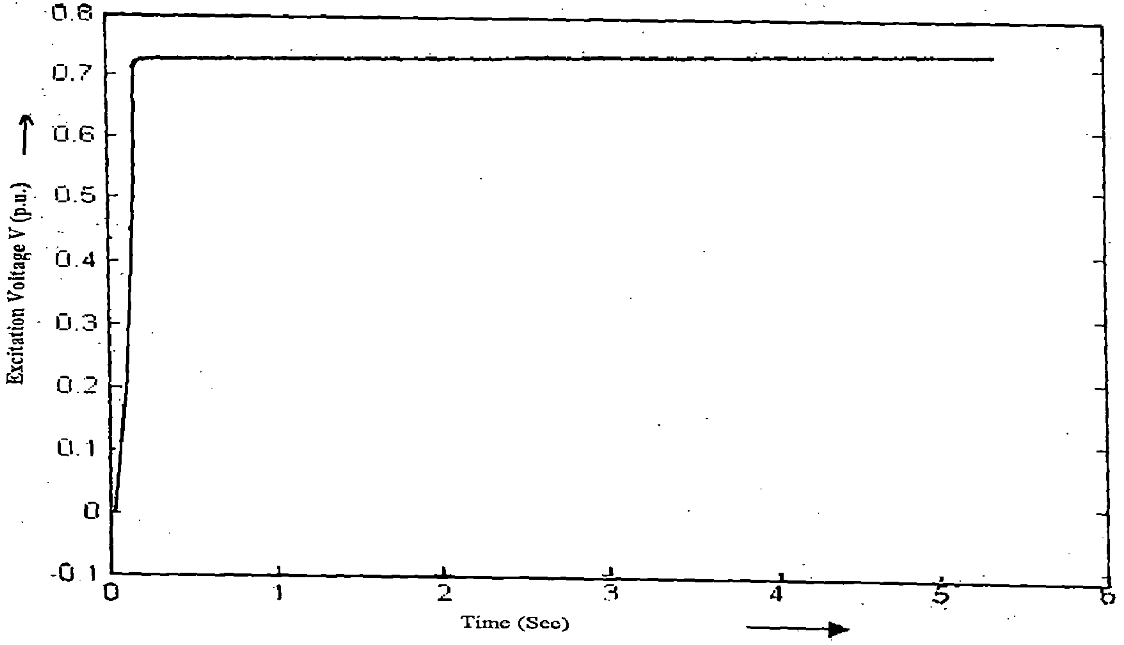


Fig 5.12 Excitation voltage from excitation system

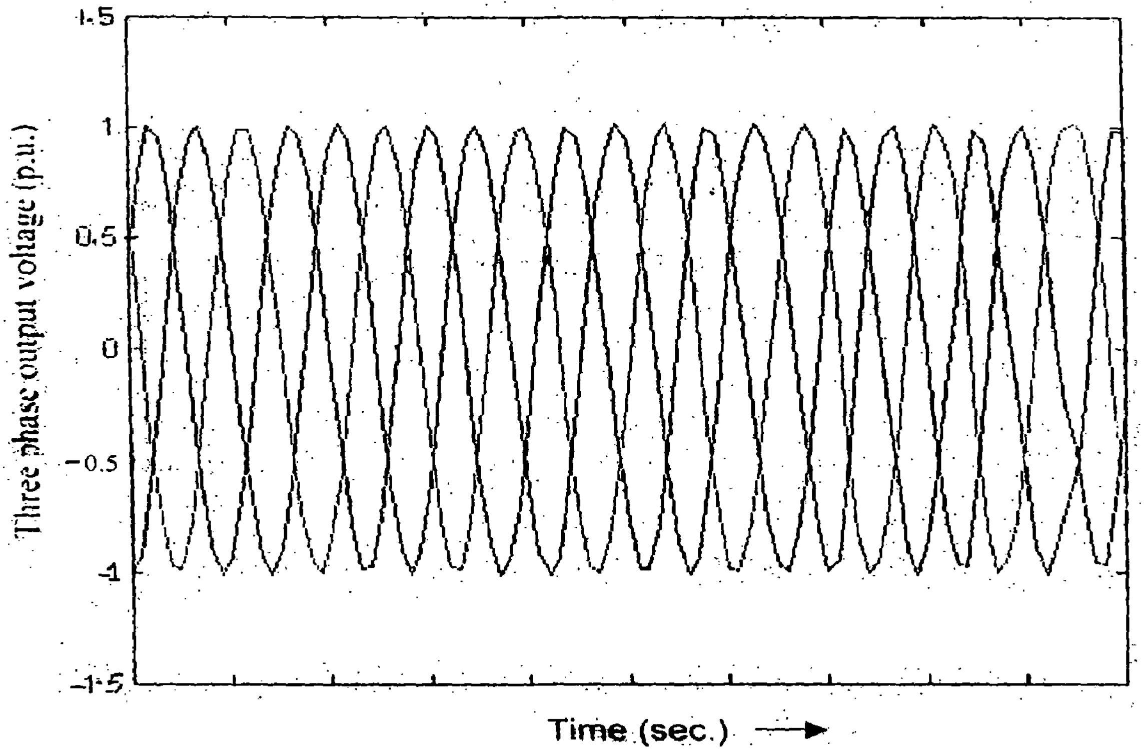


Fig 5.13 Three-phase Output Voltage

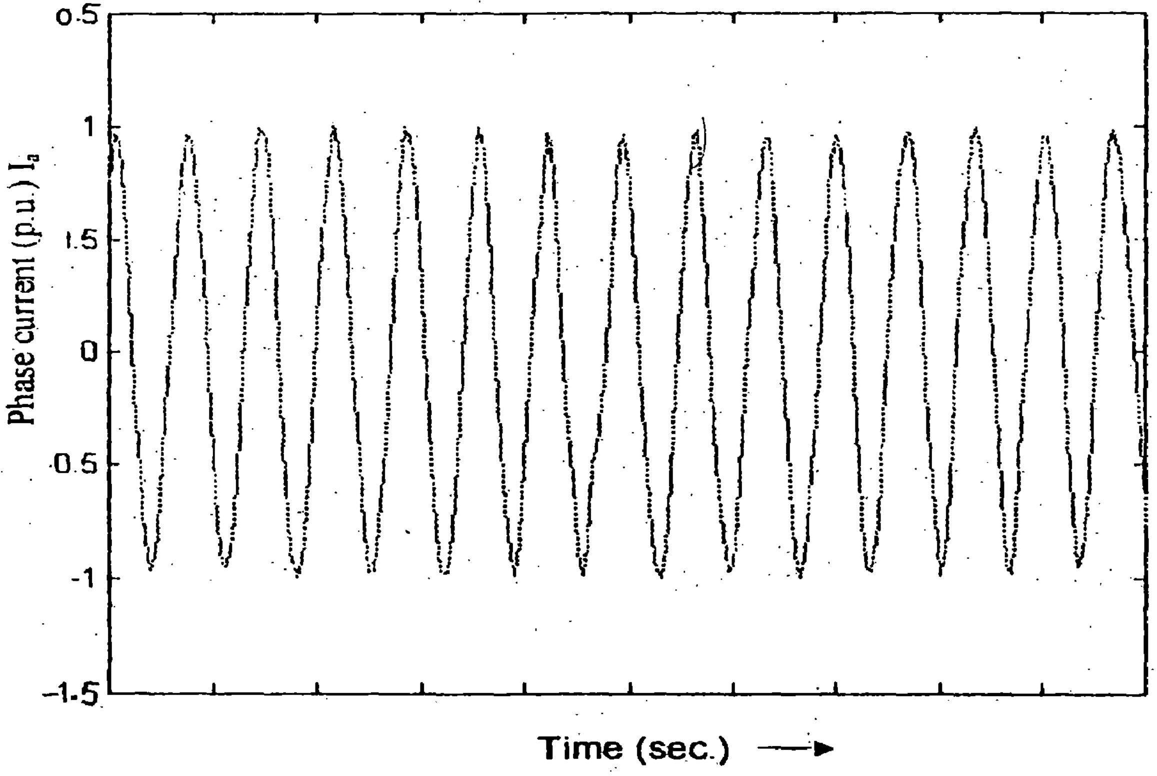


Fig 5.14 Phase Current

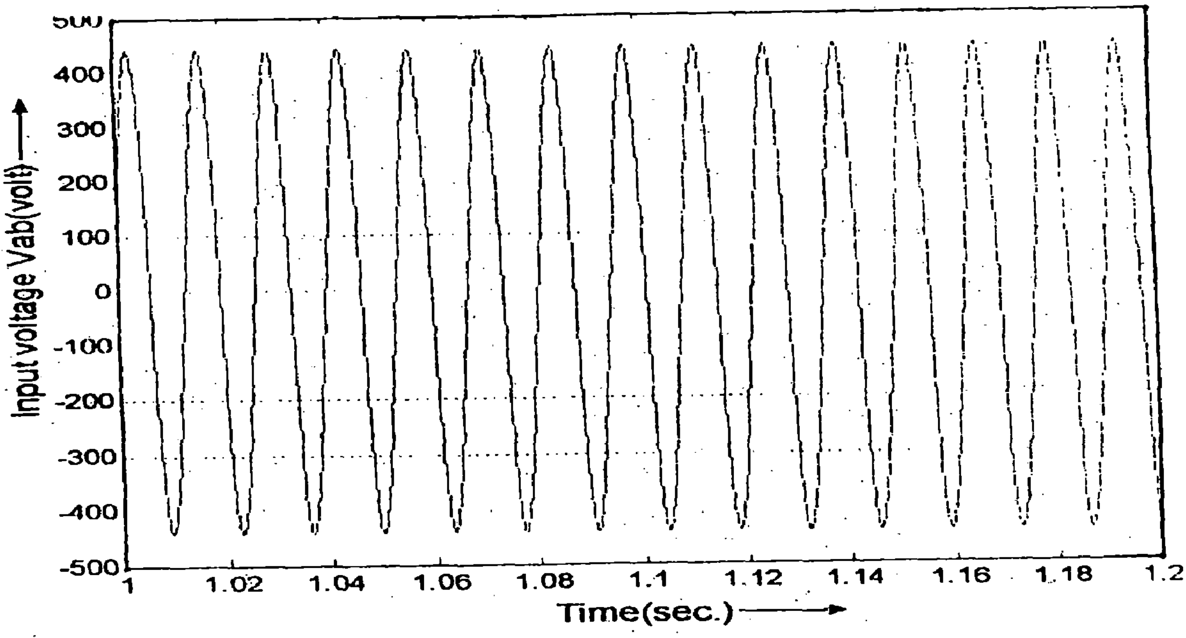


Fig 5.15 Input Voltage to the Rectifier

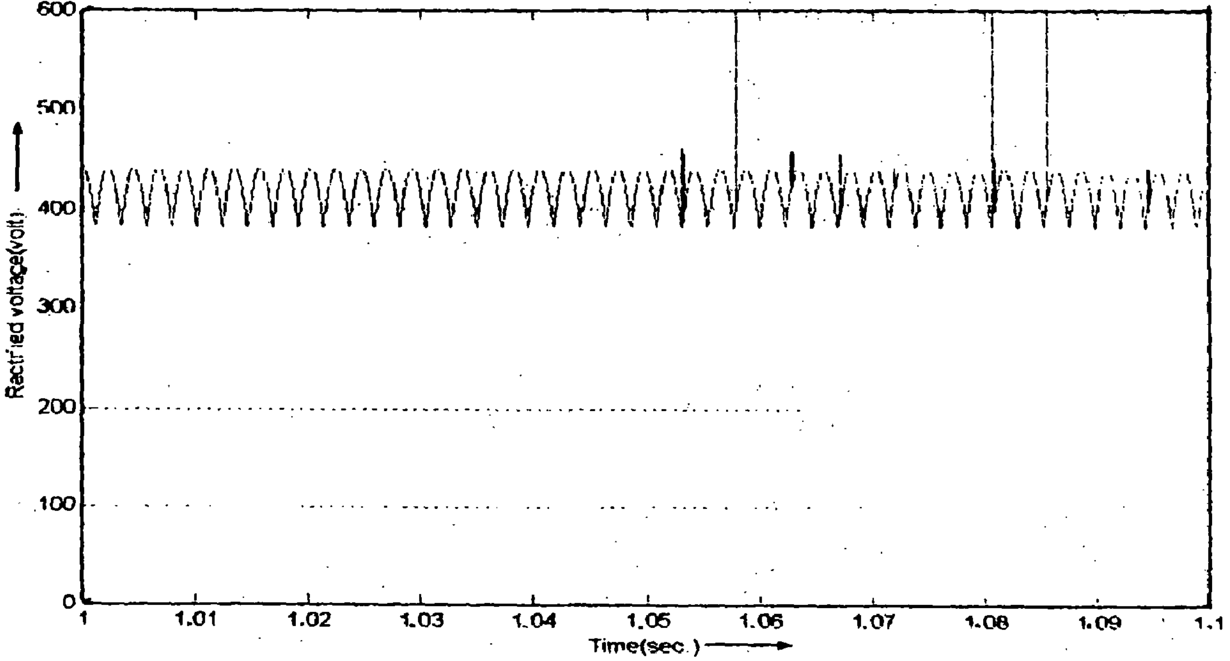


Fig 5.16 Rectifier Output Voltage

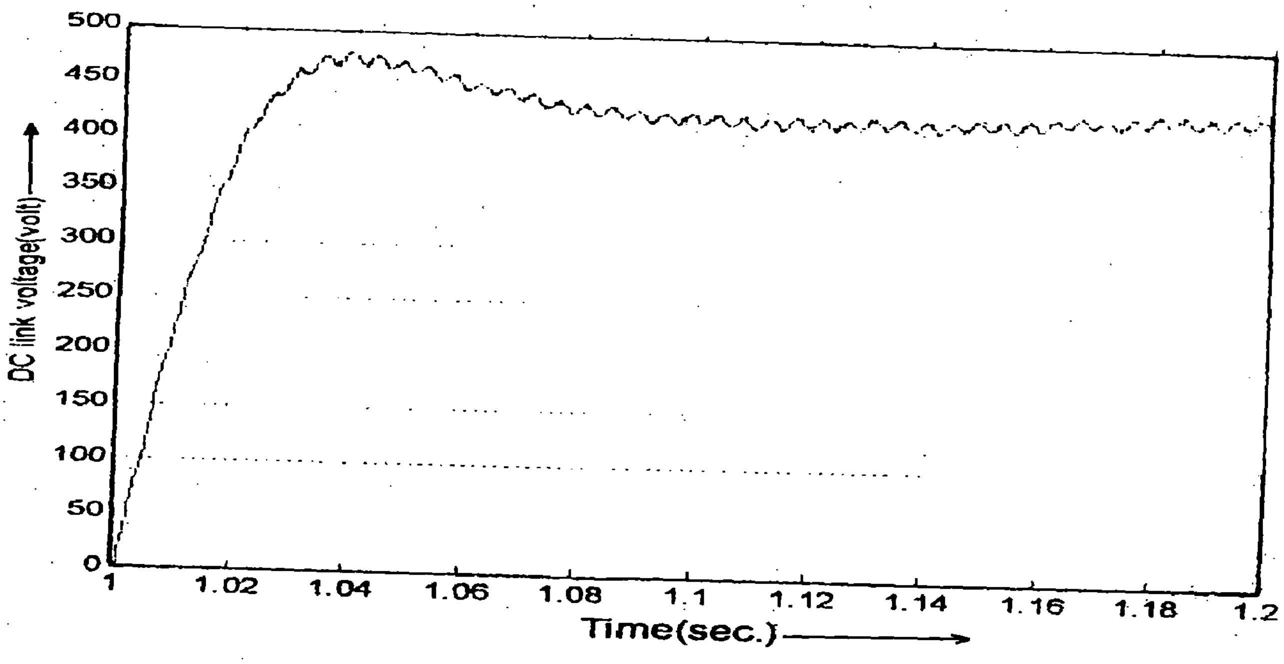


Fig 5.17 Rectified dc Voltage across capacitor

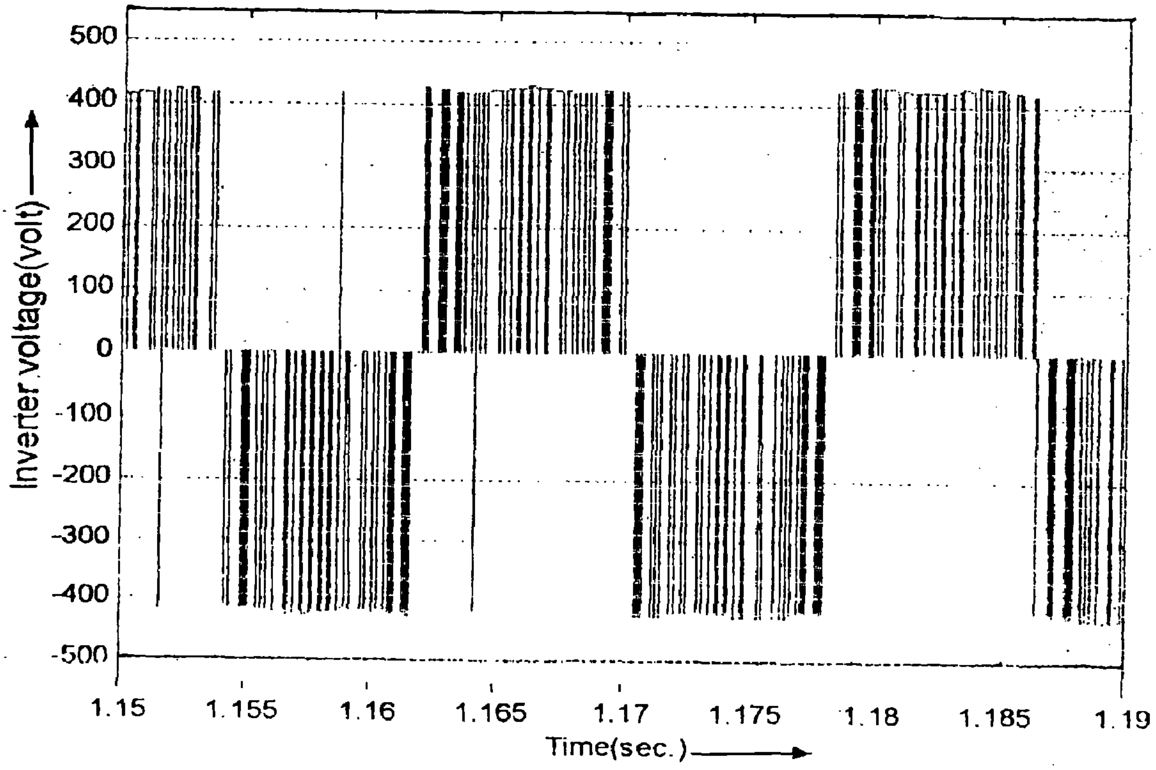


Fig 5.18 Inverter Output Line Voltage

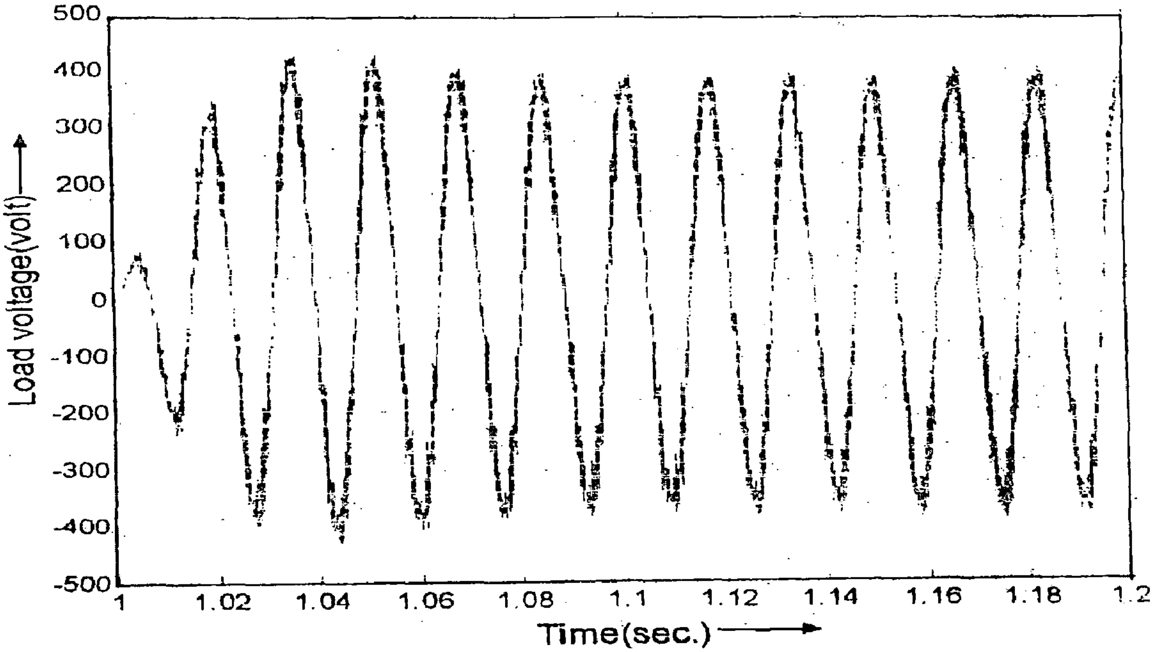


Fig 5.19 Load Voltage (Vab)

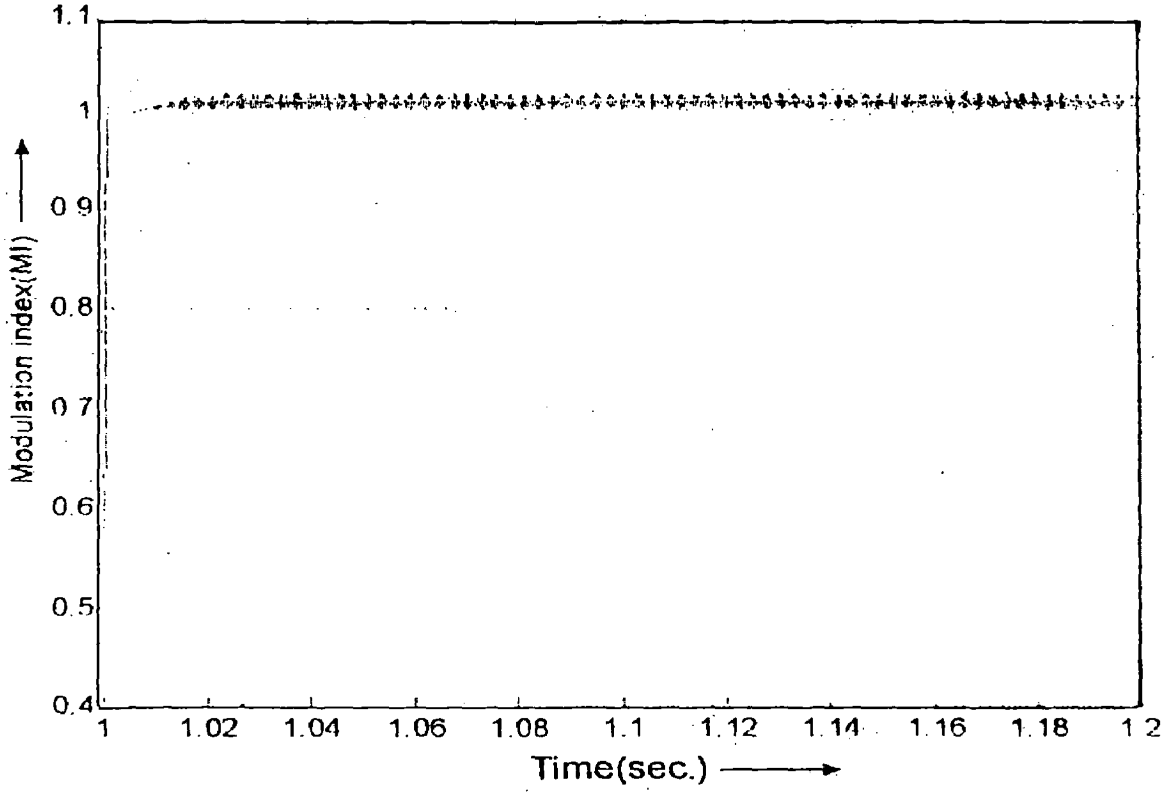


Fig 5.20 Modulation Index

CHAPTER – 6

CONCLUSION

Various schemes using synchronous and induction generator with converter for power generator for variable speed constant frequency generation are available in literature. In present work, synchronous generator with exciter is considered as variable speed constant frequency generator. A hardware of VSCF power conversion scheme has been fabricated. Also a simulink based model for synchronous generator has been developed and simulated under various load conditions. A three-phase rectifier is connected with the various frequency and voltage source to convert it into fixed voltage across a large capacitor. A sinusoidal pulse width modulation is connected for control harmonics and keep the output voltage at constant frequency supply. The performance of the load PWM inverter under various conditions is studied. An algorithm for tracking peak power has been discussed.

Future work:

The model developed for synchronous generator and the inverter model with load may be integrated. The effect of speed on excitation current of the exciter and voltage of generator may be studied to judge the suitability of the exciter under variable load conditions.

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APPENDIX – A

VARIOUS PHOTOGRAPHS OF DEVELOPED VSCF SCHEME

The PCB maps for different modules used in VSCF power conversion scheme are given below.

A. Bottom copper layer of module 1 (dc Supply)

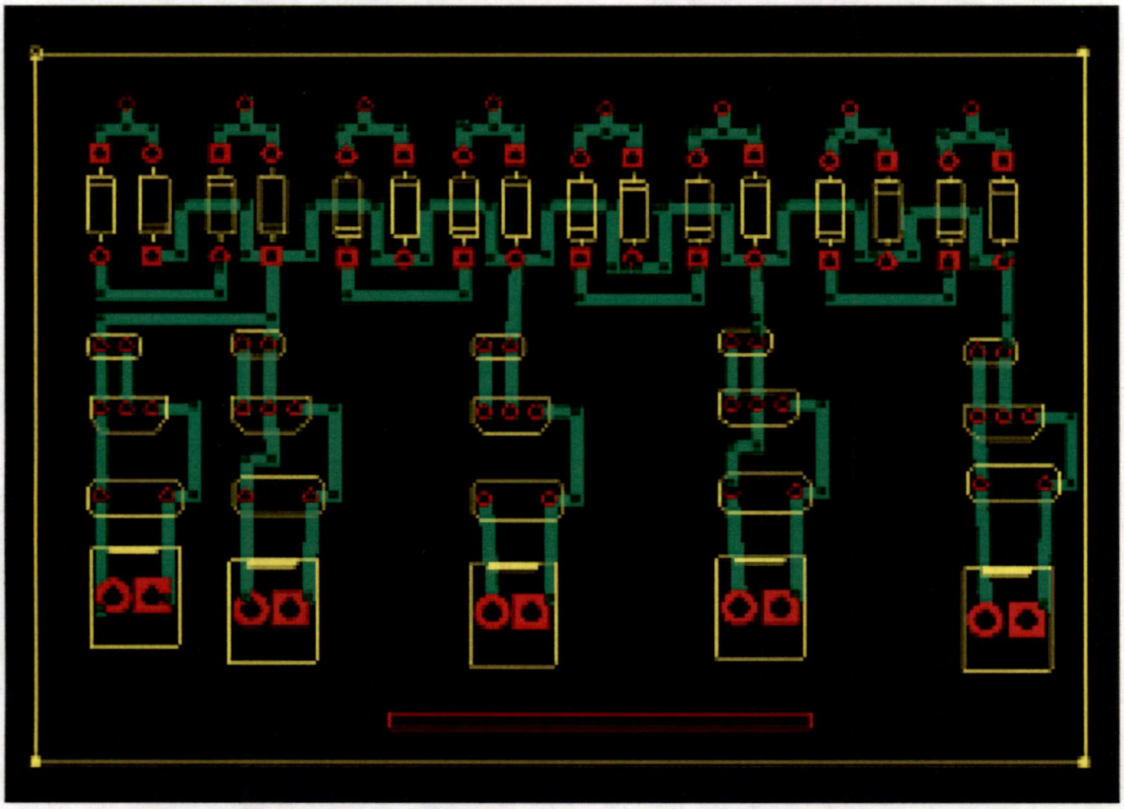

Fig A-1. An actual size, single side PCB for module1

B. Bottom copper layer for module 2 (Firing Pulse Generator Circuit)

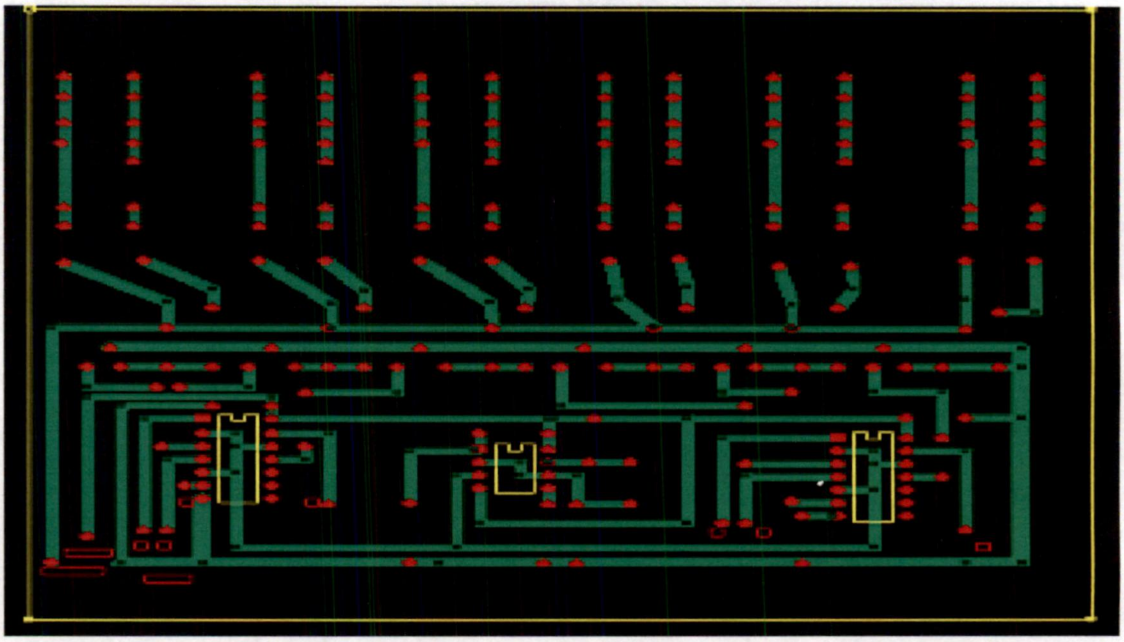

Fig A-2 An actual size, single side PCB for module 2

C. Bottom copper layer for module 3 (Signal Generator For Firing Circuit)

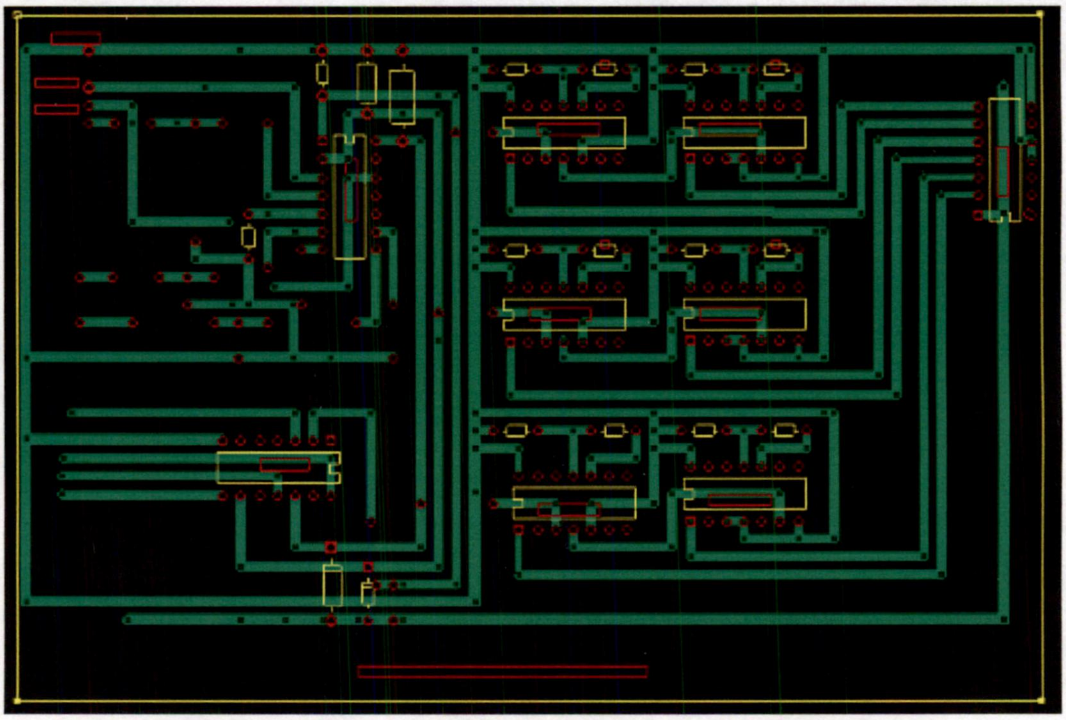

Fig A-3 An actual size, single side PCB for module 3

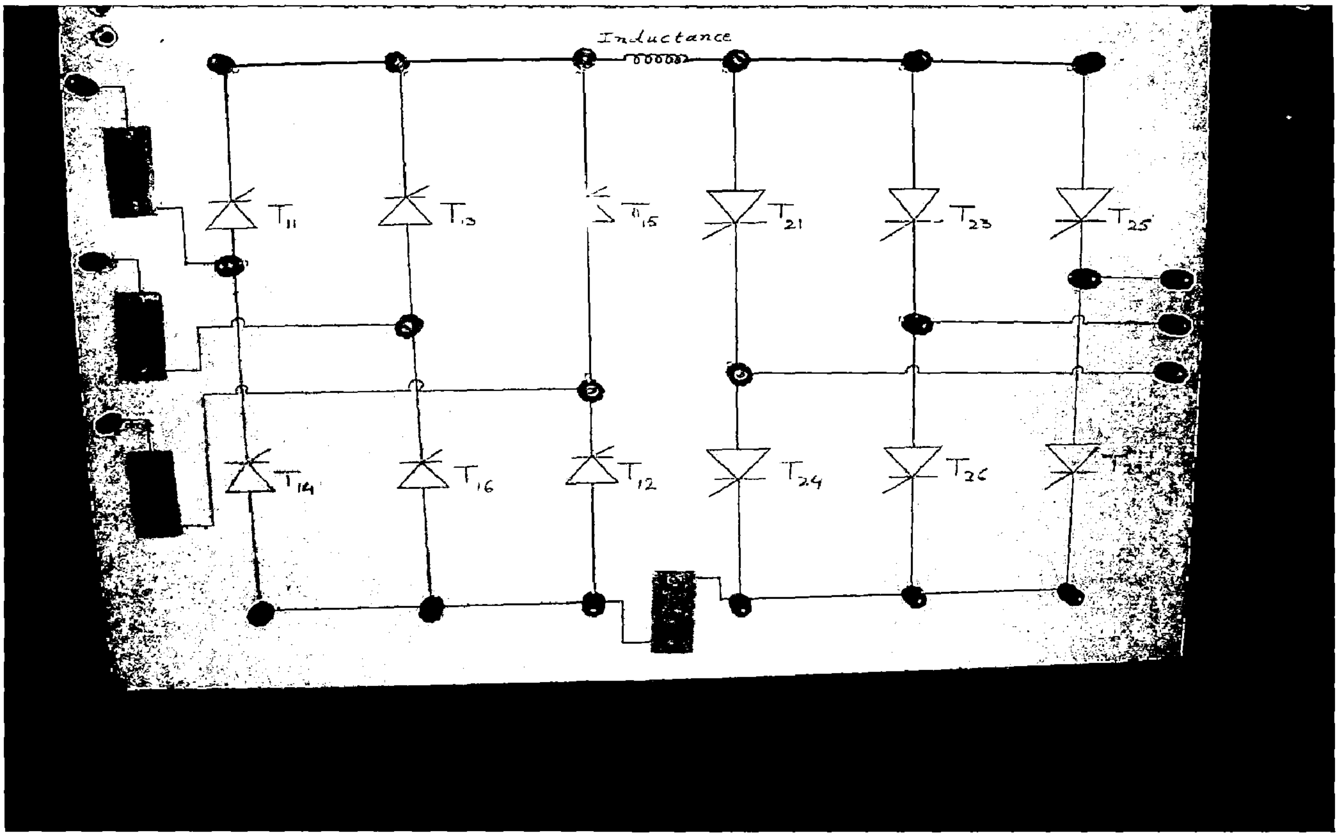

Fig A-4 VSCF Power Conversion Scheme

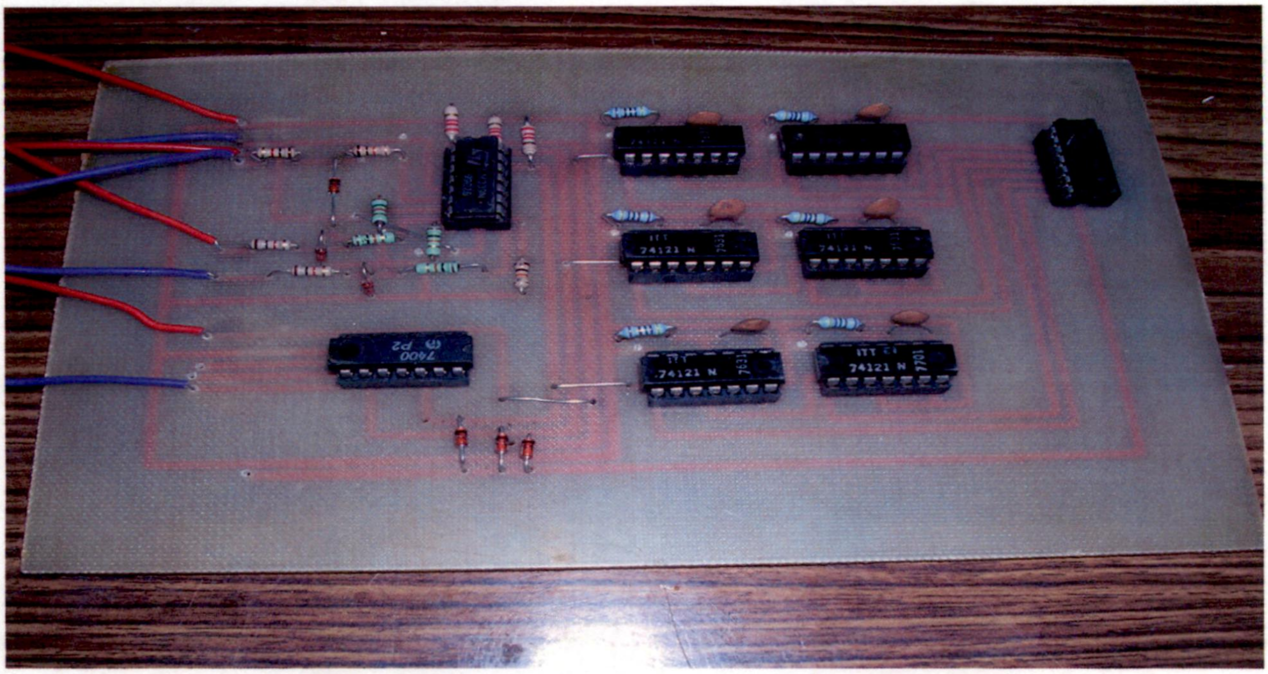

Fig A-5 Signal Generator For Firing Circuit

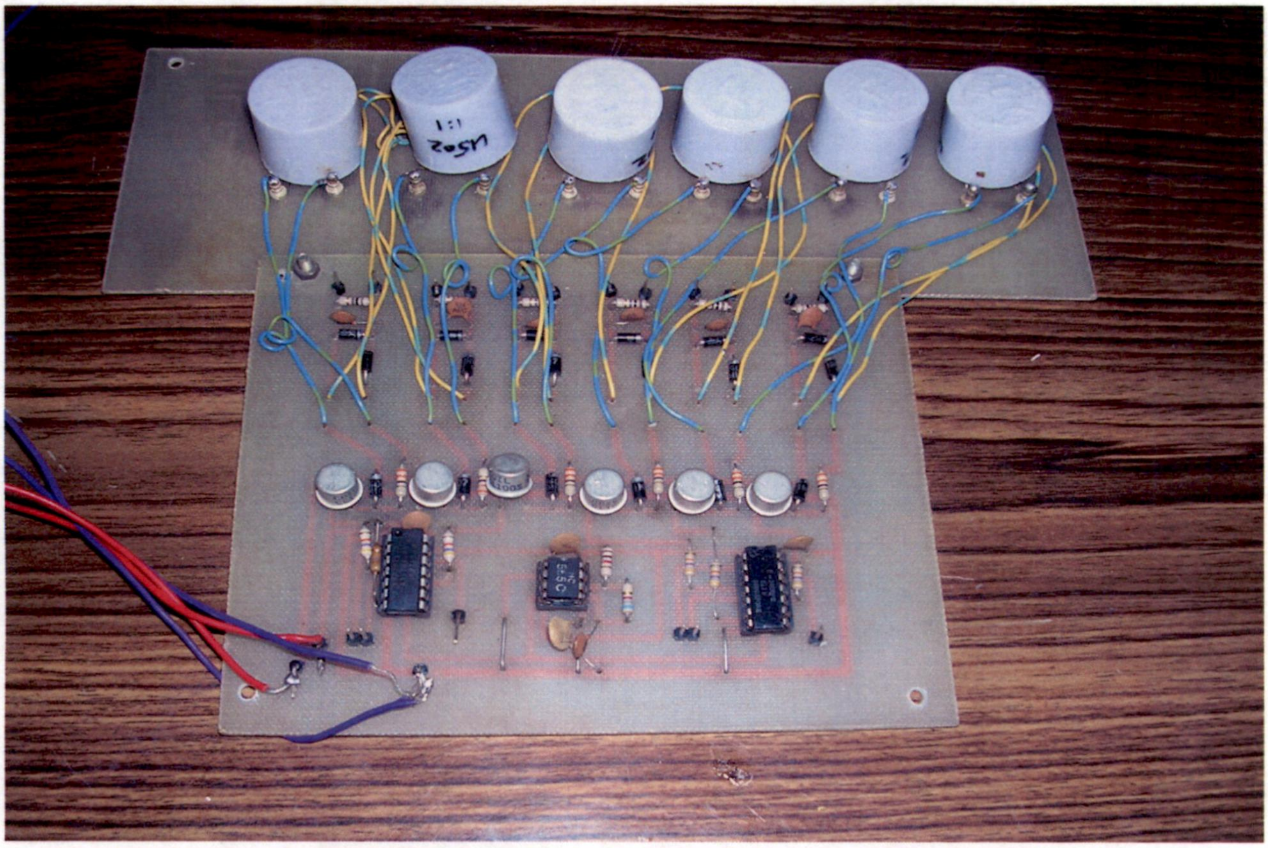

Fig A-6 Firing Pulse generator circuit

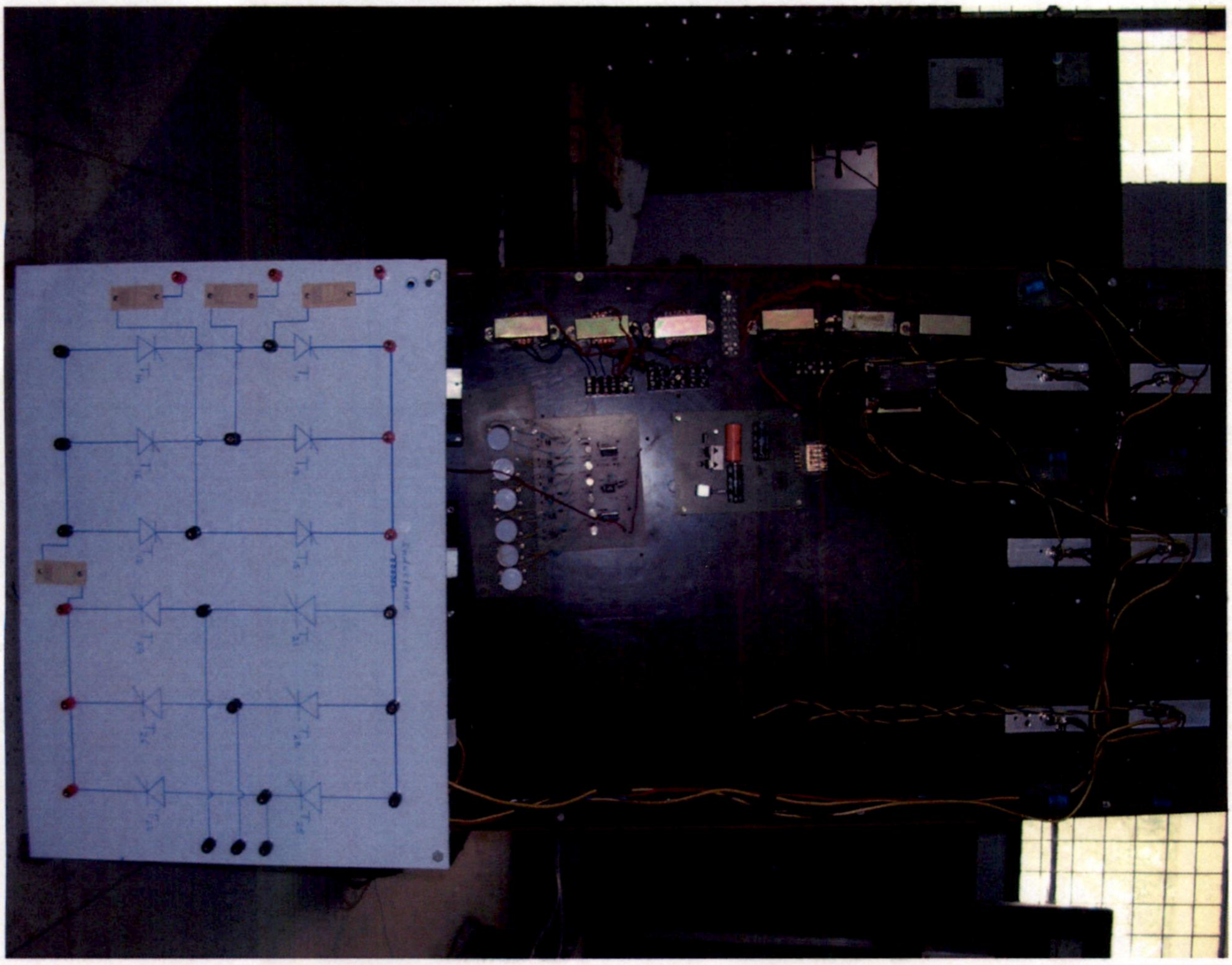

Fig A-7 VSCF system configuration