A Novel Circuit Configuration for Reactive Power Compensation in Induction Generators

A Project Report

Submitted by

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in partial fulfillment for the award of the degree

of

Master of Engineering

in

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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

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COIMBATORE – 641 049

(An Autonomous Institution Affiliated to Anna University of Technology, Coimbatore.)

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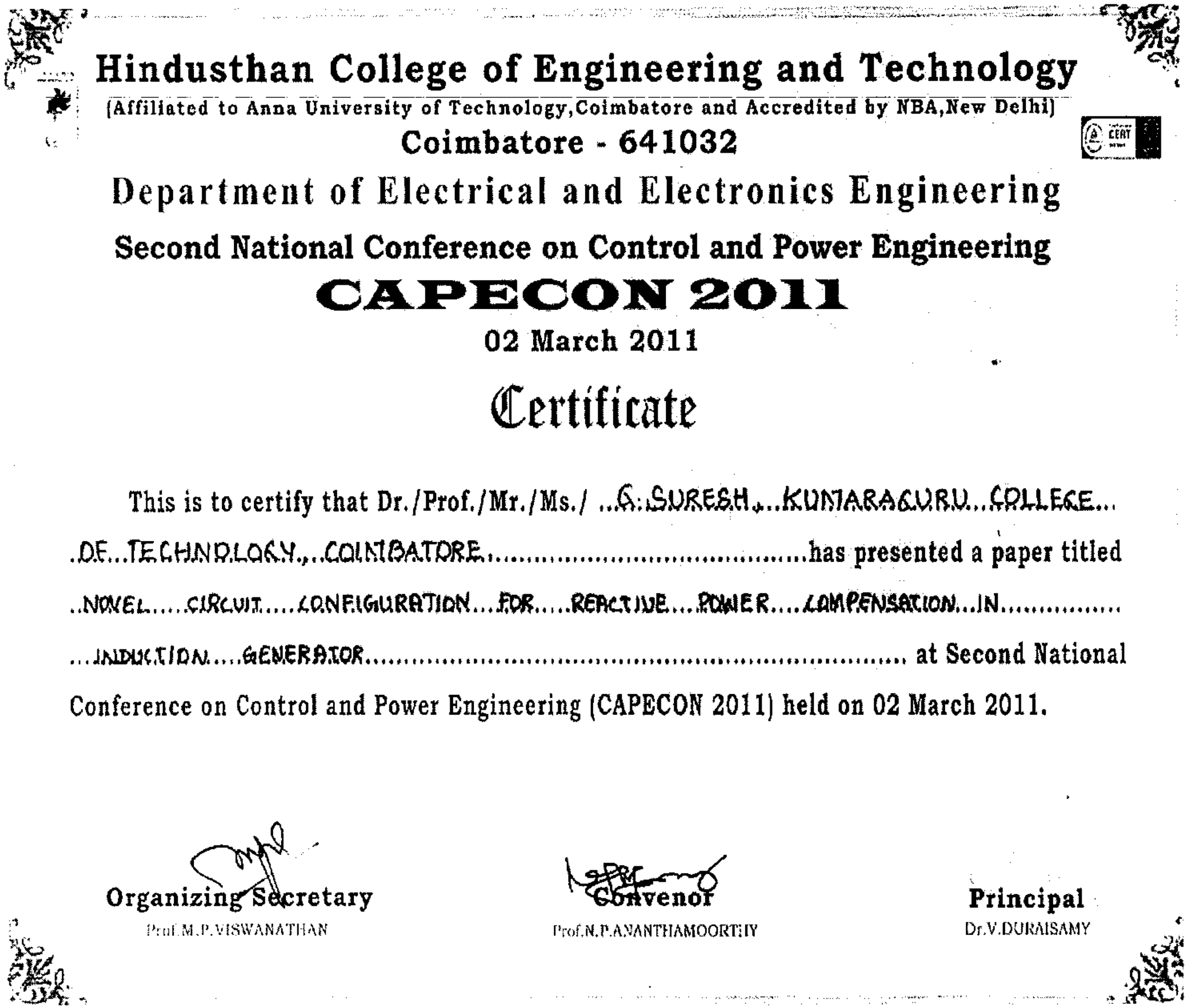

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ABSTRACT

A novel circuit configuration for compensating for the reactive power of an induction generator is proposed in this paper. This reactive power compensator includes an ac power capacitor set serially connected to a small-capacity power converter. The ac power capacitor is adapted to provide basic reactive power and reduce the voltage rating and power capacity of the power converter. Because, the ac power capacitor set can also effectively block the dc voltage generated by the power converter to the utility, the salient point of the proposed reactive power compensator is that only a two-arm structure is required for the power converter in the three-phase three-wire application. Consequently, the required number of power electronic switches for the power converter is reduced. The current, generated by the induction generator system, supplied back to the utility is sinusoidal and in phase with the utility voltage following compensation of the proposed reactive power compensator.

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ABREVIATIONS

DC	-	Direct Current
STATCOM	-	Static Synchronous Compensator
PWM	-	Pulse Width Modulation
PCC	-	Point of Common Coupling
THD	-	Total Harmonic Distortion

CHAPTER 1

CHAPTER I

INTRODUCTION

1.1 INTRUDUCTION

The conventional energy sources for electrical power generation are hydrogen electric, fossil fuels, and nuclear energy. However, the earth's environment has been seriously damaged due to the use of these energy sources and since the supply of fossil fuels will be exhausted in the future, their costs will increase evidently. Hence, renewable energy sources, such as wind and solar are becoming increasingly important. Because the cost of wind power is dropping very fast to the point where it is very close in cost to conventional electric power generation, wind power use has recently rapidly increased worldwide. The induction generator is generally applied in the wind turbine industry. Based on the rotor construction, induction generators can be divided into wound-rotor induction generators and squirrel-cage induction generators. The stator of wound-rotor induction generators is directly connected to the utility grid, and the rotor is also connected to the utility grid through a power converter set. Since both the stator and rotor of wound-rotor induction generators can transfer power, they are also termed as double-fed induction generators. The rotor speed of a double-fed induction generator can be higher or lower than the synchronous speed, hence, the double-fed induction generator can operate under a wide range of wind speed. The stator of a squirrel-cage induction generator is also connected to the utility grid. Since the rotor of a squirrel-cage induction generator cannot be controlled, the squirrel-cage induction generator can only operate under rotor speeds higher than the synchronous speed. Therefore, the range of wind speed that can be used to generate power is limited. Although the range of wind speed for the squirrel-cage induction generator is limited, the squirrel cage induction generator still has some advantages, such as low cost, small size, ruggedness, brushless design, ease of maintenance, as well as self-protection against severe overloads and short circuits. Establishing a magnetic field in the rotor of a squirrel-cage induction generator requires an external reactive power supply to sustain self-excitation. This reactive power can be supplied from the utility in a grid-connected squirrel-cage induction generator, although, this results in a very low power factor. Because most interconnection standards, specify that the power factor of renewable generation must be higher than 0.95, an extra reactive power compensator is required while using the squirrel-cage induction generator.

Furthermore, the reactive power of the induction generator varies significantly due to the variation in the rotor speed. Hence, a reactive power compensator, which can adjust the reactive power along with variations in wind speed, is required to obtain a high power factor for the squirrel-cage induction generator. AC power capacitors are usually used to supply leading power to compensate for the power factor. In order to properly adjust the reactive power provided by ac power capacitors, an automatic power factor regulator (APFR) was developed. The reactive power supplied from the APFR can be adjusted by changing the total number of ac power capacitors that are switched on. Furthermore, the reactive power compensation can be adjusted linearly by controlling the firing angle of the thyristor switch in other technology, such as fixed-capacitor thyristor-controlled-reactor (FC-TCR). However, this method will generate a harmonic problem, because the thyristor switch cannot conduct a full cycle. On the other hand, harmonic pollution in the industrial power system has seriously increased due to the wide use of nonlinear loads. Hence, a reactive power compensator, which can adjust the reactive power along with variations in wind speed, is required to obtain a high power factor for the squirrel-cage induction generator.

Therefore, controllable reactive power (VAR) supporters, such as Static Synchronous Compensators (STATCOM) are in some cases necessary to provide dynamic voltage support with their actively controllable VAR injection, especially under voltage depression. This paper presents results from the investigation into the impact of installing a STATCOM at an existing wind farm. This wind farm consists of fixed speed induction generators and is integrated through a weakly connected utility system. A STATCOM is to be installed at the Point of Common Coupling (PCC), where the wind farm is integrated with the utility system. It utilizes a new power electronic device, the Gate Turn-Off Thyristor (GTO), for enhanced high-power switching performance, simplified triggering technology, and overall reduced device and system costs. The STATCOM is connected at the Point of Common Coupling (PCC). The STATCOM is modeled as three controllable voltage sources.

The controllers of the STATCOM are designed according to commonly known control principles. The outputs of the STATCOM controller are amplified and used as the controllable inputs of the three-phase voltage source. If the STATCOM source voltage is larger than the voltage at the PCC (V_{PCC}), the STATCOM generates reactive power. Otherwise, the STATCOM withdraws reactive power.

Since, the ac power capacitor for power factor correction provides a low impedance path for the harmonic current, ac power capacitors are frequently damaged by harmonics. In addition, it results in harmonic resonance between the power capacitor and the distribution

power system. As a result, the power capacitor may be damaged due to there being too much voltage or current. Furthermore, the may damage the neighbouring electrical power facilities and even result in public accidents. In order to solve the application problems of the ac power capacitors used for reactive power compensation, the power converter- based reactive power compensator was previously developed. Accordingly, the power converter can provide either a leading reactive power or a lagging reactive power by controlling its operation. This means that the reactive power can be adjusted linearly. Advantageously, no power resonance problem occurs between the power converter and the distribution power system, and there is no problem of harmonic current injection due to the neighbouring nonlinear loads. However, the power converter is employed to provide overall reactive power compensation in response to the full load, and the capacity of the power converter is large. This paper proposes a novel circuit configuration for compensating for the reactive power of the induction generator. This reactive power compensator employs an ac power capacitor set serially connected to a power converter. The proposed reactive
Power compensator has the following advantages:

1) no power resonance problems;
2) small capacity of power converter;
3) less power electronic switches in the power converter.

The current, generated by the induction generator system, fed back to the utility is sinusoidal and in phase with the utility voltage following compensation of the proposed reactive power compensator. A prototype is developed and tested to verify the performance of the proposed reactive power compensator.

1.2 OBJECTIVES OF THE PROJECT

The Wind farms are becoming important distributed renewable energy resources. However, voltage stability issues with wind farms employing fixed-speed induction generators may require such systems to be augmented with dynamic compensation devices, such as STATCOM units. The induction generator absorbs reactive power during starting so the stability of the system affected. In the wind farm induction generators are connected in series it actually absorb more reactive power from the system. So the voltage collapse occurs in the system and it also reduces the power factor of the system. To improve the system stability we are going for STATCOM. The STATCOM is introduced at the point of common coupling to come across this disadvantages present in the existing system. The purpose of including STATCOM in the system is to provide reactive power to the induction generators while it starting. The load may be inductive or capacitive in nature and it also consumes inductive or capacitive power from the supply. Depending upon system needs the STATCOM provide or absorb the reactive power from the system. The control signal to the STATCOM is generated based on the system reference.

The proposed power converter is connected at the point of common coupling where the STATCOM is connected in the circuit. The proposed power converter has the two arm structure and it reduces the number of switches required for the power converter. The proposed power converter is used for replacement for the STATCOM in the power circuit. The circuit configuration of the proposed reactive power compensator applied to the three-phase three-wire induction generator system. The three-phase three-wire induction generator is driven by a wind turbine and generates power for the utility, and the reactive power compensator is used to supply reactive power to the induction generator. So the real power is flowing into the utility. The proposed reactive power compensator consists of an ac power capacitor set serially connected to a power converter. The ac power capacitor set provides fundamental reactive power and is also used to withstand the major fundamental component of the utility voltage that may reduce the capacity of the power converter. And the ac power capacitor set can also block the dc voltage generated from the power converter to the utility. The power converter is used to solve the harmonic problems of the ac power capacitor, and it permits the proposed reactive power compensator to provide compensation reactive power. The power converter consists of a dc capacitor, a power electronic switch set, and a filter inductor set. The dc capacitor acts as an energy buffer, and provides dc voltage for normally operating the power converter.

1.3 PROBLEM DEFINITION

The induction generator absorbs reactive power during starting so the stability of the system affected. In the wind farm induction generators are connected in series it actually absorb more reactive power from the system. So the voltage collapse occurs in the system and it also reduces the power factor of the system. In existing system to improve the system stability we are going for STATCOM. The purpose of including STATCOM in the system is to provide reactive power to the induction generators while it starting. The load may be inductive or capacitive in nature and it consumes inductive or capacitive power from the supply. Depending upon system needs the STATCOM provide or absorb the reactive power to the system. The control signal to the STATCOM is generated based on the system reference. In proposed system we are using proposed power converter circuit instead of STATCOM at the point of common coupling. The proposed power converter generates the reactive power based on the system needs.

1.4 ORGANIZATION OF THESIS

This gives an overall outline of the project report.

CHAPTER 1

It describes the general introduction, objective and problem definition.

CHAPTER 2

It describes the block diagram of STATCOM and Proposed Power Converter

CHAPTER 3

It describes the Reactive power regulation and the Control Circuit for the Proposed Power Converter

CHAPTER 4

It includes the introduction MATLAB (simulink), simulation details of individual block and simulation results of the system.

CHAPTER 5

It includes the proposed system model and description of all components used in the hardware. It shows the schematic diagram of the hardware and output waveforms and test results.

CHAPTER 6

It gives the conclusion and recommendations for the future work.

CHAPTER 2

CHAPTER 2

METHODOLOGY

2.1 STATCOM

The STATCOM is connected at the Point of Common Coupling (PCC). The STATCOM is modeled as three controllable voltage sources. The controllers of the STATCOM are designed according to commonly known control principles. The outputs of the STATCOM controller are amplified and used as the controllable inputs of the three-phase voltage source. If the STATCOM source voltage is larger than the voltage at the PCC (V_{PCC}), the STATCOM generates reactive power. Otherwise, the STATCOM withdraws reactive power. The power is controlled by the voltage angle difference between the STATCOM and the PCC.

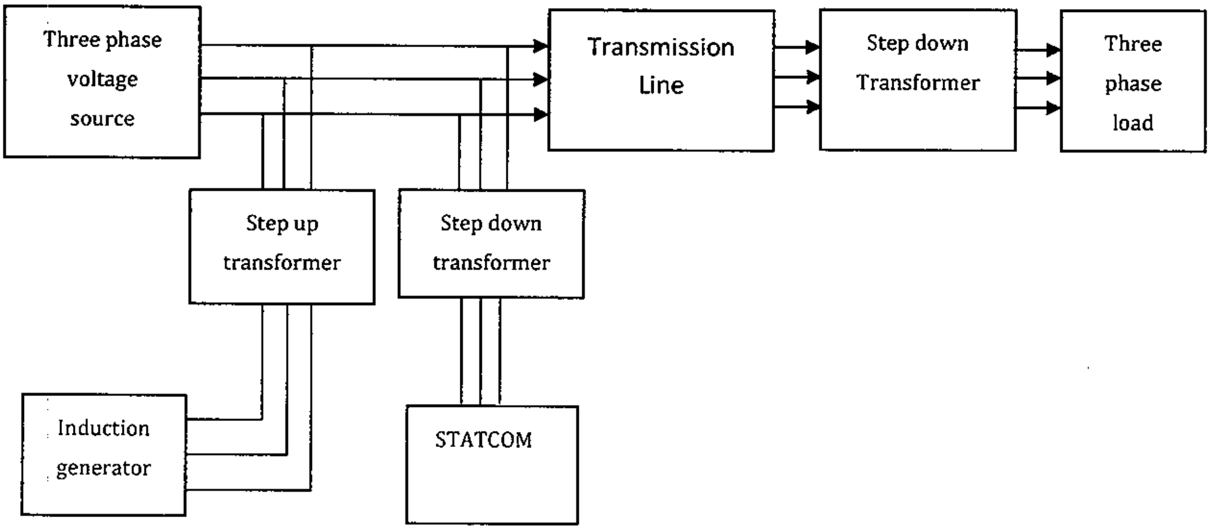

Fig.2.1 Block Diagram of STATCOM

The power is controlled by the voltage angle difference between the STATCOM and the PCC. In this study, the real power request from the DC link capacitor voltage control is always zero ($V_{DC} = V_{DCref}$). STATCOM based on VSI (voltage source inverter) is a synchronous voltage source connected to the utility mains in parallel through a link reactor (L_l) as shown in the Fig.2.1.

Injection and absorb of reactive power as explained in Fig.2.2, inverter output voltage should be controlled to inject or absorb the reactive current on STACOM. Inverter output voltage of VSI can be generally expressed by equation.

$V_{invpeak} = MI\ V_{dc}$ (1)

where, $v_{invpeak}$ -> inverter output voltage (peak) [V],

MI-> modulation index of switching pattern,

Vdc->dc capacitor voltage [V],

From the equation (1), there are two different methods of controlling the inverter output voltage to generate the leading or lagging reactive power from VSI. One is to change the dc capacitor voltage indirectly by controlling the phase angle between inverter output voltage and source voltage of utility mains. STATCOM without independently regulated dc source can be controlled by this method. The other is to control the modulation index of the inverter switching pattern directly while dc capacitor voltage is separately regulated well by another controller.

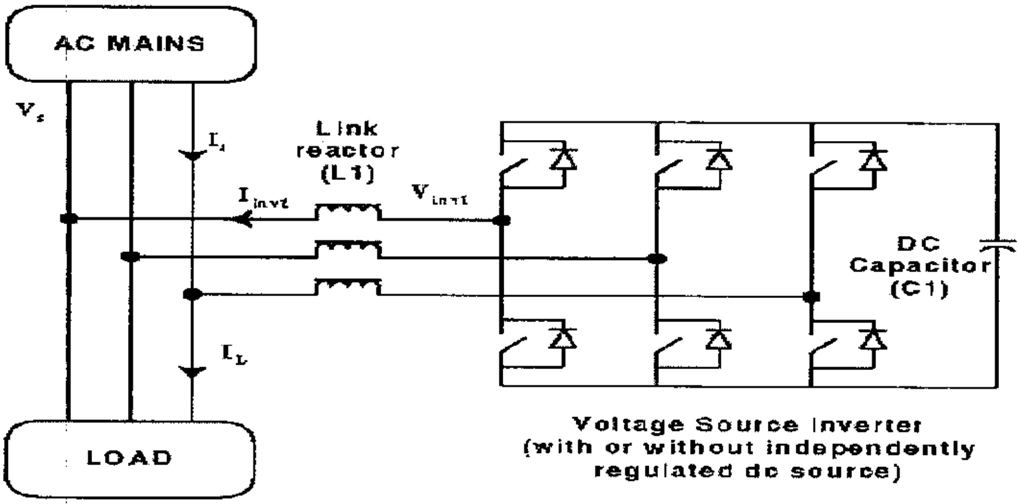

Fig.2.2 STATCOM system based on VSI

STATCOM with independently regulated dc source can be controlled by this method. To achieve more fast dynamic response of reactive power compensation while dc capacitor voltage is regulated well, modulation index control for the required reactive power generation and phase angle control for the regulation of dc capacitor voltage can be done at the same time.

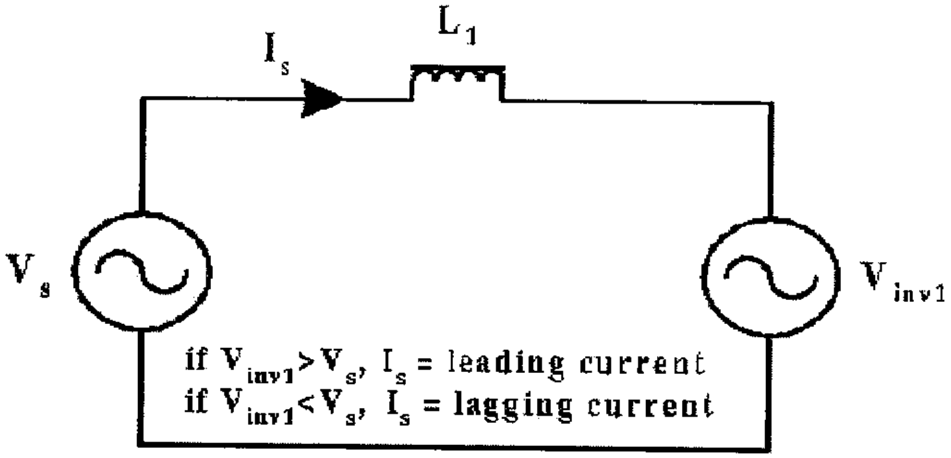

Fig.2.3. Single phase equivalent circuit

The STATCOM is a device connected in power system, basically composed of a coupling transformer, that serves of link between the electrical power system (EPS) and the voltage synchronous controller (VSC), that generates the voltage wave comparing it to the one of the electric system to realize the exchange of reactive power. The control system of the STATCOM adjusts at each moment the inverse voltage so that the current injected In the network is in quadrature to the network voltage, in these conditions P=0 and Q=0. In its most general way, the STATCOM can be modeled as a regulated voltage source Vi connected to a voltage bar Vs through a transformer.

The figure shows the equivalent circuit of a STATCOM system. The GTO converter with a dc voltage source and the power system are illustrated as variable ac voltages in this figure. These two voltages are connected by a reactance representing the transformer leakage inductance. Using the classical equations that describe the active and reactive power flow in a line in terms of Vi and Vs, the transformer impedance (which can be assumed as ideal) and the angle difference between both bars, we can defined P and Q. The angle between the Vs and Vi in the system is d. When the STATCOM operates with d=0 we can see how the active power send to the system device becomes zero while the reactive power will mainly depend on the voltage module.

This operation condition means that the current that goes through the transformer must have a +/-90° phase difference to Vs. In other words, if Vi is bigger than Vs, the reactive will be send to the STATCOM of the system (capacitive operation), originating a current flow in this direction. In the contrary case, the reactive will be absorbed from the system through the STATCOM (inductive operation) and the current will flow in the opposite direction. Finally if the modules of Vs and Vi are equal, there won´t be nor current nor reactive flow in the system. Thus, we can say that in a stationary state Q only depends on the module difference between Vs and Vi voltages. The amount of the reactive power is proportional to the voltage difference between Vs and Vi.

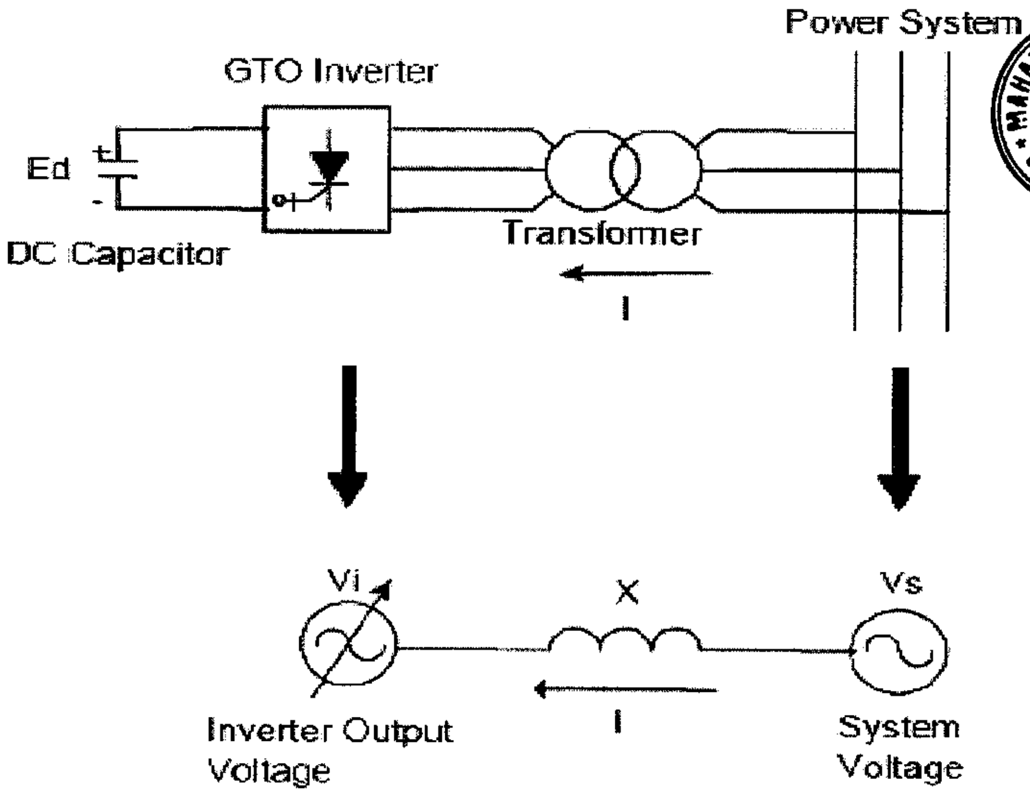

Fig.2.4. Equivalent circuit of STATCOM

There can be a little active power exchange between the STATCOM and the EPS. The exchange between the inverter and the AC system can be controlled adjusting the output voltage angle from the inverter to the voltage angle of the AC system. This means that the inverter cannot provide active power to the AC system form the DC accumulated energy if the output voltage of the inverter goes before the voltage of the AC system. On the other hand, the inverter can absorb the active power of the AC system if its voltage is delayed in respect to the AC system voltage.

2.2 THE PROPOSED POWER CONVERTER

The proposed power converter is connected at the point of common coupling where the STATCOM is connected in the circuit. The proposed power converter has the two arm structure and it reduces the number of switches required for the power converter. The Fig.2.5 shows that the proposed power converter is used for replacement for the STATCOM in the power circuit. The circuit configuration of the proposed reactive power compensator applied to the three-phase three-wire induction generator system. The three-phase three-wire induction generator is driven by a wind turbine and generates power for the utility, and the reactive power compensator is used to supply reactive power to the induction generator. So the real power is flowing into the utility. The proposed reactive power compensator consists of an ac power capacitor set serially connected to a power converter. The ac power capacitor set provides fundamental reactive power and is also used to withstand the major fundamental component of the utility voltage that may reduce the capacity of the power converter.

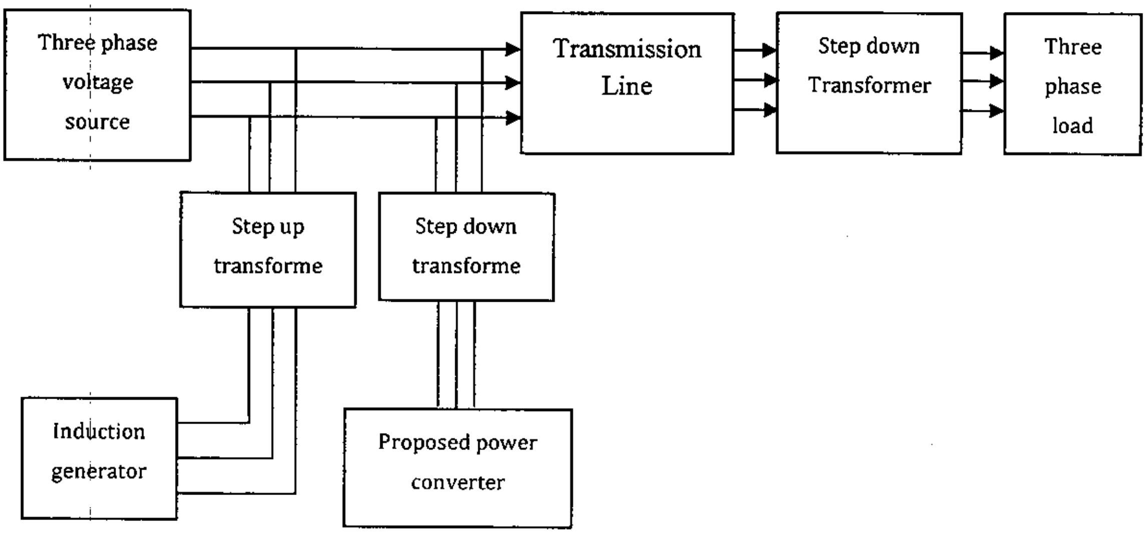

Fig 2.5. Block Diagram of Proposed Power Converter

The ac power capacitor set can also block the dc voltage generated from the power converter to the utility. The power converter is used to solve the harmonic problems of the ac power capacitor, and it permits the proposed reactive power compensator to provide compensation reactive power. The power converter consists of a dc capacitor, a power electronic switch set, and a filter inductor set. The dc capacitor acts as an energy buffer, and provides dc voltage for normally operating the power converter.

2.3 CIRCUIT CONFIGURATION

The circuit configuration of the proposed reactive power compensator applied to the three-phase three-wire induction generator system. The three-phase three-wire induction generator is driven by a wind turbine and generates power for the utility, and the reactive power compensator is used to supply reactive power to the induction generator. Then, only real power is flowing into the utility. The proposed reactive power compensator consists of an ac power capacitor set serially connected to a power converter. The ac power capacitor set provides fundamental reactive power and is also used to withstand the major fundamental component of the utility voltage that may reduce the capacity of the power converter.

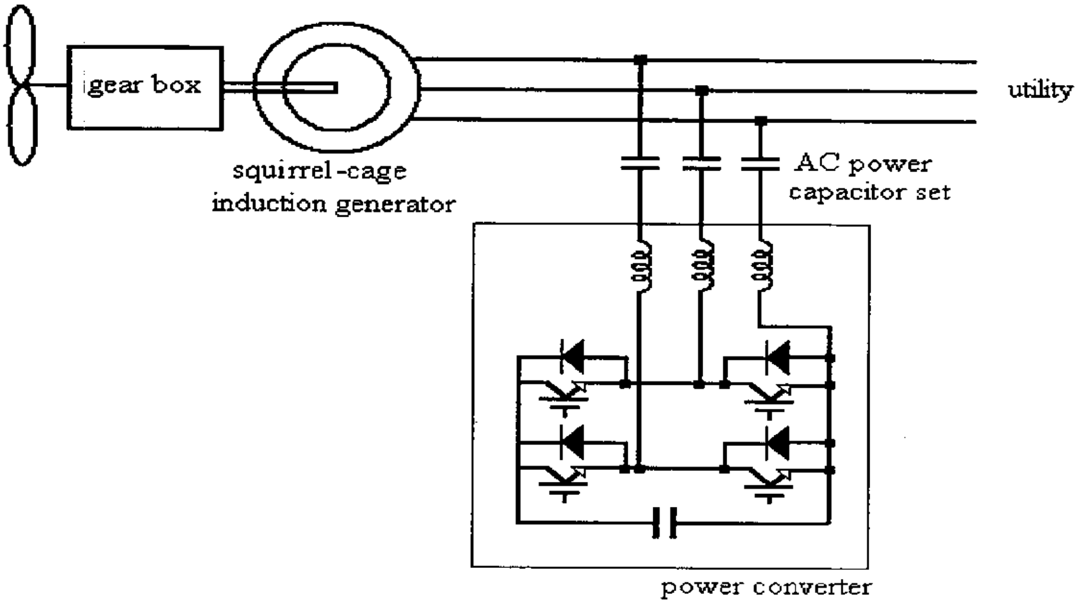

Fig.2.6.Circuit Diagram of Proposed Power Converter

The ac power capacitor set can also block the dc voltage generated from the power converter to the utility. The power converter is used to solve the harmonic problems of the ac power capacitor, and it permits the proposed reactive power compensator to provide compensation reactive power that can be adjusted within a predetermined range in response to the variation in wind speed. The power converter consists of a dc capacitor, a power electronic switch set, and a filter inductor set. The dc capacitor acts as an energy buffer, and provides dc voltage for normally operating the power converter. The power electronic switch set is connected to the dc capacitor, switching the dc voltage to generate a desired compensation current.

Because the ac power capacitor set can effectively block the dc voltage generated from the power converter to the utility, only a two-arm bridge structure is required for the power electronic switch set in the three-phase three-wire system. In consequence, this permits one of the ac power capacitor set to be directly connected to the negative dc terminal of the power electronic switch set through an inductor of filter inductor set without passing any power electronic switches. The filter inductor set is adapted to filter out the high-frequency ripple current due to the switching operation of the power electronic switch set. Due to the existence of the ac power capacitor set, the operating voltage of the dc capacitor and the capacity of the power converter can be reduced, and two power electronic switches can be saved. Thereby, the manufacturing cost of the reactive power compensator is reduced.

CHAPTER 3

CHAPTER 3

REACTIVE POWER REGULATION

3.1 REACTIVE POWER REGULATION

A dc capacitor is connected to the dc bus of the power converter, this power converter is a voltage-source power converter. The voltage-source power converter is controlled by the pulse width modulation (PWM) strategy in which a modulation signal is compared with a high-frequency carrier. In ideal PWM operation, the output voltages $v_{cona}(t)$ and $v_{conb(t)}$ of two-arm power electronic switch set can be represented as

$$v_{cona}(t) = V_{dc}/2 + k_{con}v_{ma}(t) + v_{rpa}(t) \quad (2)$$

$$v_{conb}(t) = V_{dc}/2 + k_{con}v_{mb}(t) + v_{rpb}(t) \quad (3)$$

Where V_{dc} is the dc bus voltage, $v_{rpa}(t)$ and $v_{rpb}(t)$ are the switching ripple voltages, $v_{ma}(t)$ and $v_{mb}(t)$ are the modulation signals, and k_{con} is the gain of the power converter. The gain of the power converter can be represented as

$$k_{con} = V_{dc}/2V_{car} \quad (4)$$

Where V_{car} is the amplitude of the high frequency carrier. The frequency of switching ripple voltages is centred on the integer-times carrier frequency. Since the switching frequency of the power converter is very high compared with the interesting harmonic frequency of power system analysis, it can be effectively filtered out by the filter inductor set. Hence, the switching ripple voltages of power converter can be neglected in the following discussion. Consequently, only two components of power converter output voltages, dc component and low frequency ac components, are considered. Fig.3.1 is the dc equivalent circuit of the proposed reactive power compensator.

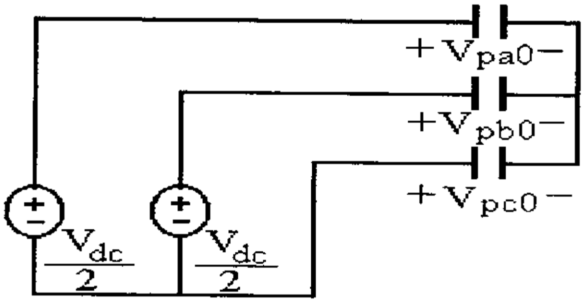

Fig. 3.1. DC equivalent circuit.

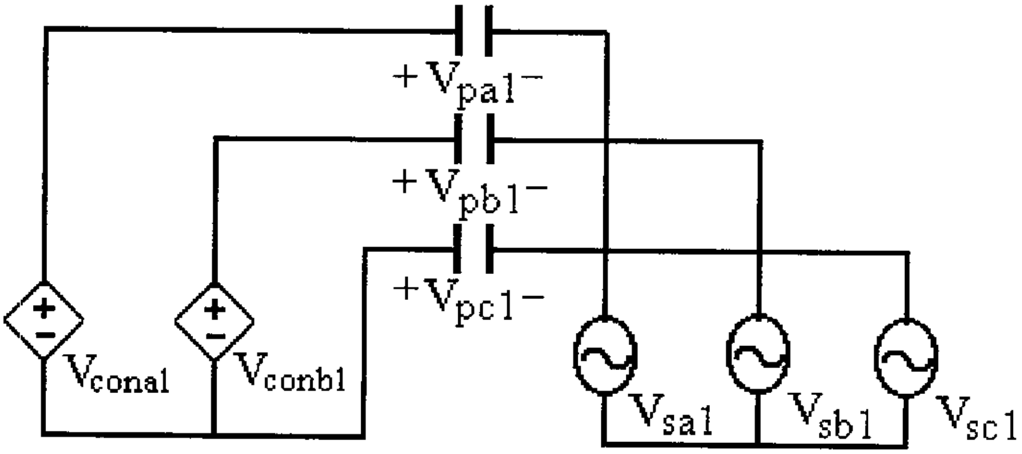

Fig.3.2..Fundamental frequency equivalent circuit.

Since the voltages of utility and induction generator contain no dc component, they are regarded as short circuits. The power converter contains two dc voltage sources in phase *a* and in phase *b*. The dc voltage components appearing in the ac power capacitor set can be derived as

$$V_{\mathrm{pa0}} = V_{\mathrm{pb0}} = 1/6V_{\mathrm{dc}} \tag{5}$$

$$V_{\mathrm{pc0}} = -1/3V_{\mathrm{dc}} \tag{6}$$

Where V_{pa0}, V_{pb0}, and V_{pc0} are the dc voltage components appearing in the ac power capacitor set, respectively. Since ac power capacitors exist in all paths of the power converter to block the dc component of the power converter output voltage, no dc current will be generated by the power converter and injected into the utility. For simplifying the analysis, the utility is assumed very strong. The short circuit level to wind farm capacity (SCR) is high. Hence, the induction generator cannot affect the voltages across the reactive power compensator. Consequently, the effect of induction generator can be neglected in the analysis of fundamental frequency. Fig.3.2 shows the fundamental frequency equivalent circuit of the proposed reactive power compensator. The fundamental components of power converter output voltages are $v_{\mathrm{cona1}}(t)$ and $v_{\mathrm{conb1}}(t)$ and are regarded as two dependent voltage sources. The amplitudes of $v_{\mathrm{cona1}}(t)$ and $v_{\mathrm{conb1}}(t)$ are proportional to the fundamental components of the modulation signals $v_{\mathrm{ma}}(t)$ and $v_{\mathrm{mb}}(t)$. This figure shows that the power converter generates only two ac output voltages. In order to obtain the balanced three-phase compensation reactive current, the voltages across the ac power capacitor set must be derived under losing one phase ac voltage of the power converter. Using the principle of superposition, the effects of the utility voltages and the power converter output voltages to the ac power capacitor set can be analyzed separately. The method of symmetrical components is also used in the following analysis. Since the utility voltages contain only the positive-sequence component under the ideal three-phase power system, the ac power capacitor voltages from the utility voltages still contain only the positive-sequence component. The ac power capacitor voltages ($V_{pa1,c}$, $V_{pb1,c}$, and $V_{pc1,c}$) from the power converter output voltages are unbalanced, and they can be derived as

$$V_{pa1,c} = (2V_{cona1} - V_{conb1})/3 \tag{7}$$

$$V_{pb1,c} = (-V_{cona1} + 2V_{conb1})/3 \tag{8}$$

$$V_{pc1,c} = (-V_{cona1} - V_{conb1})/3. \tag{9}$$

The symmetrical components of ac power capacitor voltages from the power converter output voltages can be derived as

$$\begin{bmatrix} V^{(0)}_{pa1,c} \\ V^{(1)}_{pa1,c} \\ V^{(2)}_{pa1,c} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{pa1,c} \\ V_{pb1,c} \\ V_{pc1,c} \end{bmatrix}$$

where $V^{(0)}_{pa1,c}$, $V^{(1)}_{pa1,c}$, and $V^{(2)}_{pa1,c}$ are the zero-sequence, the positive-sequence, and the negative-sequence components of ac power capacitor voltages from the power converter output voltages. The operator a is represented as

$$a = 1\angle 120^\circ.$$

(10)

Because no zero-sequence current passes in the three-phase three-wire distribution power system, the zero-sequence component of the ac power capacitor set voltages from the power converter output voltages can be neglected. In order to obtain the balanced compensation reactive current of the reactive power compensator, the negative-sequence component $V^{(2)}_{pa1,c}$ of ac power capacitor voltages from the power converter output voltages must be zero. Hence, the following equation can be obtained

$$1/3(V_{pa1,c} + a^2 V_{pb1,c} + a V_{pc1,c}) = 0.$$

(11)

After substituting (6)–(8) into (11), the relationship of the power converter output voltages can be derived as

$$V_{conb1} = -aV_{cona1}.$$

(12)

Equation (12) indicates that Vconb1 lags Vcona1 by 60°. It can be seen from (7)–(9), the positive-sequence component of ac power capacitor voltages due to the power converter output voltages can be derived as

$$V^{(1)}_{\mathrm{pa1,c}} = (V_{\mathrm{cona1}} + aV_{\mathrm{conb1}})/3.$$

(13)

Substituting (12) into (13) then results in

$$V^{(1)}_{\mathrm{pa1,c}} = (V_{\mathrm{cona1}} - a^2 V_{\mathrm{cona1}})/3$$
$$= V_{\mathrm{cona1}}\ 30°/\sqrt{3}.$$

(14)

Considering the effects of both the utility voltages and the power converter output voltages, the positive-sequence component of ac power capacitor voltages can be derived as

$$V^{(1)}_{\mathrm{pa1}} = V_{\mathrm{sa1}} - V_{\mathrm{cona1}}\ 30/\sqrt{3}$$

(15)

Where V_{sa1} is the phase *a* utility voltage. To obtain the desired fundamental reactive current of the reactive power compensator, the positive-sequence component of power converter output voltages must be in phase with that of utility voltage. The equation given in (15) shows that the power converter output voltage of phase *a* must lag the phase *a* utility voltage by 30°. Consequently, the power converter output voltage of phase *b* must lag the phase *a* utility voltage by 90°. The compensation reactive power can be adjusted by controlling the amplitude of the fundamental component of power converter output voltages. Because the power converter output voltages can be controlled to be positive or negative, the three-phase reactive power (Q_h) supplied from the reactive power compensator can be derived as

$$Q_h = 3\omega C\, V_{\mathrm{sa1}}\, (V_{\mathrm{sa1}} \pm V_{\mathrm{cona1}}/\sqrt{3})$$

(16)

Where V_{sa1} and V_{cona1} are the rms values of the fundamental component for the utility voltage and the power converter output voltage. The maximum rms value ($V_{\mathrm{cona,max}}$) of the fundamental voltage generated by the power converter without over modulation is dependent on the dc bus voltage of power converter, and it can be represented as

$$V_{\mathrm{cona1,max}} = (1/2\sqrt{2})V_{dc}.$$

(17)

Then, the minimum and maximum compensation reactive power can be derived by substituting (17) into (16). Hence, the proposed reactive power compensator can linearly adjust the supplied reactive power between the minimum and maximum compensation reactive power. If the variation range of the reactive power demanded by the induction generator is known in advance, the voltage of dc bus and the capacitance of the ac power capacitor set can be determined.

3.2. CONTROL BLOCK DIAGRAM

The control block diagram of phase *a* for the proposed reactive power compensator is shown in the Fig.3.3. The voltage-mode control is adapted in the proposed reactive power compensator. The modulation signal of the power converter contains three parts, a fundamental reactive component S_1, a harmonic component S_2, and a fundamental real component S_3.

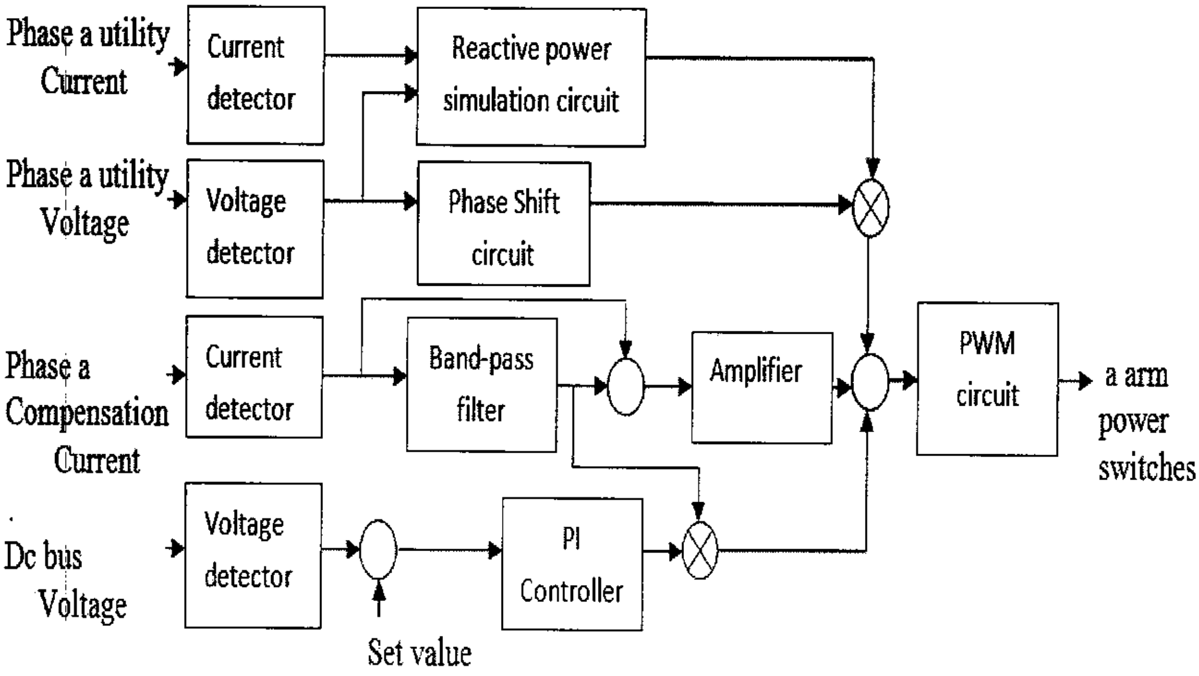

Fig. 3.3.Control block diagram of phase *a*

The fundamental reactive component S_1 is used to adjust the compensation reactive power, and the harmonic component S_2 is used to block the injecting harmonic current. To balance the power loss of the power converter and the operation of the virtual harmonic resistor, the fundamental real component S_3 is required. As shown in Fig.3.3, the utility voltage and utility current of phase *a* are detected by a voltage sensor and a current sensor, respectively, and then sent to the reactive power calculation circuit to calculate the compensation reactive power. The output of the reactive power calculation circuit is the amplitude of the fundamental reactive component. The output of the reactive power calculation circuit may be positive or negative depending on the compensation reactive power. The power converter output voltage of phase *a* must lag the phase *a* utility voltage by 30° to generate the required compensation reactive current. The detected phase *a* utility voltage is sent to a phase shift circuit. The phase shift circuit will generate a fundamental sinusoidal signal which lags the utility voltage by 30°. The outputs of the reactive power calculation circuit and the phase shift circuit are sent to a multiplier to obtain the fundamental reactive component S_1. The power converter must generate a harmonic voltage proportional to the harmonic component of the compensation current to act as a harmonic damping resistor to suppress the harmonic current being injected into the reactive power compensator. The compensation current is detected by a current sensor and sent to a band-pass filter to extract the fundamental component.

The harmonic component of the compensation current is obtained by subtracting the fundamental component from the compensation current. The harmonic component of the compensation current is sent to an amplifier in order to obtain the harmonic component S_2. In order to regulate the fundamental real power, the power converter must generate a voltage with adjustable amplitude and in phase with the fundamental component of the compensation current. Since the dc capacitor of the power converter acts as the energy buffer, the dc bus voltage can be used as an index to indicate the condition of real power for the power converter and to determine the amplitude of the fundamental real component S_3. If the dc bus voltage of the power converter is higher (lower) than the setting value, this indicates that the injected real power of the power converter is too large (not enough) and the amplitude of the fundamental real component S_3 must be decreased (increased). In order to regulate the real power, the dc bus voltage of the power converter is detected by a voltage sensor and compared to a setting value, and the compared result is sent to a proportional–integral (PI) controller to obtain the amplitude of the fundamental real component S_3. The outputs of the PI controller and the band-pass filter are sent to a multiplier to obtain the fundamental real component S_3.

Finally, the modulation signal of the power converter is obtained by summing the fundamental reactive component S_1, the harmonic component S_2, and the fundamental real component S_3. The modulation signal is sent to a PWM circuit to generate the driving signals of the power electronic switches of arm a in the power electronic switches set. The control block diagram of phase *b* for the proposed reactive power compensator is similar to that of phase *a*.

3.3 STATCOM MATHEMATICAL MODEL

Figure 3.4, shows a single line of the power circuit of the system and a STATCOM. The STATCOM is composed of a three-phase GTO based voltage source inverter, shunt transformer and a dc voltage storage source. A mathematical model for the STATCOM with parallel transmission lines is illustrated in Figure3.5. A synchronous machine feed the active power P1 and reactive power Q_1 to an infinite busbar via a two parallel transmission lines. It is decided to place the STATCOM in the first quarter of the line closer to the generation side. Vs is the sending end voltage and Vr is the receiving end voltage which is the reference voltage. d is the load transmission angle before the compensation and X_2, X_3 and X_4 are the transmission lines impedances and Xsh is the leakage reactance of the shunt transformer which are assumed pure inductive for simplicity.

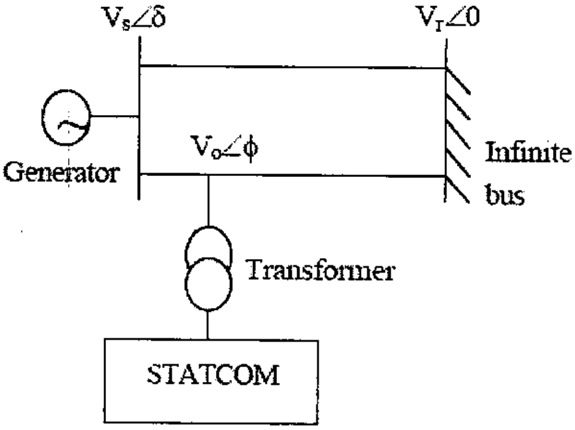

Fig.3.4 Schematic diagram of system

The voltage injected by the STATCOM is Vsh and it has a phasor angle b with respect to Vr. Vo is the transmission line voltage at which the device is connected with a phasor angle f with respect to Vr.

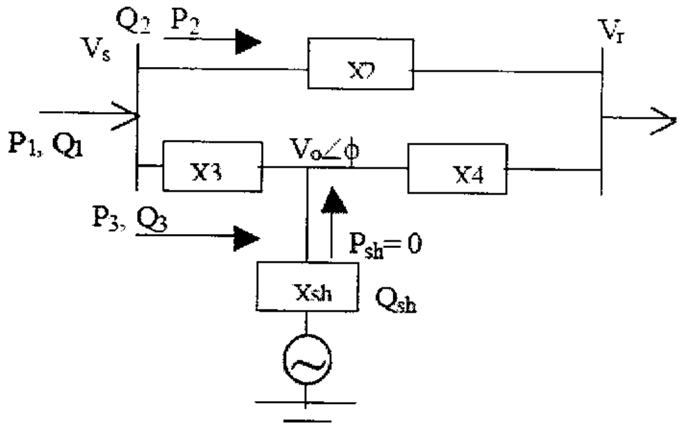

Fig.3.5 Basic mathematical model for STATCOM

Whereas, if the total complex power supplied at the sending end before injection Ish=0 is

$$S1 = Vs\ Is^* = P1 + j\ Q1$$
(18)

$$Is = (Vs - Vr)/\ jX$$
(19)

Where

$$X = X2\ //\ (X3 + X4)$$
(20)

Therefore, it can be proved easily that

$$P1 = (Vr\ Vs\ Sin\ d)\ /\ X$$
(21)

$$Q1 = (Vs2 - VrVs\ Cosd)\ /\ X$$
(22)

The active and reactive power is distributed in the

two parallel lines as follows

$$P2 = (Vr\ Vs\ Sin\ d)\ /\ X2$$
(23)

$$Q2=(Vs2 - VrVs \mathrm{Cos}\ d) / X2$$

(24)

$$P3=(Vr\ Vs\ \mathrm{Sin}\ d) / (X3 + X4)$$

(25)

$$Q3=(Vs2 - VrVs \mathrm{Cos}\ d) / (X3 + X4)$$

(26)

The voltage at the connection point of the device is

$$Vo=A + jB$$

(27)

$$A = [1 - \{X3 / (X3 + X4)\}]\ Vs\ \mathrm{Cos}\ d+\{X3/(X3+X4)\}\ Vr$$

(28)

$$B= [1 - \{X3 / (X3 + X4)\}]\ Vs\ \mathrm{Sin}\ d$$

(29)

$$f=\tan -1\ (B/A)$$

(30)

$$d= \mathrm{Sin}\ -1\ (P1X / VrVs)$$

(31)

After the injection ($Ish^{1} 0$), the line will be under control of STATCOM. The reactive power is supplied or absorbed from the line, which will effect the power flow in the whole system. The total complex power supplied at the sending end in the line, which is connected to the STATCOM, is

$$S3=VsI3$$

(32)

$$I3= (Vs - Vo) / jX\ 3$$

(33)

Therefore, it can be proven that

$$P3=\{VoVsSin\ (d¢ - f)\} / X3$$

(34)

$$Q3= \{Vs_2- VoVs\ Cos(d¢ - f)\} / X3$$

(35)

Where d¢ is the load transmission angle after the injection ($Ish^1 =0$).

Since P1 is constant, therefore P2 changes as P3 changes Therefore,

$$P2 = P1 - P3$$

(36)

$$Q2 = (Vs_2 - VrVs\ Cos\ d¢) / X2$$

(37)

The complex power at the point of connection of the device is

$$Ssh = Vsh\ Ish^*$$

(38)

$$Ish = (Vsh - Vo) / jXsh$$

(39)

$$Psh= \{VshVo\ Sin\ (b-f)\}/ Xsh$$

(40)

$$Qsh = \{(Vsh2 - VshVo)\ Cos\ (b-f)\}/ Xsh$$

(41)

Hence, the STATCOM device is operated to compensate the reactive power only, there must be no active power provided by the device. And, the active power losses are neglected. Therefore, Psh = 0 means (b = f) Vo and Vsh are in phase, and the reactive power is

$$Qsh = (Vsh2 - VoVsh) / Xsh$$

(42)

The magnitude of injected voltage by the inverter is

$$Vsh = 0.35MbVdc$$

(43)

And it is related to the Vo (before injection) in the following equation,

$$Vsh=Kvo$$

(44)

Where, K is a compensation factor controlled by the modulation index Mb. K determines the control percentage of the transmission line voltage that reflects the VAR compensation. By substitution of

$$Qsh=KVo2\ (K-1) / Xsh$$

(45)

So, the STATCOM device compensates the reactive power according to the value of K. If K=1 means the reactive power is neither supplied nor absorbed from the system. And, if the K > 1 means the device supplies reactive power to the system. Whereas, if K< 1 the STATCOM device absorbs the reactive from the system. In general, the device can compensate the reactive power by changing the modulation index Mb as shown in where K is a function of Mb. Equation show that the distribution of the active power in each line is controlled by changing Mb. It can be proved that:

$$(Xt*Vo - Vsh)* \text{Cos } f - (Xsh/X3)*Vs* \text{Cos d¢} - (Xsh/X4)*Vr = 0$$

(46)

$$(Xt*Vo - Vsh)* \text{Sin } f - (Xsh/X3)*Vs* \text{Sin d¢} = 0$$

(47)

$$X3* Vr *Vs* \text{Sin d¢} + X2*Vo\ Vs* \text{Sin } (\text{d¢} - f) - P1*X2 *X3 = 0$$

(48)

Where,

$$Xt = (1 + Xsh/X3 + Xsh/X4)$$

(49)

By solving the system of nonlinear equation for the three variables Vo, f and d¢ by using Newton-Raphson method, the steady state can be simulated.

CHAPTER 4

CHAPTER 4

SIMULATION

4.1 MATLAB

The name MATLAB stands for matrix laboratory. MATLAB is a high-performance language for technical computing. It Integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. In this project the modelling and simulation of the proposed system is done using MATLAB (using simulink and power system block set tool boxes).

4.1.1 SIMULINK

Simulink is a software package for modeling, simulating, and analyzing non linear dynamical systems. It is a graphical mouse-driven program that allows somebody to model a system by drawing a block diagram on the screen and manipulating it dynamically. Simulink is a platform for multi domain simulation and Model-Based Design for dynamic systems. It provides an interactive graphical environment and a customizable set of block libraries, and can be extended for specialized applications.

4.1.2 POWER SYSTEM BLOCK SET

The Power System Block set allows scientists and engineers to build models that simulate power systems. The block set uses the Simulink environment, allowing a model to be built using click and drag procedures. Not only can the circuit topology be drawn rapidly, but also the analysis of the circuit can include its interactions with mechanical, thermal, control, and other disciplines. SimPowerSystems extends Simulink with tools for modelling and simulating basic electrical circuits and detailed electrical power systems. These tools let you model the generation, transmission, distribution, and consumption of electrical power, as well as its conversion into mechanical power. Sim Power Systems is well suited to the development of complex, self-contained power systems, such as those in automobiles, aircraft, manufacturing plants, and power utility applications

4.2 SIMULATION MODEL

4.2.1 SIMULATION DIAGRAM OF A STATCOM

Here the Fig.4.1 shows the STATCOM connected to the wind farm at the point of common coupling. The utility system voltage at the point of common coupling is 25KV. The wind farm output is 400V which is stepped up using step up transformer at the point of common coupling. The controller circuit get the reference signal from the point where wind farms are connected to the utility system. Basically the STATCOM source voltage is larger than the voltage at the PCC (VPCC), the STATCOM generates reactive power. Otherwise, the STATCOM withdraws reactive power.

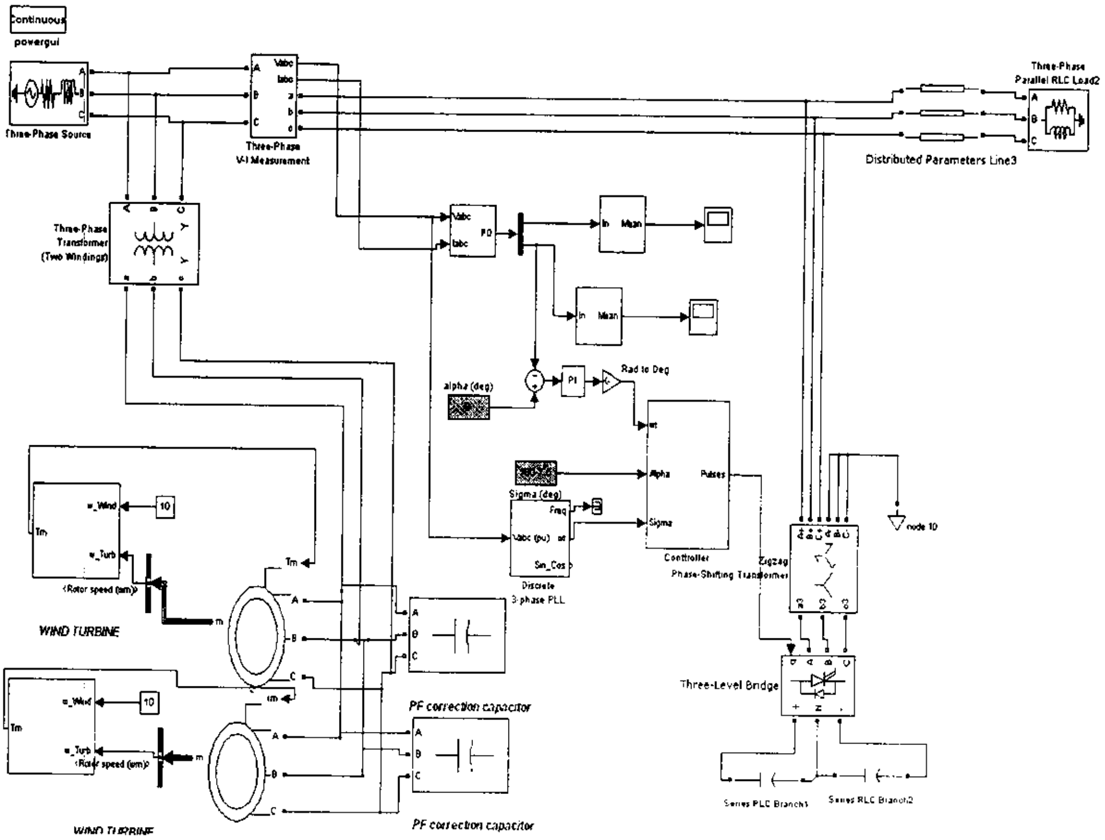

Fig 4.1 Simulation Diagram of STATCOM

Here the induction generators are connected to the system at the point of common coupling where we introduce the STATCOM to compensate the reactive power absorbed by the induction generators during its starting. The capacity of the induction generators are connected to the system is power 215HP, speed 1487rpm, generating voltage 400V and frequency of 50Hz.

Table 4.1. Simulation Specifications of STATCOM Circuit

Sl.No	Source/Elements	Parameter specification	
1	Supply Voltage	25KVp-p	
2	Induction Generator	Power	=215HP
		Voltage	= 400V
		Frequency	=50Hz
		Speed	=1487rpm
3	Transformer	Nominal Power	=250*10^6VA
		Frequency	=50Hz
		Primary voltage	=25KV
		Secondary Voltage	=400V
4	Transmission line Parameters	Resistance per unit length	= 0.01273(ohms/km)
		Inductance per unit length	=0.9337*10^-3 (H/km)
		Capacitance per unit length	=12.74*10^-9(F/km)
		Line Length	=100km
5	Load	Voltage phase to phase	=25KV
		Active Power	= 1000W
		Inductive Reactive Power	= 100Var
		Frequency	= 50Hz
6	STATCOM	Power	=100Mvar
		Frequency	=50Hz

The STATCOM is connected at the point of common coupling and its capacity is 100MVar. The transmission line parameters are Line Length 100km, Resistance per unit length 0.01273(ohms/km) Inductance per unit length =0.9337*10^-3 (H/km) and Capacitance per unit length =12.74*10^-9(F/km).

4.2.2 SIMULATION DIAGRAM OF PROPOSED POWER CONVERTER

The proposed power converter is connected at the point of common coupling where the STATCOM is connected in the circuit. The proposed power converter has the two arm structure and it reduces the number of switches required for the power converter. The Fig.4.2 shows that the proposed power converter is used for replacement for the STATCOM in the power circuit.

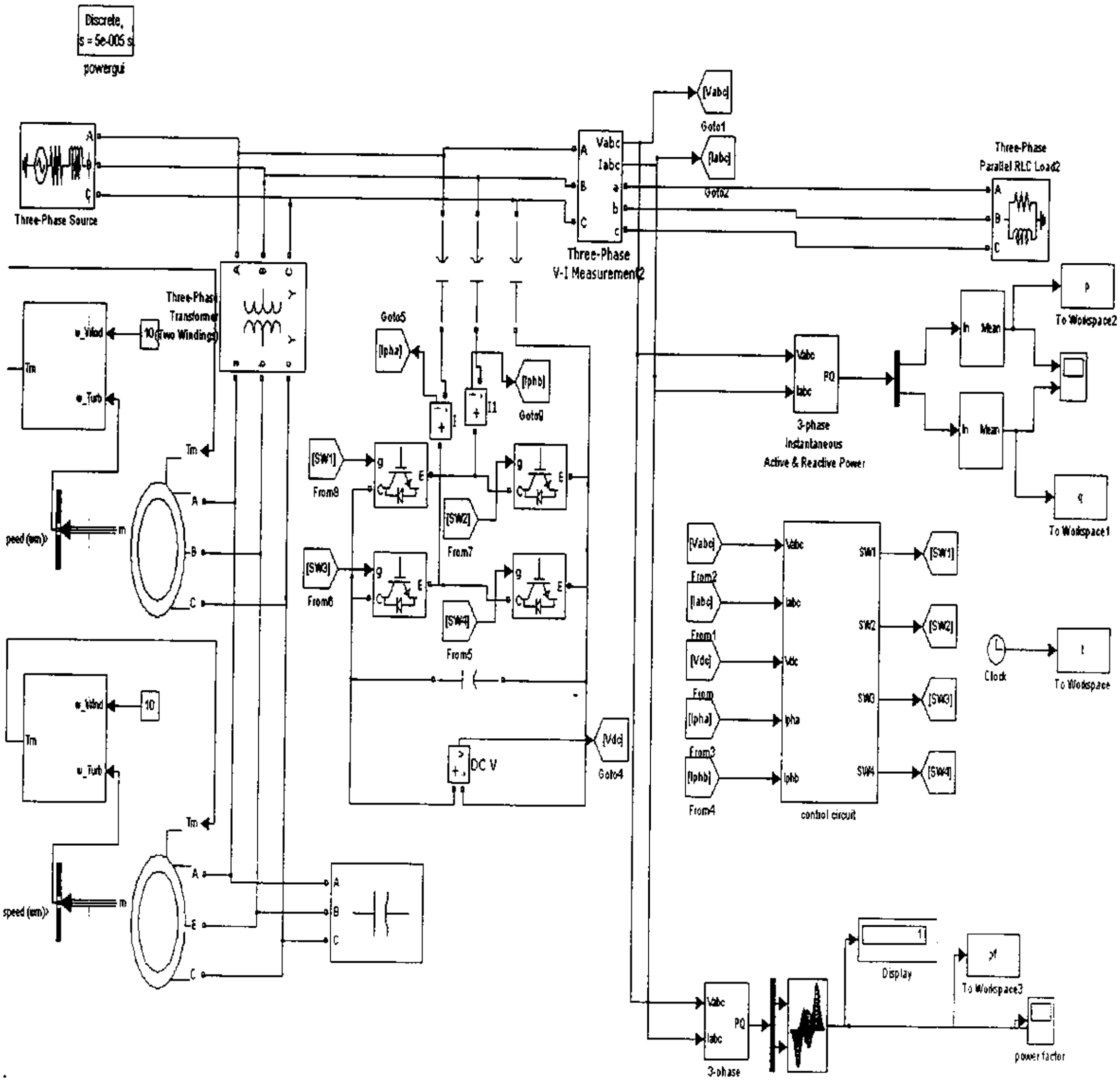

Fig 4.2. Simulation Diagram of Proposed Power Converter

The circuit configuration of the proposed reactive power compensator applied to the three-phase three-wire induction generator system. The three-phase three-wire induction generator is driven by a wind turbine and generates power for the utility, and the reactive power compensator is used to supply reactive power to the induction generator. So the real power is flowing into the utility. The proposed reactive power compensator consists of an ac power capacitor set serially connected to a power converter. The ac power capacitor set provides fundamental reactive power and is also used to withstand the major fundamental component of the utility voltage that may reduce the capacity of the power converter.

The ac power capacitor set can also block the dc voltage generated from the power converter to the utility. The power converter is used to solve the harmonic problems of the ac power capacitor, and it permits the proposed reactive power compensator to provide compensation reactive power. The power converter consists of a dc capacitor, a power electronic switch set, and a filter inductor set. The dc capacitor acts as an energy buffer, and provides dc voltage for normally operating the power converter.

4.2.3 CONTROL CIRCUIT OF PROPOSED POWER CONVERTER

The utility voltage and utility current of phase *a* are detected by a voltage sensor and a current sensor, respectively, and then sent to the reactive power calculation circuit to calculate the compensation reactive power. The output of the reactive power calculation circuit is the amplitude of the fundamental reactive component. The output of the reactive power calculation circuit may be positive or negative depending on the compensation reactive power. The power converter output voltage of phase *a* must lag the phase *a* utility voltage by 30° to generate the required compensation reactive current. The detected phase *a* utility voltage is sent to a phase shift circuit. The phase shift circuit will generate a fundamental sinusoidal signal which lags the utility voltage by 30°. The outputs of the reactive power calculation circuit and the phase shift circuit are sent to a multiplier to obtain the fundamental reactive component S_1. The power converter must generate a harmonic voltage proportional to the harmonic component of the compensation current to act as a harmonic damping resistor to suppress the harmonic current being injected into the reactive power compensator. The compensation current is detected by a current sensor and sent to a band-pass filter to extract the fundamental component. Finally, the modulation signal of the power converter is obtained by summing the fundamental reactive component S_1, the harmonic component S_2, and the fundamental real component S_3. The modulation signal is sent to a PWM circuit to generate the driving signals of the power electronic switches of arm a in the power electronic switches set.

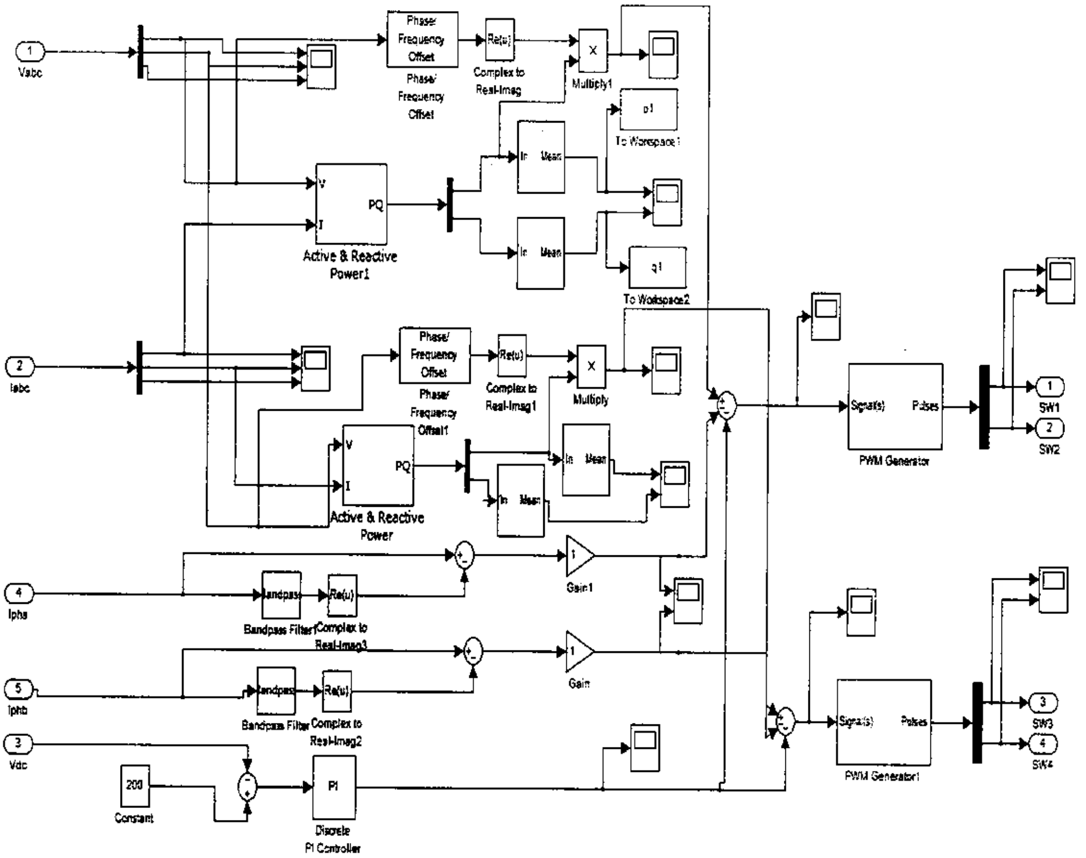

Fig 4.3.Control Circuit of Proposed Power Converter

The harmonic component of the compensation current is obtained by subtracting the fundamental component from the compensation current. The harmonic component of the compensation current is sent to an amplifier in order to obtain the harmonic component S_2. In order to regulate the fundamental real power, the power converter must generate a voltage with adjustable amplitude and in phase with the fundamental component of the compensation current. Since the dc capacitor of the power converter acts as the energy buffer, the dc bus voltage can be used as an index to indicate the condition of real power for the power converter and to determine the amplitude of the fundamental real component S_3. If the dc bus voltage of the power converter is higher (lower) than the setting value, this indicates that the injected real power of the power converter is too large (not enough) and the amplitude of the fundamental real component S_3 must be decreased (increased). In order to regulate the real power, the dc bus voltage of the power converter is detected by a voltage sensor and compared to a setting value, and the compared result is sent to a proportional–integral (PI) controller to obtain the amplitude of the fundamental real component S_3. The outputs of the PI controller and the band-pass filter are sent to a multiplier to obtain the fundamental real component S_3. Finally, the modulation signal of the power converter is obtained by summing the fundamental reactive component S_1, the harmonic component S_2, and the fundamental real component S_3. The modulation signal is sent to a PWM circuit to generate the driving signals of the power electronic switches of arm a in the power electronic switches set.

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Sl.No	Source/Elements	Parameter specification
1	Supply Voltage	25KVp-p
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3	Transformer	Nominal Power =250*10^6VA Frequency =50Hz Primary voltage =25KV Secondary Voltage =400V
4	Transmission Line Parameters	Resistance per unit length = 0.01273 (ohms/km) Inductance per unit length =0.9337*10^-3 (H/km) Capacitance per unit length =12.74*10^-9(F/km) Line Length =100km
5	Load	Voltage phase to phase =25KV Active Power = 1000W Inductive Reactive Power = 100Var Frequency = 50Hz

4.3 REAL TIME DATAS OF WIND INDUCTION GENERATOR

Rated power output	900 kW
Cut-in wind speed	3 m/s
Rated wind speed	12 m/s
Cut-out wind speed	25 m/s
Rotor diameter	56 m
Rotor swept area	2,463 m^2
Rotor speed	6-28 rpm
Operating temperature range	-20°C to +45°C
Power factor	0.95 ind. to 0.95 cap.
Certification	IEC 61400 TC IIA and DIBt WZ III
Gearbox	One planetary and two spur gears
Gear ratio	1:54.2
Mechanical brake	Disc brake on high speed shaft (hydraulic)
Yaw drive	3 AC motor drives with planetary gear
Yaw brake	Friction brake
Generator	Asynchronous, water-cooled (optional: synchronous permanent magnet, air-cooled)
Nominal rotation	1,500 rpm
Tower	Conical steel tower
Hub height	59 m or 71 m
Blade length	27.1 m
Number of blades	3
Grid connection	50 Hz ,690 V

4.4 SIMULATION RESULTS

In order to verify the performance of the proposed reactive power compensator for a squirrel-cage induction generator, a three-phase prototype with a utility line voltage of 25kV and a utility frequency of 50 Hz is developed. Both the real power and the reactive power of induction generator are proportional to the rotor speed, and the power factor of the induction generator is very poor. The dc bus voltage of the power converter and the capacitance of the power capacitor depend on the maximum and minimal values of compensation reactive power. The dc bus voltage of the power converter and the capacitance of the ac power capacitor calculated by using the compensation reactive power value.

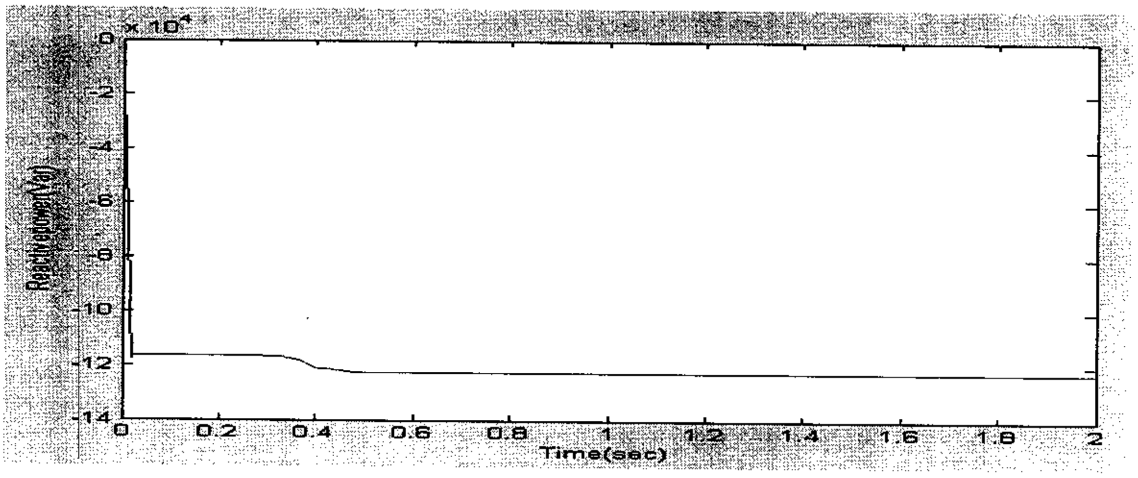


Fig.4.4. Active Power before applying the reactive power compensator.

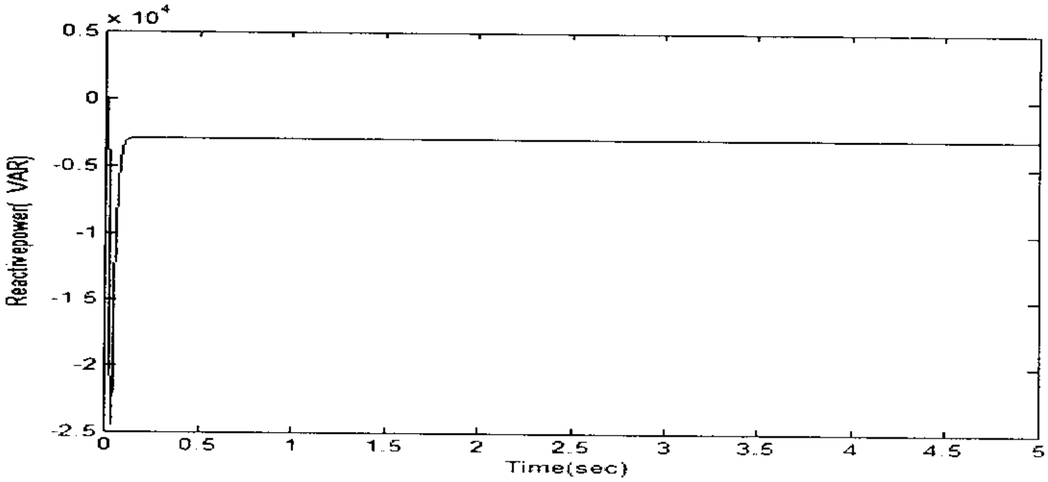


Fig.4.5 Reactive Power after applying the STATCOM.

The proposed power converter circuit provides reactive power to the Induction generator during its operation. So the power factor of the circuit gets improved after applying the proposed power converter. Fig.4.4 shows the simulation result of a reactive power absorbed by the Induction generator without power converter circuit. After applying the STATCOM circuit the reactive power is compensated this is shown in the Fig.4.5. The reactive power generated by the proposed power converter is shown in the Fig.4.6. If there is no compensating circuit the power system means it reduces the system power factor and it also leads to voltage disturbances. After applying the STATCOM reactive power is injected into the system which is shown in the Fig.4.5 When the proposed power converter applied to the system, the reactive power becomes positive it shows that the proposed power converter is better than the STATCOM.

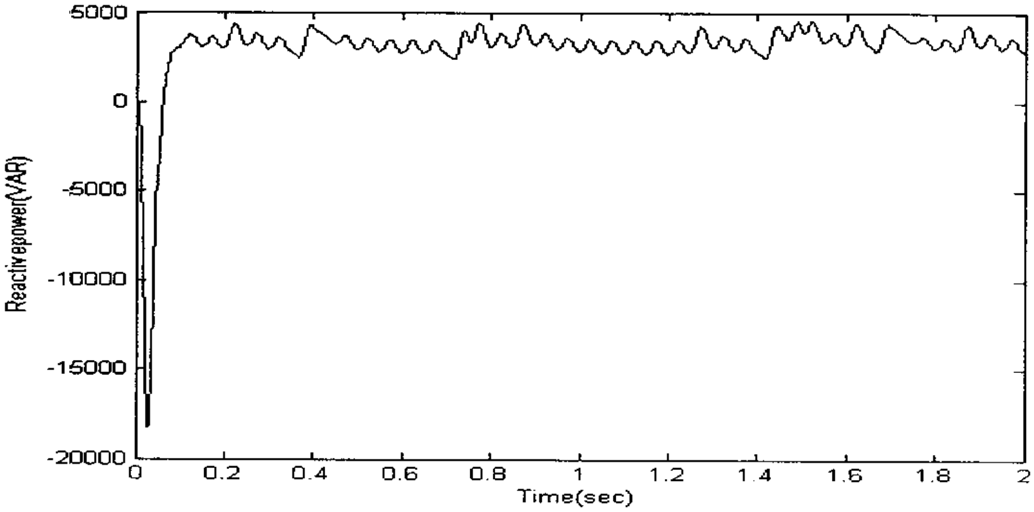


Fig.4.6. Reactive Power after applying the reactive power compensator.

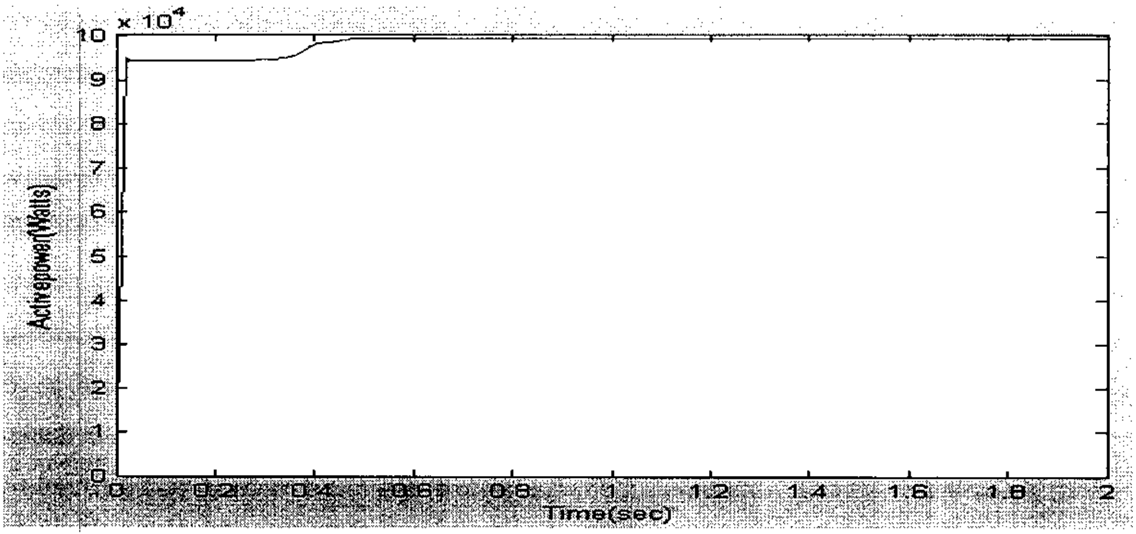


Fig.4.7. Active Power before applying the reactive power compensator.

The Fig.4.7 shows that the active power in the circuit before applying the proposed power converter in the circuit and the Fig.4.8 shows that the active power in the circuit does not depend on the reactive power compensation and it depends on the load. The Fig.4.7 and Fig.4.8 shows the active power in the system remain same after and before applying the compensation circuit in the system.

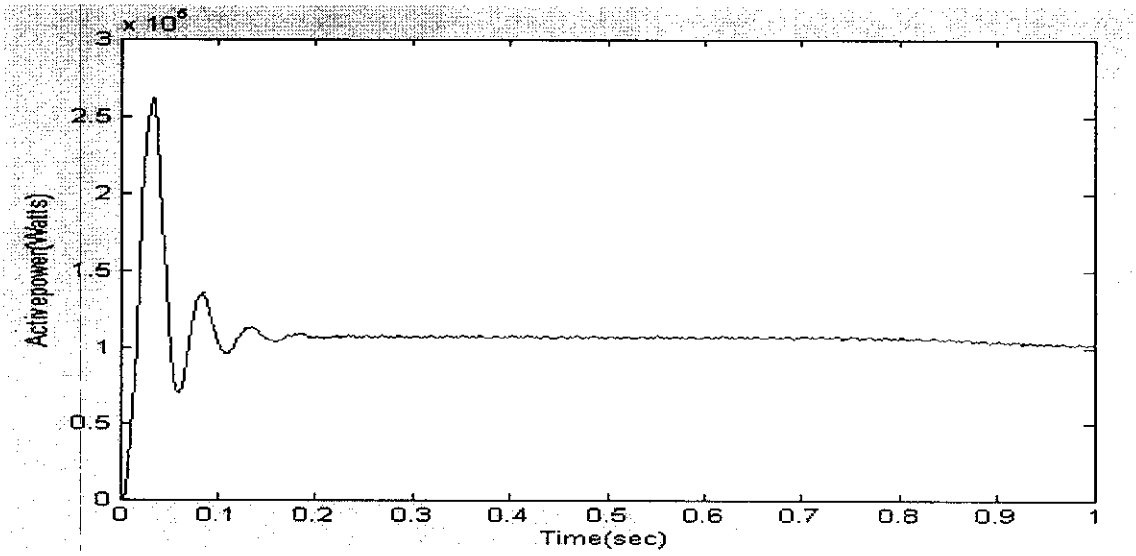


Fig.4.8. Active Power after applying the reactive Power Compensator

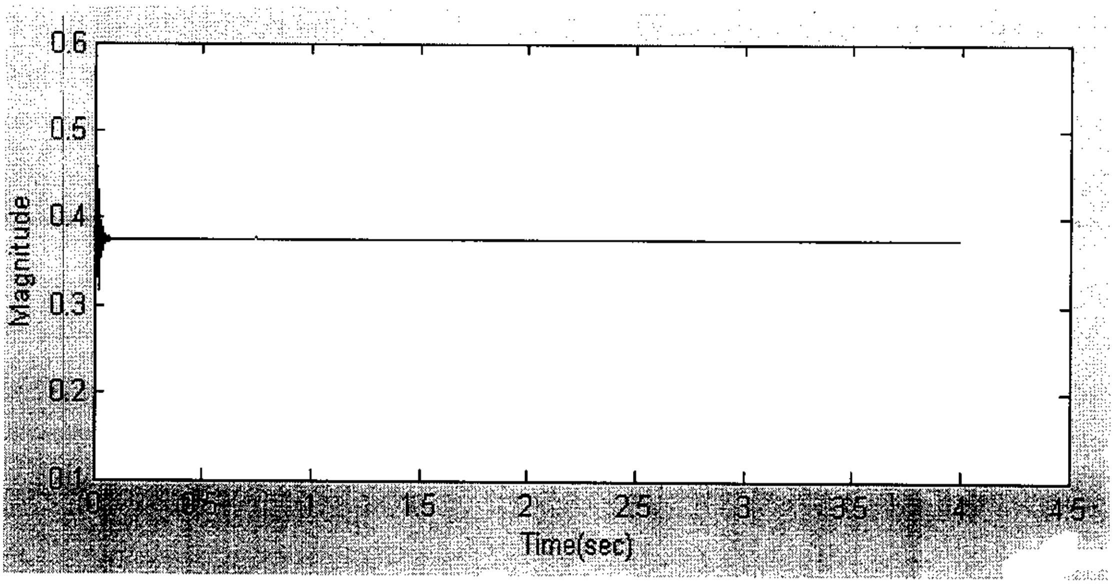


Fig.4.9. Power Factor before applying the reactive power compensator.

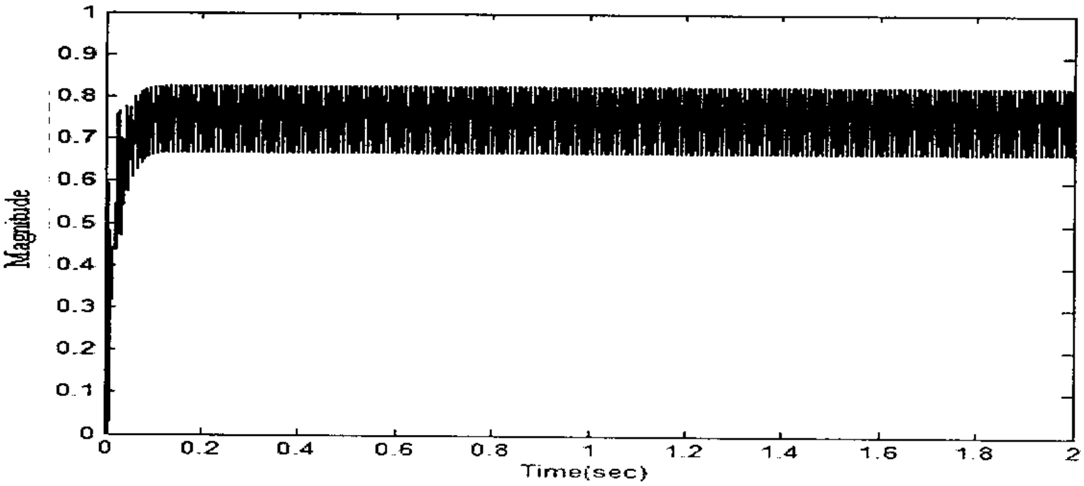


Fig.4.10. Power Factor after applying the STATCOM.

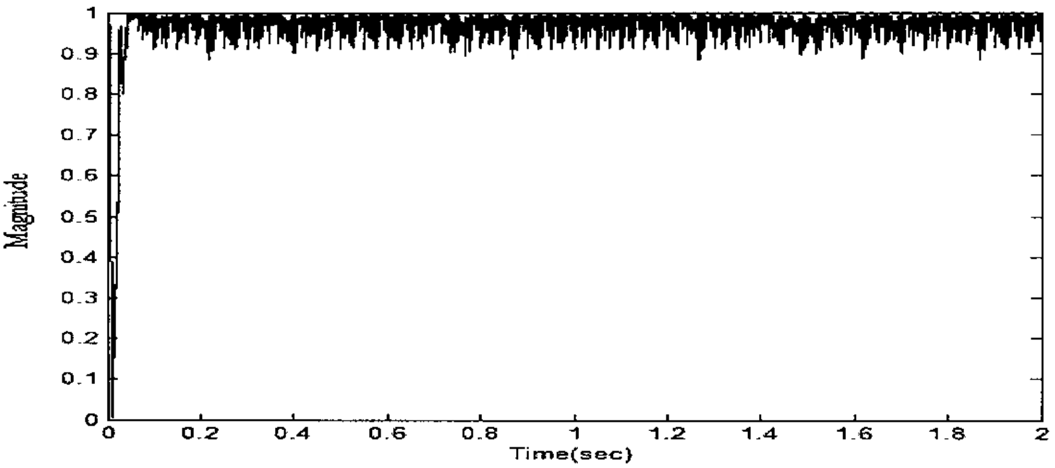


Fig.4.11. Power Factor after applying the reactive power compensator.

The power factor of the system gets improved when the proposed power converter is applied to the system. It's used to compensate the reactive power in the system. The Fig.4.9 shows the power factor of the circuit which is 0.38 when there is no compensation circuit in the system. After applying the SATCOM circuit the power factor is improved to 0.75, which is shown in the Fig.4.10. The power of the system is nearer to unity when we applied the proposed power converter in the system which is shown in the Fig.4.11.

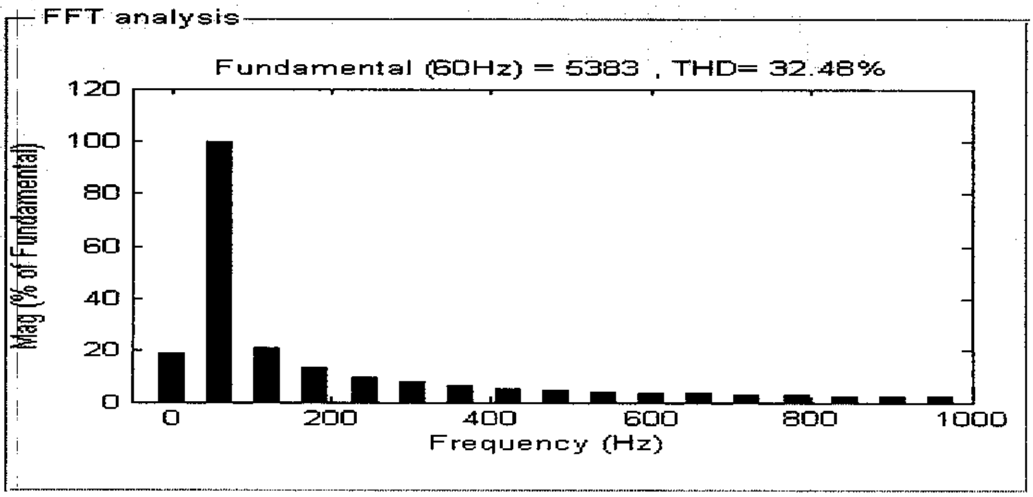


Fig.4.12. THD before applying the reactive power compensator .

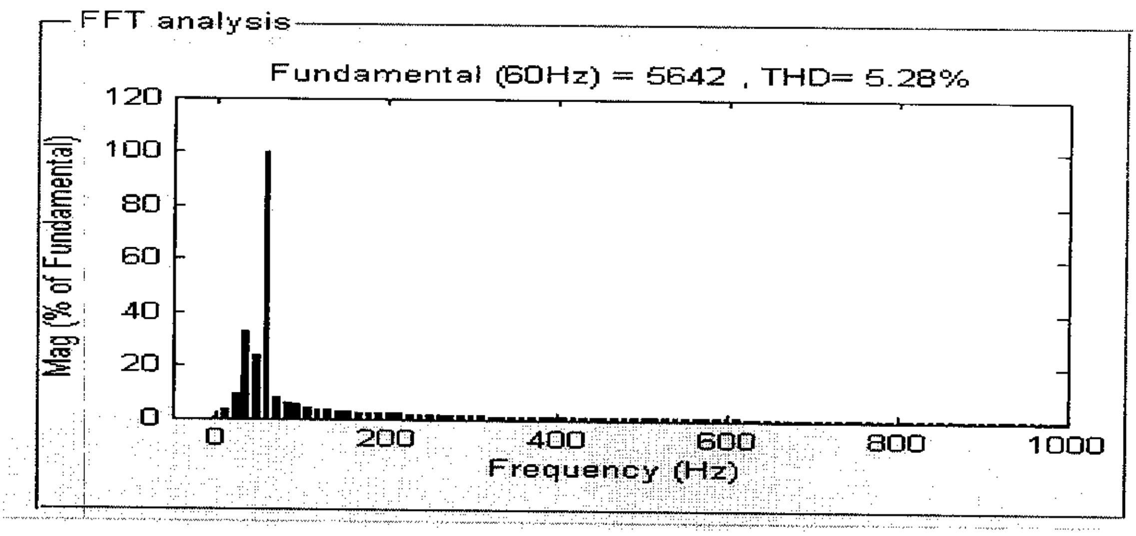


Fig.4.13. THD after applying the STATCOM .

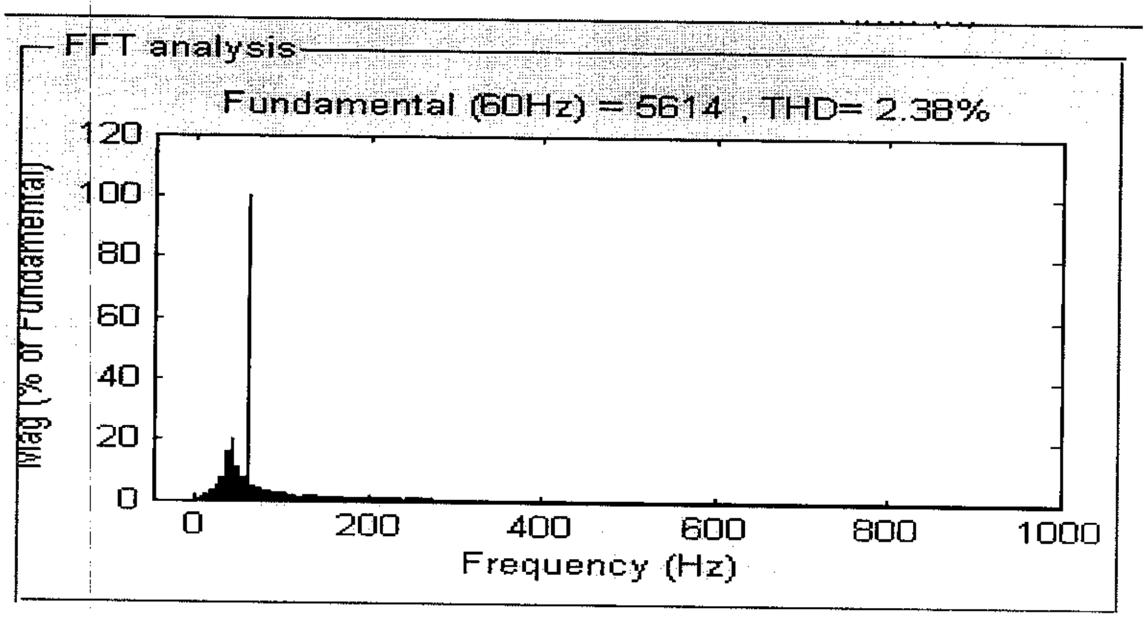


Fig.4.14. THD after applying the reactive power compensator.

CHAPTER 5

CHAPTER 5

HARDWARE IMPLEMENTATION

5.1 HARDWARE BLOCK DIAGRAM

This chapter explains the block diagram and components used for the hardware prototype of the proposed system. It includes the photographs of the fabricated model and output waveforms. The prototype is done only for single phase inverter. The voltage of the system is reduced to 24V. The schematic is done in AutoCAD.

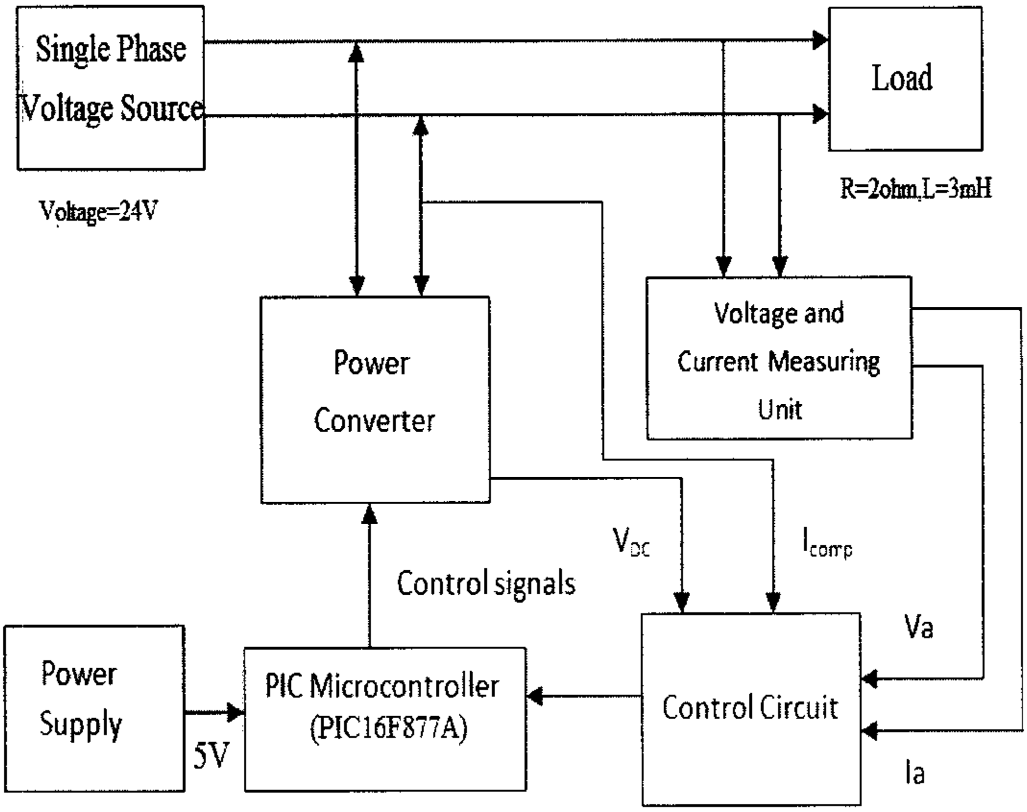


Fig 5.1. Block Diagram of Prototype

The prototype of the proposed system has single phase load, single phase converter and micro controller (PIC16F877A) with 5V power supply. These parts are explained with schematic diagram in following sections. The proposed power converter is connected at the system where we need to compensate the reactive power in the system. The control signal for the proposed power converter is generated by using the PIC Microcontroller (PIC16F877A). The load connected to the system is inductive in nature.

5.2 SINGLE PHASE CONVERTER CIRCUIT WITH LOAD

The single phase proposed power converter circuit with the inductive load is shown in the Fig 5.2. The inductive load is connected to the system through the diode rectifier. The value of the inductive element connected to the system is 5mH and the resistor value of 5ohm. The proposed power converter is a single phase inverter which is connected to the system to compensate the inductive power generated by the load. To measure the source voltage by connecting resistors in parallel with the source. The non linear load consisting of a single phase diode rectifier with inductive or capacitive loads is connected to a sinusoidal voltage source. The inductive or capacitive load is considered as a R-L or a shunt R-C respectively, which is connected to the dc side of the rectifier.

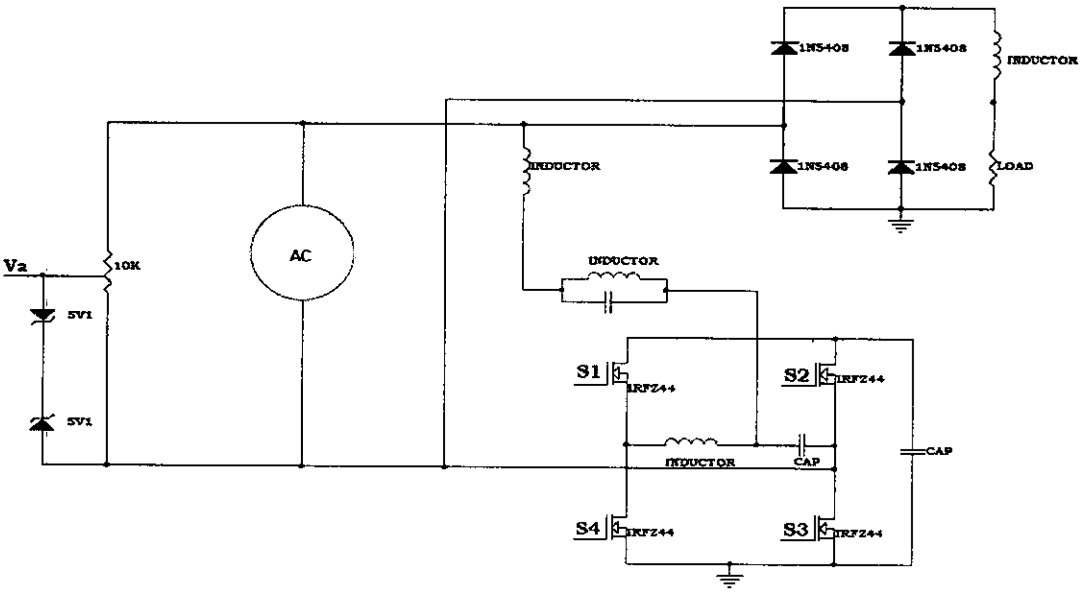


Fig 5.2.Single phase converter with load circuit

The band stop filter generates reference harmonic currents which should be tracked by active filter. The active power filter is shown with an ideal voltage to current converter and should track the harmonic currents generated by band stop filter in order to make sinusoidal source current and also correct the supply side power factor.

5.3 MICROCONTROLLER

The gate pulse for the converter switches are generated by PIC16F877A controller. This micro controller circuit works in 5V power supply. The detail about PIC16F877A is given in APPENDIX I. This controller is isolated from the main circuits by means of opto-coupler. The schematic of micro controller circuit is shown in Fig.5.3.

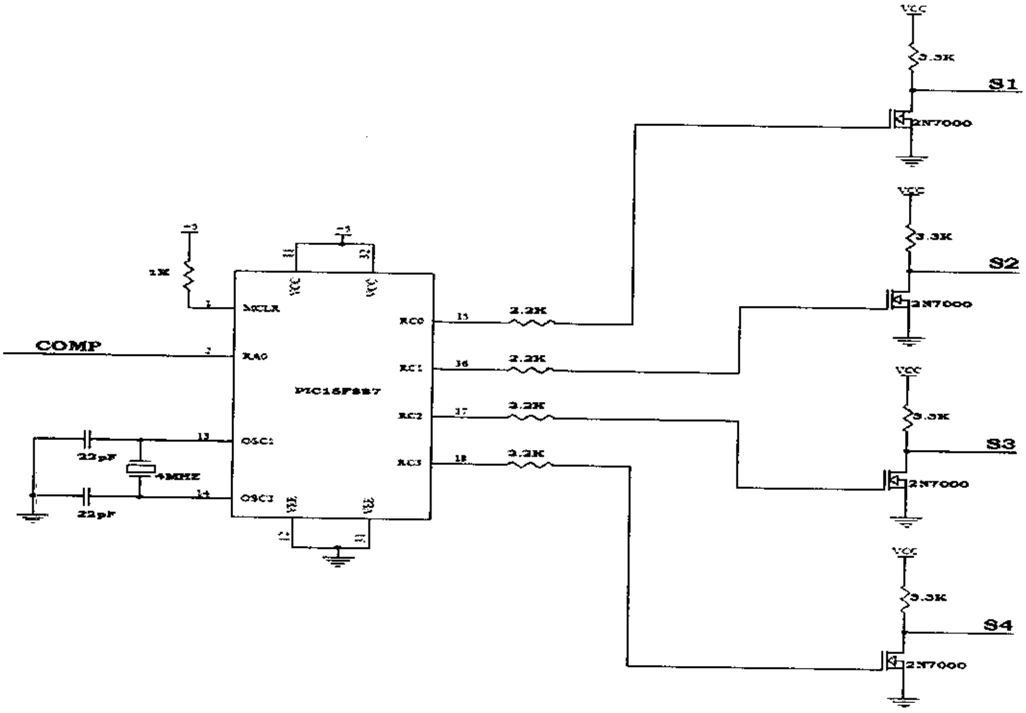
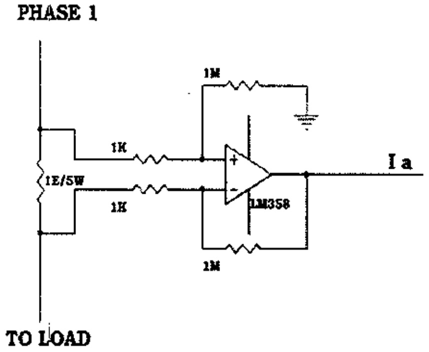


Fig 5.3 Schematic of Microcontroller circuit

The PIC Microcontroller (PIC16F877A) is used to generate the control pulse for the proposed power converter circuit. The output of the PIC controller is connected to the converter circuit through the opto-coupler. The operating frequency of the PIC microcontroller is 4MHz.

5.4 CONTROLLER CIRCUIT

The phase voltage and phase current measuring units are shown in the Fig 5.4.1 and Fig 5.4.2. The control circuit to generate the compensation current is shown in the Fig 5.4. Here the op-amp is used to as an error amplifier, and actually it detects the phase difference between the phase voltage and the phase current and amplifies. The output of this control circuit is given to the PIC microcontroller to generate the control pulses for the proposed power converter circuit.



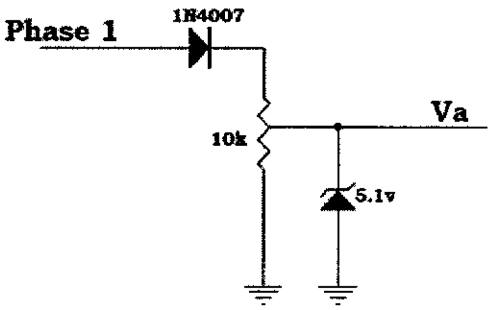


Fig 5.4.1. Phase current measuring circuit Fig 5.4.2. Phase voltage measuring circuit

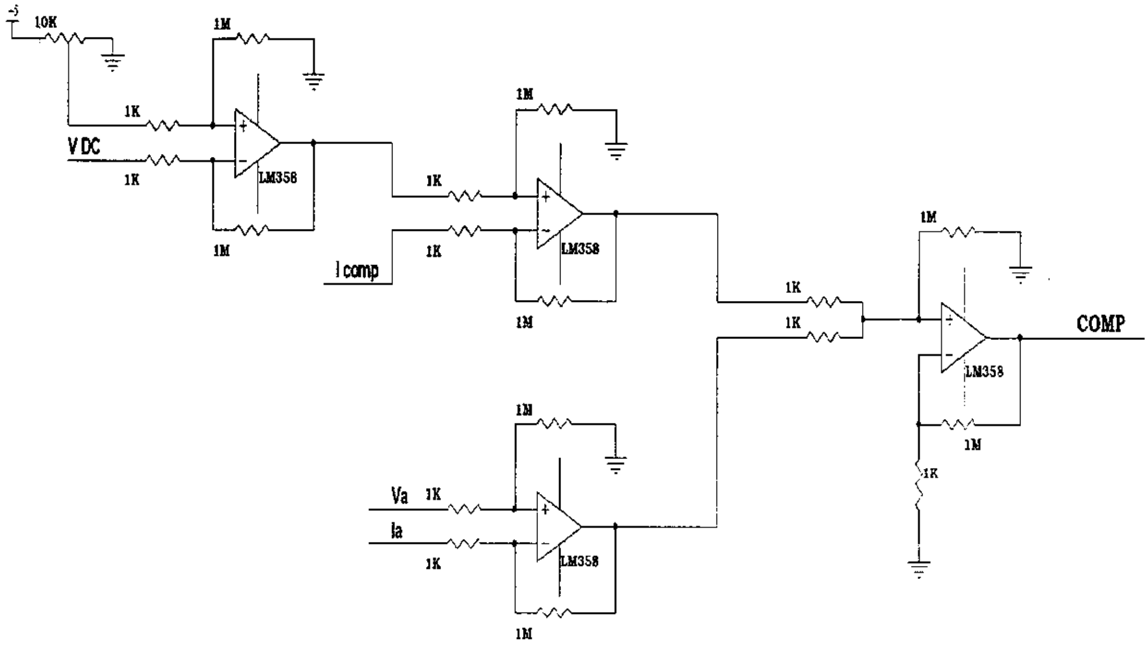


Fig 5.4. Control circuit for the converter

5.5 POWER SUPPLY FOR THE MICROCONTROLLER

Since all electronic circuits work only with low D.C. voltage we need a power supply unit to provide the appropriate voltage supply. This unit consists of transformer, rectifier, filter and regulator. A.C. voltage typically 230V rms is connected to a transformer which steps that AC voltage down to the level to the desired AC voltage.

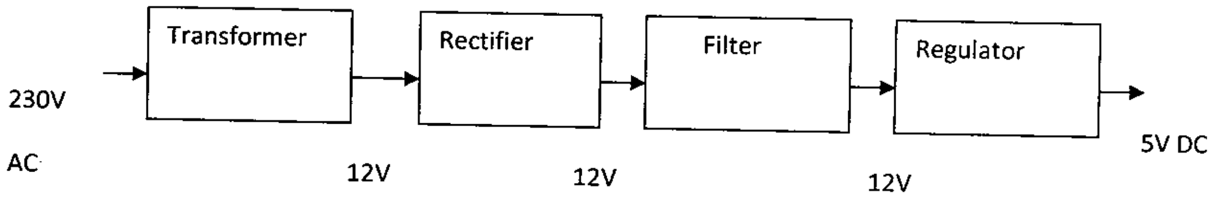


Fig 5.5. Power Supply Block Diagram

A diode rectifier then provides a full-wave rectified voltage that is initially filtered by a simple capacitor filter to produce a DC voltage. This resulting DC voltage usually has some ripple or AC voltage variations. regulator circuit can use this DC input to provide DC voltage that not only has much less ripple voltage but also remains the same DC value even the DC voltage varies some what, or the load connected to the output DC voltage changes. The power supply unit is a source of constant DC supply voltage. The required DC supply is obtained from the available AC supply after rectification, filtration and regulation.

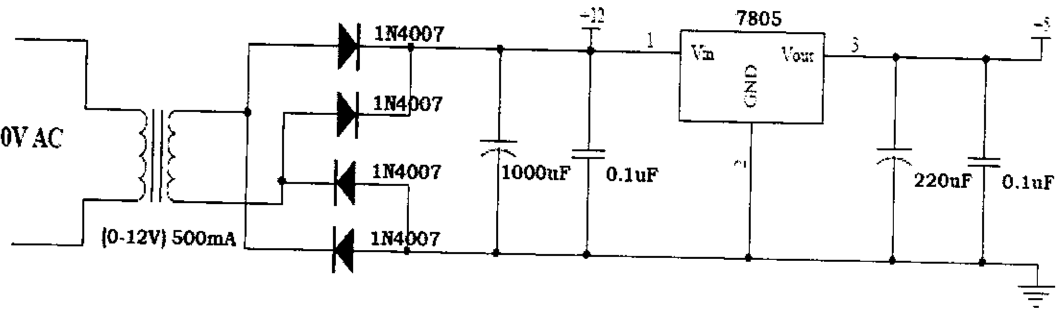


Fig 5.6. Power supply for Microcontroller

5.6 PHOTOCOPY OF HARDWARE

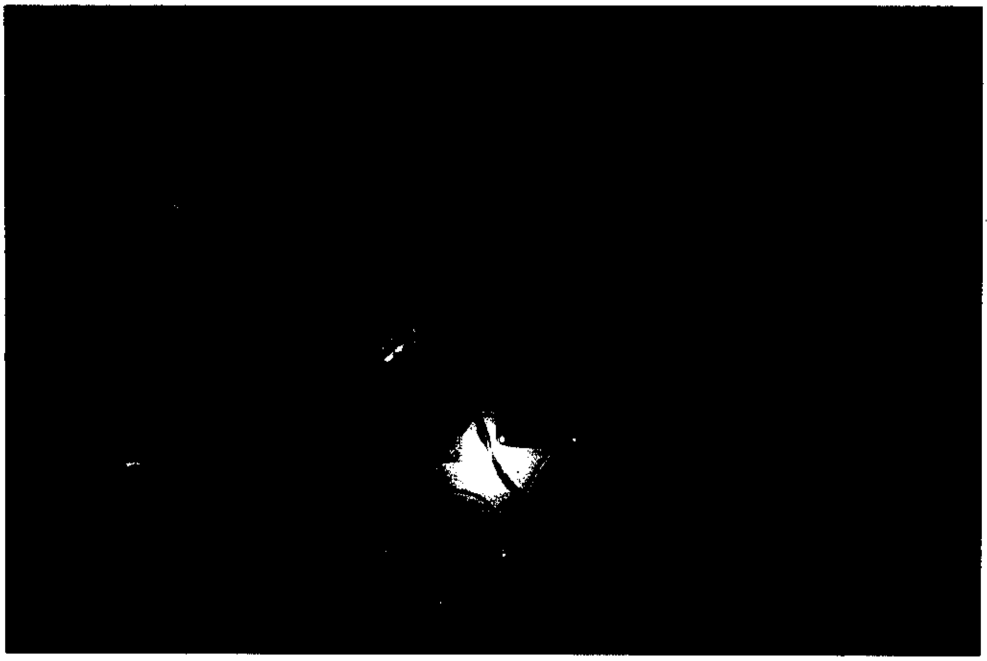


Fig 5.7 Photo Copy of Hardware

5.3 HARDWARE OUTPUT

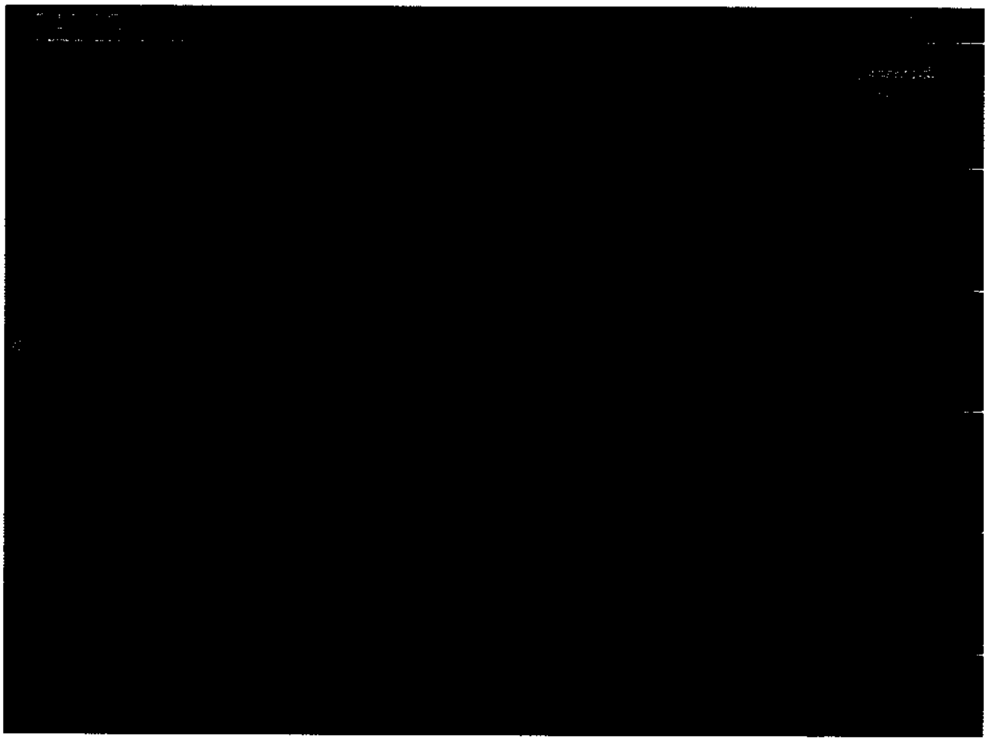


Fig 5.8 Current Waveform without Power Converter

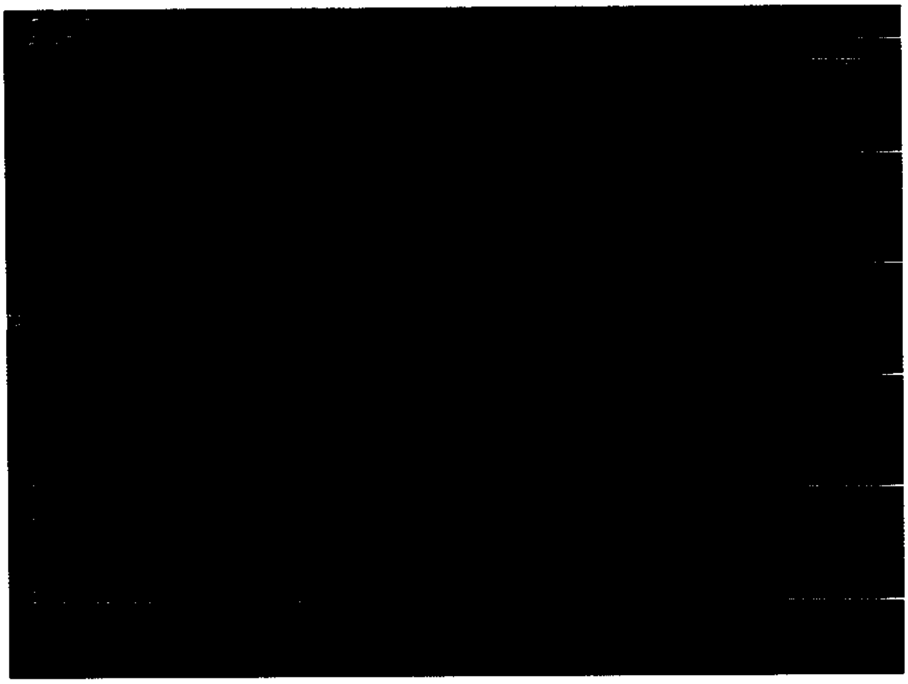


Fig 5.9 Current Waveform with Power Converter

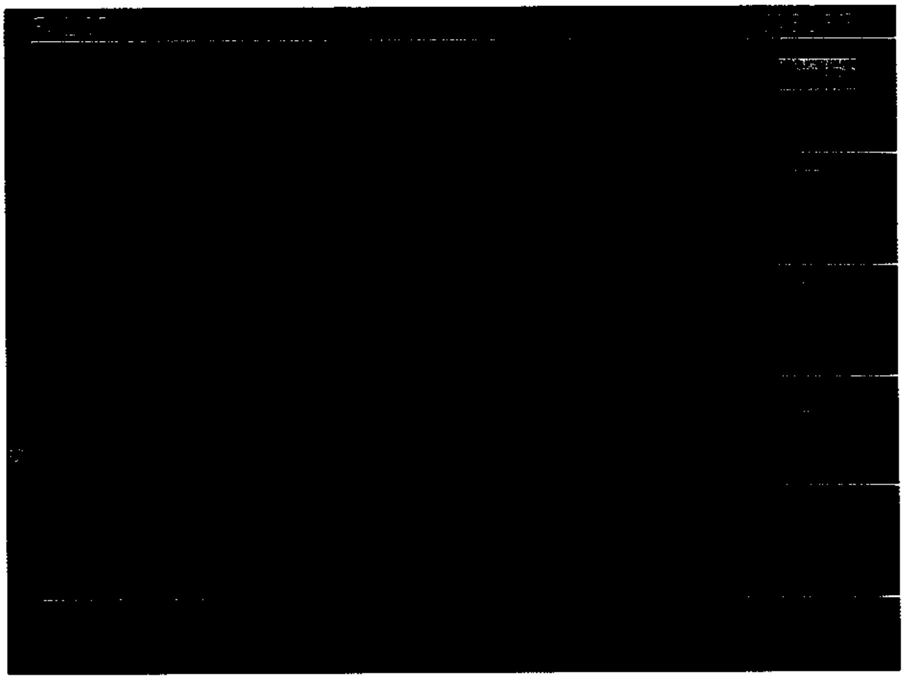


Fig 5.10 PWM Signals

CHAPTER 6

CHAPTER 6

CONCLUSION

6.1 CONCLUSION

The squirrel-cage induction generator has the advantages of low cost and high durability, it is used in wind power generation. This paper proposes a reactive power compensator, comprising an ac power capacitor set in series with a novel circuit configuration of power converter, to improve the power factor for the squirrel-cage induction generator. The salient points of the proposed reactive power compensator are that only a two-arm structure is required for the power converter in the three-phase three-wire application and the capacity of the power converter is small. The simulation results indicate that the proposed reactive power compensator can effectively compensate for the reactive power of the squirrel-cage induction generator.

REFERENCES

[1] C. Chompoo-inwai, C. Yingvivatanapong, K. Methaprayoon, and W. J. Lee, "Reactive compensation techniques to improve the ride-through capability of wind turbine during disturbance," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 666–672, May/Jun. 2005.

[2] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy onvers.*, vol. 18, no. 2, pp. 194–204, Jun. 2003.

[3] S. Muller, M. Deicke, and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Ind. Appl. Mag.*, vol. 8, no. 3, pp. 26–33, May/Jun. 2002.

[4] F. Zhou, G. Joos, and B. T. Ooi, "AC power transmission from remote large scale wind park based on squirrel-cage induction generator," in *Proc. IEEE Int. Conf. Power Syst. Technol. PowerCon,* Nov. 21–24, 2004, vol. 1, pp. 52–57.

[5] K. K. Sasi and S. Basu, "Technology options for utility grade electric power generation from wind," in *Proc. IEEE Int. Conf. Ind. Technol.,* Jan. 19–22, 2000, vol. 1, pp. 638–643.

[6] A. A. Bayod, J. A. Dominguez, J. Mur, and J. J. Melero, "Combined system for reactive power control in wind farms," in *Proc. IEEE IECON,* Nov. 5–8, 2002, vol. 4, pp. 3291–3296.

[7] N. Garcia and A. Medina, "Fast periodic steady state solution of systems containing thyristor switched capacitors," in *Proc. IEEE Power Electron. Spec. Conf.,* Jul. 16–20, 2000, vol. 2, pp. 1127–1132.

[8] N. Mohan, T. M. Undeland, and W. P. Robbins, "Power electronics converters, applications and design," in *Media Enhanced,* 3rd ed. New York: Wiley, 2003. [9] C.Wang, T. C. Cheng, G. Zheng,Y. D. L. Mu,B. Palk, and M. Moon, "Failure analysis of composite dielectric of power capacitors in distribution systems," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 5, no. 4, pp. 583–588, Aug. 1998.

[10] J. R. Harbaugh and J. E. Harder, "Important considerations for capacitor applications in the petroleum and chemical process industries," *IEEE Trans. Ind. Appl.*, vol. IA-18, no. 1, pp. 31–40, Jan./Feb. 1982.

[11] B. Singh, S. S. Murthy, and S. Gupta, "Analysis and design of STATCOM-based voltage regulator for self-excited induction generators," *IEEE Trans. Energy Convers.*, vol. 19, no. 4, pp. 783–790, Dec. 2004.

[12] M. B. C. Salles, W. Freitas, and A. Morelato, "Comparative analysis between SVC and DSTATCOM devices for improvement of induction generator stability," in *Proc. IEEE MELECON,* May 12–15, 2004, vol. 3, pp. 1025–1028.

[13] L. Xu, V. G. Agelidis, and E. Acha, "Development considerations of DSPcontrolled PWM VSC-based STATCOM," *Inst. Electr. Eng. Proc. Electr. Power Appl.*, vol. 148, no. 5, pp. 449–455, Sep. 2001.

[14] J. J. Grainger andW. D. Stevenson, *Power System Analysis.* NewYork:McGraw-Hill, 1994. [15] J. C. Wu, H. L. Jou, K. D. Wu, and N. C. Shen, "Power converter based method for protecting three-phase power capacitor from harmonic destruction," *IEEE Trans. Power Del.*, vol. 19, no. 3, pp. 1434–1441, Jul. 2004.

APPENDIX I

Philips Semiconductors — Product specification

N-channel enhancement mode TrenchMOS™ transistor

IRFZ44N

GENERAL DESCRIPTION

N-channel enhancement mode standard level field-effect power transistor in a plastic envelope using 'trench' technology. The device features very low on-state resistance and has integral zener diodes giving ESD protection up to 2kV. It is intended for use in switched mode power supplies and general purpose switching applications.

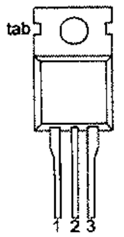
QUICK REFERENCE DATA

SYMBOL	PARAMETER	MAX.	UNIT
V_{DS}	Drain-source voltage	55	V
I_D	Drain current (DC)	49	A
P_{tot}	Total power dissipation	110	W
T_j	Junction temperature	175	˚C
$R_{DS(ON)}$	Drain-source on-state resistance $V_{GS} = 10$ V	22	mΩ

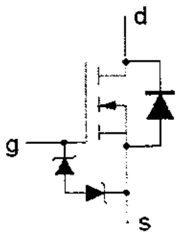
PINNING - TO220AB

PIN	DESCRIPTION
1	gate
2	drain
3	source
tab	drain

PIN CONFIGURATION



SYMBOL



LIMITING VALUES

Limiting values in accordance with the Absolute Maximum System (IEC 134)

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_{DS}	Drain-source voltage	-	-	55	V
V_{DGR}	Drain-gate voltage	$R_{GS} = 20$ kΩ	-	55	V
$\pm V_{GS}$	Gate-source voltage	-	-	20	V
I_D	Drain current (DC)	$T_{mb} = 25$ ˚C	-	49	A
I_D	Drain current (DC)	$T_{mb} = 100$ ˚C	-	35	A
I_{DM}	Drain current (pulse peak value)	$T_{mb} = 25$ ˚C	-	160	A
P_{tot}	Total power dissipation	$T_{mb} = 25$ ˚C	-	110	W
T_{stg}, T_j	Storage & operating temperature	-	- 55	175	˚C

ESD LIMITING VALUE

SYMBOL	PARAMETER	CONDITIONS	MIN.	MAX.	UNIT
V_C	Electrostatic discharge capacitor voltage, all pins	Human body model (100 pF, 1.5 kΩ)	-	2	kV

THERMAL RESISTANCES

SYMBOL	PARAMETER	CONDITIONS	TYP.	MAX.	UNIT
$R_{th\ j\text{-}mb}$	Thermal resistance junction to mounting base	-	-	1.4	K/W
$R_{th\ j\text{-}a}$	Thermal resistance junction to ambient	in free air	60	-	K/W

STATIC CHARACTERISTICS

T_j = 25°C unless otherwise specified

SYMBOL	PARAMETER	CONDITIONS	MIN.	TYP.	MAX.	UNIT
$V_{(BR)DSS}$	Drain-source breakdown voltage	V_{GS} = 0 V; I_D = 0.25 mA;	55	-	-	V
		T_j = -55°C	50	-	-	V
$V_{GS(TO)}$	Gate threshold voltage	V_{DS} = V_{GS}; I_D = 1 mA	2.0	3.0	4.0	V
		T_j = 175°C	1.0	-	-	V
		T_j = -55°C	-	-	4.4	
I_{DSS}	Zero gate voltage drain current	V_{DS} = 55 V; V_{GS} = 0 V;	-	0.05	10	μA
		T_j = 175°C	-	-	500	μA
I_{GSS}	Gate source leakage current	V_{GS} = ±10 V; V_{DS} = 0 V	-	0.04	1	μA
		T_j = 175°C	-	-	20	μA
$\pm V_{(BR)GSS}$	Gate source breakdown voltage	I_G = ±1 mA;	16	-	-	V
$R_{DS(ON)}$	Drain-source on-state resistance	V_{GS} = 10 V; I_D = 25 A	-	15	22	mΩ
		T_j = 175°C	-	-	42	mΩ

DYNAMIC CHARACTERISTICS

T_{mb} = 25°C unless otherwise specified

SYMBOL	PARAMETER	CONDITIONS	MIN.	TYP.	MAX.	UNIT
g_{fs}	Forward transconductance	V_{DS} = 25 V; I_D = 25 A	6	-	-	S
C_{iss}	Input capacitance	V_{GS} = 0 V; V_{DS} = 25 V; f = 1 MHz	-	1350	1800	pF
C_{oss}	Output capacitance		-	330	400	pF
C_{rss}	Feedback capacitance		-	155	215	pF
Q_g	Total gate charge	V_{DD} = 44 V; I_D = 50 A; V_{GS} = 10 V	-	-	62	nC
Q_{gs}	Gate-cource charge		-	-	15	nC
Q_{gd}	Gate-drain (miller) charge		-	-	26	nC
$t_{d\,on}$	Turn-on delay time	V_{DD} = 30 V; I_D = 25 A;	-	18	26	ns
t_r	Turn-on rise time	V_{GS} = 10 V; R_G = 10 Ω	-	50	75	ns
$t_{d\,off}$	Turn-off delay time	Resistive load	-	40	50	ns
t_f	Turn-off fall time		-	30	40	ns
L_d	Internal drain inductance	Measured from contact screw on tab to centre of die	-	3.5	-	nH
L_d	Internal drain inductance	Measured from drain lead 6 mm from package to centre of die	-	4.5	-	nH
L_s	Internal source inductance	Measured from source lead 6 mm from package to source bond pad	-	7.5	-	nH

REVERSE DIODE LIMITING VALUES AND CHARACTERISTICS

T_j = 25°C unless otherwise specified

SYMBOL	PARAMETER	CONDITIONS	MIN.	TYP.	MAX.	UNIT
I_{DR}	Continuous reverse drain current		-	-	49	A
I_{DRM}	Pulsed reverse drain current		-	-	160	A
V_{SD}	Diode forward voltage	I_F = 25 A; V_{GS} = 0 V	-	0.95	1.2	V
		I_F = 40 A; V_{GS} = 0 V	-	1.0	-	
t_{rr}	Reverse recovery time	I_F = 40 A; $-dI_F/dt$ = 100 A/μs;	-	47	-	ns
Q_{rr}	Reverse recovery charge	V_{GS} = -10 V; V_R = 30 V	-	0.15	-	μC

MC78XX/LM78XX

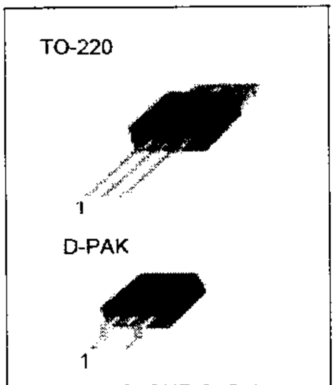
3-terminal 1A positive voltage regulator

Features

- Output Current up to 1A
- Output Voltages of 5, 6, 8, 9, 10, 11, 12, 15, 18, 24V
- Thermal Overload Protection
- Short Circuit Protection
- Output Transistor Safe Operating area Protection

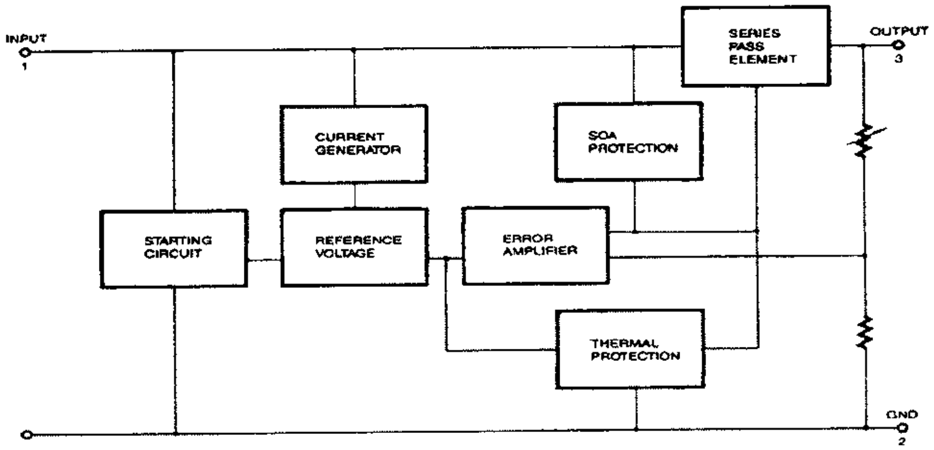
Description

The MC78XX/LM78XX series of three-terminal positive regulators are available in the TO-220/D-PAK package and with several fixed output voltages, making them useful in a wide range of applications. Each type employs internal current limiting, thermal shut-down and safe operating area protection, making it essentially indestructible. If adequate heat sinking is provided, they can deliver over 1A output current. Although designed primarily as fixed voltage regulators, these devices can be used with external components to obtain adjustable voltages and currents.



1. Input 2. GND 3. Output

Internal Block Digram



Absolute Maximum Ratings

Parameter	Symbol	Value	Unit
Input Voltage (for V_O = 5V to 18V) (for V_O = 24V)	V_I V_I	35 40	V V
Thermal Resistance Junction-Cases	$R_{\theta JC}$	5	°C/W
Thermal Resistance Junction-Air	$R_{\theta JA}$	65	°C/W
Operating Temperature Range (MC78XXCT/LM78XXCT/MC78XXCDT)	T_{OPR}	0 ~ +125	°C
Storage Temperature Range	T_{STG}	-65 ~ +150	°C

Electrical Characteristics (MC7805/LM7805)

(Refer to test circuit ,0°C < T_J < 125°C, I_O = 500mA, V_I = 10V, C_I= 0.33μF, C_O= 0.1μF, unless otherwise specified)

Parameter	Symbol	Conditions		MC7805/LM7805			Unit
				Min.	Typ.	Max.	
Output Voltage	V_O	T_J =+25 °C		4.8	5.0	5.2	V
		5.0mA ≤ Io ≤ 1.0A, P_O ≤ 15W V_I = 7V to 20V V_I = 8V to 20V		4.75	5.0	5.25	
Line Regulation	ΔV_O	T_J=+25 °C	V_O = 7V to 25V	-	4.0	100	mV
			V_I = 8V to 12V	-	1.6	50	
Load Regulation	ΔV_O	T_J=+25 °C	I_O = 5.0mA to1.5A	-	9	100	mV
			I_O =250mA to 750mA	-	4	50	
Quiescent Current	I_Q	T_J =+25 °C		-	5.0	8	mA
Quiescent Current Change	ΔI_Q	I_O = 5mA to 1.0A		-	0.03	0.5	mA
		V_I= 7V to 25V		-	0.3	1.3	
Output Voltage Drift	$\Delta V_O/\Delta T$	I_O= 5mA		-	-0.8	-	mV/ °C
Output Noise Voltage	V_N	f = 10Hz to 100KHz, T_A=+25 °C		-	42	-	μV
Ripple Rejection	RR	f = 120Hz V_O = 8V to 18V		62	73	-	dB
Dropout Voltage	V_O	I_O = 1A, T_J =+25 °C		-	2	-	V
Output Resistance	R_O	f = 1KHz		-	15	-	mΩ
Short Circuit Current	I_{SC}	V_I = 35V, T_A =+25 °C		-	230	-	mA
Peak Current	I_{PK}	T_J =+25 °C		-	2.2	-	A

- Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.

Electrical Characteristics (MC7806)

(Refer to test circuit ,0°C < T_J < +125°C, I_O = 500mA, V_I = 11V, C_I= 0.33μF, C_O= 0.1μF, unless otherwise specified)

Parameter	Symbol	Conditions		MC7806			Unit
				Min.	Typ.	Max.	
Output Voltage	V_O	T_J =+25 °C		5.75	6.0	6.25	V
		5.0mA ≤ I_O ≤ 1.0A, P_D ≤ 15W V_I = 8.0V to 21V V_I = 9.0V to 21V		5.7	6.0	6.3	
Line Regulation	ΔV_O	T_J =+25 °C	V_I = 8V to 25V	-	5	120	mV
			V_I = 9V to 13V	-	1.5	60	
Load Regulation	ΔV_O	T_J =+25 °C	I_O =5mA to 1.5A	-	9	120	mV
			I_O =250mA to750A	-	3	60	
Quiescent Current	I_Q	T_J =+25 °C		-	5.0	8	mA
Quiescent Current Change	ΔI_Q	I_O = 5mA to 1A		-	-	0.5	mA
		V_I = 8V to 25V		-	-	1.3	
Output Voltage Drift	$\Delta V_O/\Delta T$	I_O = 5mA		-	-0.8	-	mV/ °C
Output Noise Voltage	V_N	f = 10Hz to 100KHz, T_A =+25 °C		-	45	-	μV
Ripple Rejection	RR	f = 120Hz V_I = 9V to 19V		59	75	-	dB
Dropout Voltage	V_O	I_O = 1A, T_J =+25 °C		-	2	-	V
Output Resistance	R_O	f = 1KHz		-	19	-	mΩ
Short Circuit Current	I_{SC}	V_I= 35V, T_A=+25 °C		-	250	-	mA
Peak Current	I_{PK}	T_J =+25 °C		-	2.2	-	A

- Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.

LM2904,LM358/LM358A,LM258/ LM258A

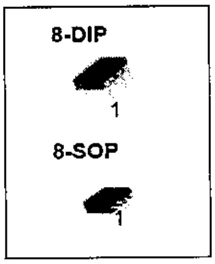
Dual Operational Amplifier

Features

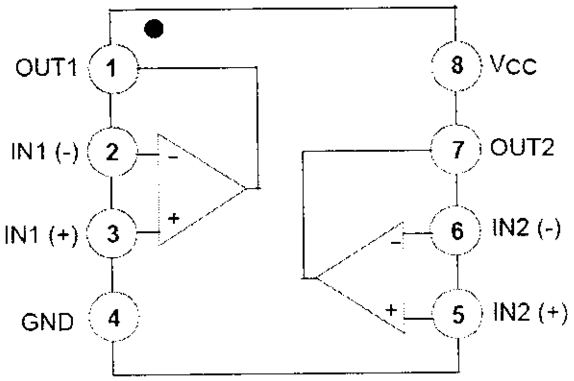
- Internally Frequency Compensated for Unity Gain
- Large DC Voltage Gain: 100dB
- Wide Power Supply Range:
  LM258/LM258A. LM358/LM358A: 3V~32V (or ±1.5V ~ 16V)
  LM2904 : 3V~26V (or ±1.5V ~ 13V)
- Input Common Mode Voltage Range Includes Ground
- Large Output Voltage Swing: 0V DC to Vcc -1.5V DC
- Power Drain Suitable for Battery Operation.

Description

The LM2904,LM358/LM358A. LM258/LM258A consist of two independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltage. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage. Application areas include transducer amplifier, DC gain blocks and all the conventional OP-AMP circuits which now can be easily implemented in single power supply systems.



Internal Block Diagram



Absolute Maximum Ratings

Parameter	Symbol	LM258/LM258A	LM358/LM358A	LM2904	Unit
Supply Voltage	V_{CC}	±16 or 32	±16 or 32	±13 or 26	V
Differential Input Voltage	$V_{I(DIFF)}$	32	32	26	V
Input Voltage	V_I	-0.3 to +32	-0.3 to +32	-0.3 to +26	V
Output Short Circuit to GND $V_{CC} \leq 15V$, $T_A = 25°C$(One Amp)	-	Continuous	Continuous	Continuous	-
Operating Temperature Range	T_{OPR}	-25 ~ +85	0 ~ +70	-40 ~ +85	°C
Storage Temperature Range	T_{STG}	-65 ~ +150	-65 ~ +150	-65 ~ +150	°C

Electrical Characteristics

($V_{CC} = 5.0V$, V_{EE} = GND, $T_A = 25°C$, unless otherwise specified)

Parameter	Symbol	Conditions	LM258			LM358			LM2904			Unit
			Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	
Input Offset Voltage	V_{IO}	$V_{CM} = 0V$ to V_{CC} -1.5V $V_{O(P)} = 1.4V$, $R_S = 0\Omega$	-	2.9	5.0	-	2.9	7.0	-	2.9	7.0	mV
Input Offset Current	I_{IO}	-	-	3	30	-	5	50	-	5	50	nA
Input Bias Current	I_{BIAS}	-	-	45	150	-	45	250	-	45	250	nA
Input Voltage Range	$V_{I(R)}$	$V_{CC} = 30V$ (LM2904, $V_{CC}=26V$)	0	-	Vcc -1.5	0	-	Vcc -1.5	0	-	Vcc -1.5	V
Supply Current	I_{CC}	$R_L = \infty$, $V_{CC} = 30V$ (LM2904, $V_{CC}=26V$)	-	0.8	2.0	-	0.8	2.0	-	0.8	2.0	mA
		$R_L = \infty$, $V_{CC} = 5V$	-	0.5	1.2	-	0.5	1.2	-	0.5	1.2	mA
Large Signal Voltage Gain	G_V	$V_{CC} = 15V$, $R_L = 2k\Omega$ $V_{O(P)} = 1V$ to 11V	50	100	-	25	100	-	25	100	-	V/mV
Output Voltage Swing	$V_{O(H)}$	$V_{CC}=30V$ (V_{CC} =26V for LM2904), $R_L = 2k\Omega$	26	-	-	26	-	-	22	-	-	V
		$V_{CC}=30V$ (V_{CC} =26V for LM2904), $R_L = 10k\Omega$	27	28	-	27	28	-	23	24	-	V
	$V_{O(L)}$	$V_{CC} = 5V$, $R_L = 10k\Omega$	-	5	20	-	5	20	-	5	20	mV
Common-Mode Rejection Ratio	CMRR	-	70	85	-	65	80	-	50	80	-	dB
Power Supply Rejection Ratio	PSRR	-	65	100	-	65	100	-	50	100	-	dB
Channel Separation	CS	f = 1kHz to 20kHz (Note1)	-	120	-	-	120	-	-	120	-	dB
Short Circuit to GND	I_{SC}	-	-	40	60	-	40	60	-	40	60	mA
Output Current	I_{SOURCE}	$V_{I(+)} = 1V$, $V_{I(-)} = 0V$ $V_{CC} = 15V$, $V_{O(P)} = 2V$	20	30	-	20	30	-	20	30	-	mA
	I_{SINK}	$V_{I(+)} = 0V$, $V_{I(-)} = 1V$, $V_{CC} = 15V$, $V_{O(P)} = 2V$	10	15	-	10	15	-	10	15	-	mA
		$V_{I(+)} = 0V$, $V_{I(-)} = 1V$, $V_{CC} = 15V$, $V_{O(P)} = 200mV$	12	100	-	12	100	-	-	-	-	μA
Differential Input Voltage	$V_{I(DIFF)}$	-	-	-	Vcc	-	-	Vcc	-	-	Vcc	V

1N4001 - 1N4007

Features

- Low forward voltage drop.
- High surge current capability.

DO-41
COLOR BAND DENOTES CATHODE

General Purpose Rectifiers (Glass Passivated)

Absolute Maximum Ratings*

T_A = 25°C unless otherwise noted

Symbol	Parameter	Value							Units
		4001	4002	4003	4004	4005	4006	4007	
V_{RRM}	Peak Repetitive Reverse Voltage	50	100	200	400	600	800	1000	V
$I_{F(AV)}$	Average Rectified Forward Current, .375 " lead length @ T_A = 75°C	1.0							A
I_{FSM}	Non-repetitive Peak Forward Surge Current 8.3 ms Single Half-Sine-Wave	30							A
T_{stg}	Storage Temperature Range	-55 to +175							°C
T_J	Operating Junction Temperature	-55 to +175							°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

Thermal Characteristics

Symbol	Parameter	Value	Units
P_D	Power Dissipation	3.0	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	50	°C/W

Electrical Characteristics

T_A = 25°C unless otherwise noted

Symbol	Parameter	Device							Units
		4001	4002	4003	4004	4005	4006	4007	
V_F	Forward Voltage @ 1.0 A	1.1							V
I_{rr}	Maximum Full Load Reverse Current, Full Cycle T_A = 75°C	30							µA
I_R	Reverse Current @ rated V_R T_A = 25°C T_A = 100°C	5.0 500							µA µA
C_T	Total Capacitance V_R = 4.0 V, f = 1.0 MHz	15							pF

Typical Characteristics

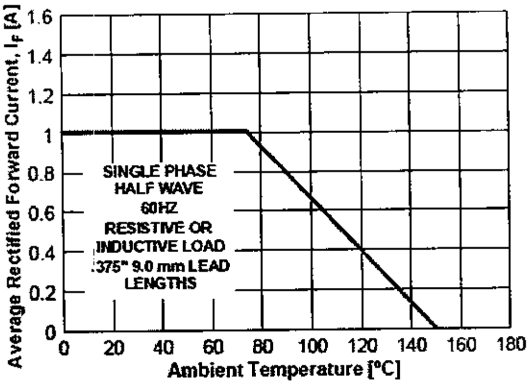


Figure 1. Forward Current Derating Curve

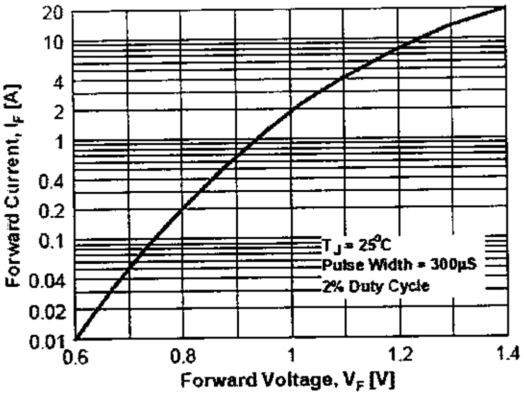


Figure 2. Forward Voltage Characteristics

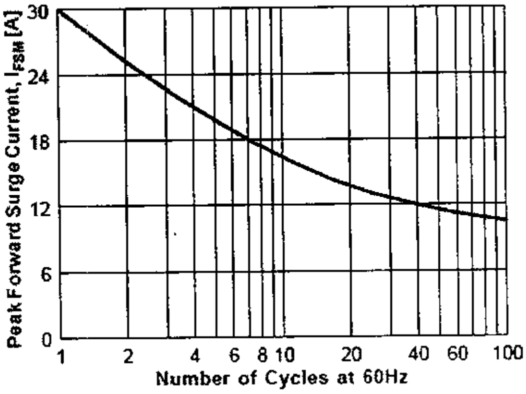


Figure 3. Non-Repetitive Surge Current

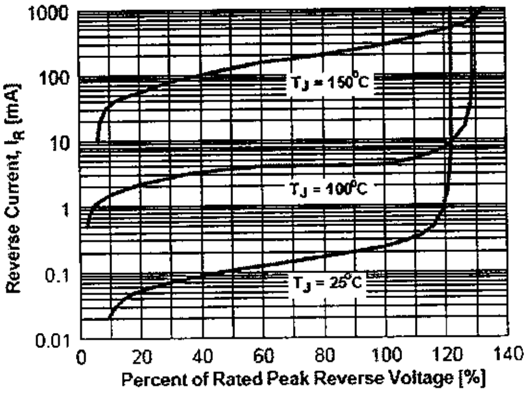
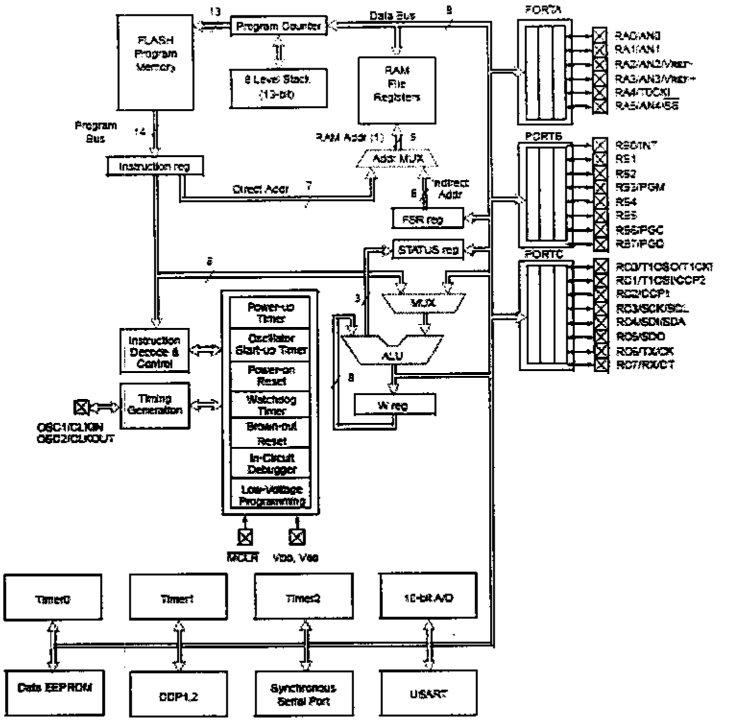


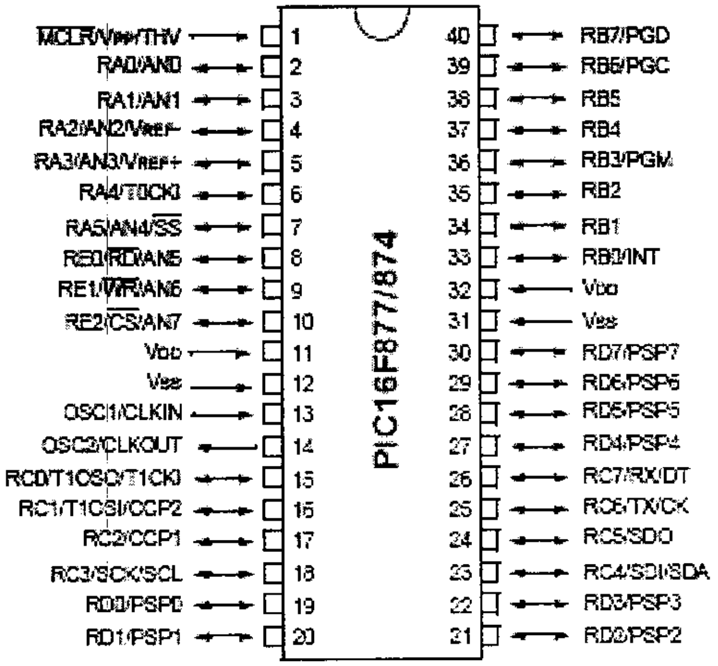
Figure 4. Reverse Current vs Reverse Voltage

ARCHITECTURE OF PIC 16F877A

Device	Program FLASH	Data Memory	Data EEPROM
PIC16F873	4K	192 Bytes	128 Bytes
PIC16F876	8K	368 Bytes	256 Bytes



Pin Configuration of PIC16F877A



TIMER 0 CONTROL REGISTER:

R/W-1	R/W-1	R/W-1	R/W-1	R/W-1	R/W-1	R/W-1	R/W-1
$\overline{\text{RBPU}}$	INTEDG	T0CS	T0SE	PSA	PS2	PS1	PS0
bit 7							bit 0

bit 7: **RBPU**

bit 6: **INTEDG**

bit 5: **T0CS**: TMR0 Clock Source Select bit

1 = Transition on T0CKI pin

0 = Internal instruction cycle clock (CLKOUT)

bit 4: **T0SE**: TMR0 Source Edge Select bit

1 = Increment on high-to-low transition on T0CKI pin

0 = Increment on low-to-high transition on T0CKI pin

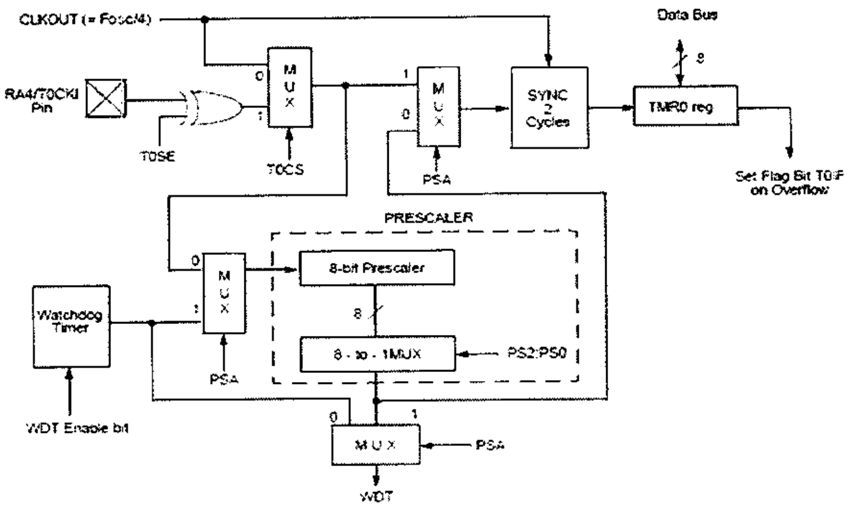
bit 3: **PSA**: Prescaler Assignment bit

1 = Prescaler is assigned to the WDT

0 = Prescaler is assigned to the Timer0 module

bit 2-0: **PS2 PS1 PS0**: Prescaler Rate Select bits

TIMER 0 BLOCK DIAGRAM:



TIMER 1 CONTROL REGISTER:

U-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	—	T1CKPS1	T1CKPS0	T1OSCEN	$\overline{\text{T1SYNC}}$	TMR1CS	TMR1ON
bit7							bit0

bit 7-6: **Unimplemented:** Read as '0'

bit 5-4: **T1CKPS1:T1CKPS0**: Timer1 Input Clock Prescale Select bits

11 = 1:8 Prescale value

10 = 1:4 Prescale value

01 = 1:2 Prescale value

00 = 1:1 Prescale value

bit 3: **T1OSCEN**: Timer1 Oscillator Enable Control bit

1 = Oscillator is enabled

0 = Oscillator is shut off (The oscillator inverter is turned off to eliminate power drain)

bit 2: **T1SYNC**: Timer1 External Clock Input Synchronization Control bit

TMR1CS = 1

1 = Do not synchronize external clock input

0 = Synchronize external clock input

TMR1CS = 0

This bit is ignored. Timer1 uses the internal clock when TMR1CS = 0.

bit 1: **TMR1CS**: Timer1 Clock Source Select bit

1 = External clock from pin RC0/T1OSO/T1CKI (on the rising edge)

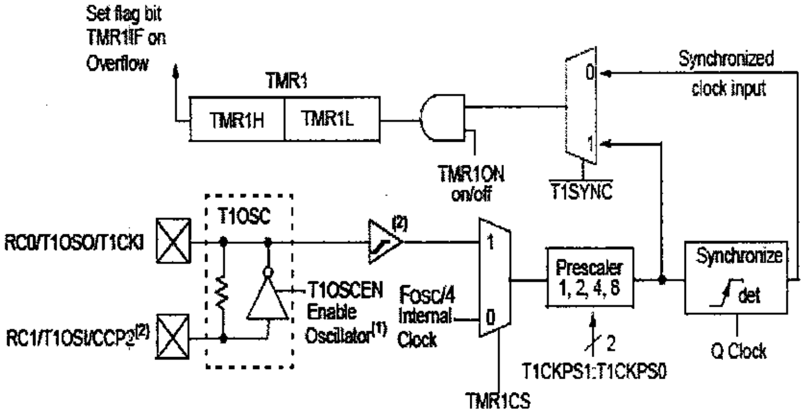
0 = Internal clock (FOSC/4)

bit 0: **TMR1ON**: Timer1 On bit

1 = Enables Timer1

0 = Stops Timer1

TIMER 1 BLOCK DIAGRAM:



TIMER 2 CONTROL REGISTER:

U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	TOUTPS3	TOUTPS2	TOUTPS1	TOUTPS0	TMR2ON	T2CKPS1	T2CKPS0
bit7							bit0

bit 7: **Unimplemented:** Read as '0'

bit 6-3: **TOUTPS3:TOUTPS0**: Timer2 Output Postscale Select bits

0000 = 1:1 Postscale

0001 = 1:2 Postscale

0010 = 1:3 Postscale

1111 = 1:16 Postscale

bit 2: **TMR2ON**: Timer2 On bit

1 = Timer2 is on

0 = Timer2 is off

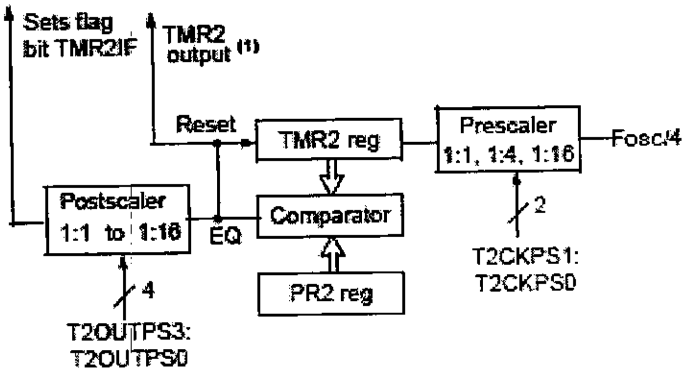
bit 1-0: **T2CKPS1:T2CKPS0**: Timer2 Clock Prescale Select bits

00 = Prescaler is 1

01 = Prescaler is 4

1x = Prescaler is 16

TIMER2 BLOCK DIAGRAM:



CCP1CON REGISTER/CCP2CON REGISTER:

U-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
—	—	CCPxX	CCPxY	CCPxM3	CCPxM2	CCPxM1	CCPxM0
bit7							bit0

bit 7-6: **Unimplemented:** Read as '0'

bit 5-4: **CCPxX :CCPxY**: PWM Least Significant bits

Capture Mode: Unused

Compare Mode: Unused

PWM Mode: These bits are the two LSB s of the PWM duty cycle. The eight MSB s are found in CCPRxL.

bit 3-0: **CCPxM3:CCPxM0**: CCPx Mode Select bits

0000 = Capture/Compare/PWM off (resets CCPx module)

0100 = Capture mode, every falling edge

0101 = Capture mode, every rising edge

0110 = Capture mode, every 4th rising edge

0111 = Capture mode, every 16th rising edge

1000 = Compare mode, set output on match (CCPxIF bit is set)

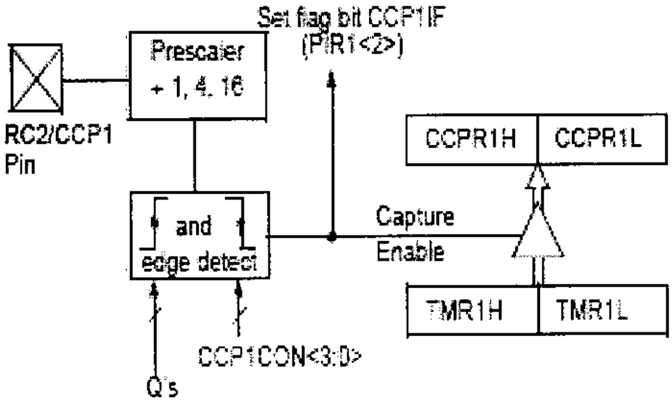
1001 = Compare mode, clear output on match (CCPxIF bit is set)

1010 = Compare mode, generate software interrupt on match (CCPxIF bit is set, CCPx pin i unaffected)

1011 = Compare mode, trigger special event (CCPxIF bit is set, CCPx pin is unaffected); CCP resets TMR1; CCP2 resets TMR1 and starts an A/D conversion (if A/D module is enabled)

11xx = PWM mode

CAPTURE MODE OPERATION BLOCK DIAGRAM:



COMPARE MODE OPERATION BLOCK DIAGRAM: