AC to DC Converter Topology for Improved Power Factor and Lower Harmonics - A REVIEW

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Abstract

Rectifier circuits are being applied in various AC to DC conversion requiring DC supply at load end as the power source is mostly AC. In most electronic power supplies, the AC input is rectified and a bulk capacitor is connected directly after the diode rectifier bridge. This type of utility interface draws excessive peak input currents; it produces a high level of harmonics, and both the input power factor (PF) and total harmonic distortion (THD) are poor. The low PF makes the efficiency of the electrical power grid to be very low. Earlier; the converters were large in size and were expensive as well. A remarkable reduction in size and price was possible due to the invention of switch mode power supply.For a better utilization of the existing electrical energy the entire power system should be operated at high efficiency. At present, various techniques of rectification by using Diode based bridge rectifier ,thyristor based bridge rectifier etc. in open loop are available but these techniques have their limitations.Therefore,PWM rectifiers are now being considered

This paper reviews the most effective techniques widely used by researchers for improving single phase and three phase converters. This, will aid further study of the inherent research problems associated with harmonic distortion (THD) and power factor correction (PFC) in converters.

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1. Introduction

As much as power electronic devices are necessary for the working of a device, the quality of power delivered to the device is equally important. With increased use of power electronic devices there arise a number of problems. One of them being the harmonic pollution that degrades the power quality and hence affects the other devices connected to the power supply. In order to make the devices perform better and decrease the power pollution it becomes necessary to reduce the harmonics and to improve the power factor of the devices present in the system that are responsible for this problem. One of the mostly used devices that cause this problem is converters. The disturbance caused in the circuit /power transmission line is due to the switching of power electronic devices.

The spreading use of electronic equipment causes mains harmonics in commercial ac lines, which trigger power capacitors to be broken down and increases voltage distortion.

In day to day life the devices that we use the most like laptops, led lamps, mobile phone chargers etc. requiring DC supply at load end need to have rectifiers in them that provide AC to DC conversion as the power source is mostly AC. During this conversion a lot of lower order harmonics are generated.

Harmonic currents, generated by non-linear electronic loads, increase power system heat losses and power bills of end-users. These harmonic-related losses reduce system efficiency, cause apparatus overheating, and increase power and air conditioning costs. As the number of harmonics-producing loads has increased over the years, it has become increasingly necessary to address their influence when making any additions or changes to a device or installation.Harmonic currents can have a significant impact on electrical distribution systems and the facilities that they feed. It is important to consider their impact when planning additions or changes to a system.

To overcome this problem the converters used in the devices, specifically the AC-DC converters are being modified in order to reduce the harmonic distortion and imnprove the power factor hence improving the overall efficiency of the system and reducing the power pollution.

The modern electronic devices operate with low DC output voltage. Rectifier circuits are being applied in various AC to DC conversion requiring DC supply at load end as the power source is mostly AC. In most electronic power supplies, the AC input is rectified and a bulk capacitor is connected directly after the diode rectifier bridge. This type of utility interface draws excessive peak input currents; it produces a high level of harmonics, and both the input power factor (PF) and total harmonic distortion (THD) are poor. The low PF makes the efficiency of the electrical power grid to be very low. Earlier; the converters were large in size and were expensive as well. A remarkable reduction in size and price was possible due to the invention of switch mode power supply. This goal was achieved by expanding the power density which is achievable by decreasing the size of the passive/energy storage components such as the inductors, capacitors and the transformers. For a better utilization of the existing electrical energy the entire power system should be operated at high efficiency. At present, various techniques of rectification in open loop are available but these techniques have their limitations. Diode based bridge rectifiers do not give controlled output voltage and source current quality is also not good because of high THD. Controlled output DC voltage can be obtained by using thyristor based bridge rectifier for voltage control less than the supply and for output voltage greater than supply value buck boost configuration in second stage can be implemented after rectification. Thus, the problem of controlled output voltage is solved but source current will still have high harmonic distortion. Thus, the shortcomings of low power factor are difficult to overcome with. The PWM rectifier is a very popular topic nowadays. With the expansion of electronics, conversion of electric parameters is also needed. For this purpose the side effects of passive rectifiers, e.g. production of harmonics and reactive power, must be taken into account. All these side effects fall away with the application of PWM rectifiers. PWM rectifier circuit can realize real-time tracking of ac voltage, ac current to obtain a rectifier with higher power factor.

To change the line frequency from ac to dc, a diode bridge rectifier is used. A large filter capacitor is necessary at the output side of the rectifier in order to absorb the ripple in the output voltage. In any case, current drawn by this converter is peaky by characteristics. This input current is high in lower order harmonics and because of the existence of these harmonics; the total harmonic distortion (THD) is high. Issues related with these are low power factor and harmonics. The utilities issue harmonic standards and rules which constrain the measure of current distortion permitted into the utility. It is greatly required to accomplish rectification at low input current distortion and near unity power factor.

2. Various types of converters

2.1 Classification

Diode rectifiers are classified into two types: Single-Phase and Three-Phase.
The Rectification can be done using three methods: Half wave rectification, Full wave rectification and Bridge rectification.

Single-Phase Half wave rectification is done with a single diode. But the output is not efficient enough for power applications.

Single-Phase Full wave rectification can be done in various ways. These are:
1) Full Wave transformer using Center-tap transformer
2) Dual polarity Full Wave Center-tap rectifier
3) Full Wave Bridge rectifier

Other than single-phase rectification, the following configurations are used:

1) Three phase full wave bridge rectifier
2) Six phase full wave bridge rectifier
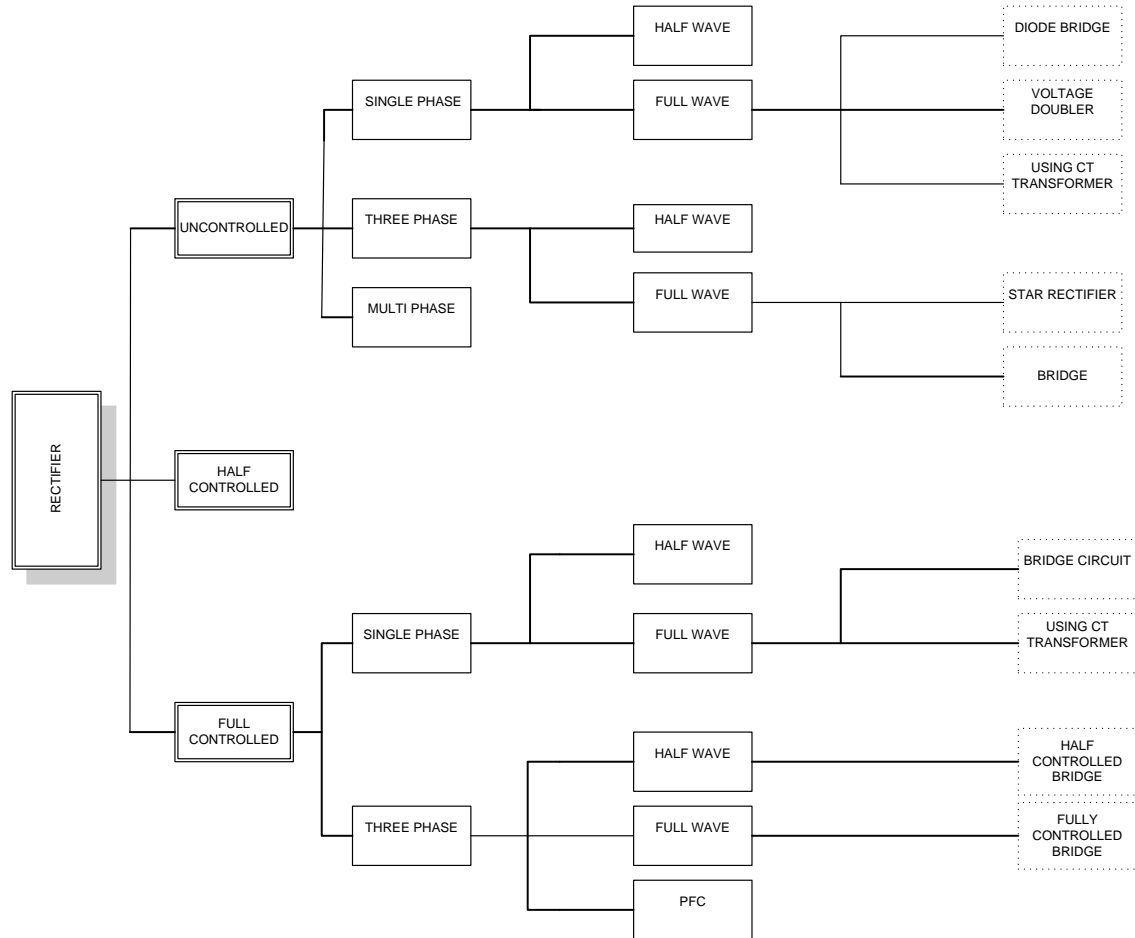3) Poly-phase rectifier circuit 3-phase 2-way 12-pulse (3Ph2W12P)

Fig.2.1: Classification of AC-DC converters

3. Review of Literature and comparison of various topologies

3.1 Diode based Bridge Rectifier

This is the simplest and probably the most widely used rectifier circuit available at relatively small power levels. The output voltage and current of this rectifier are strongly influenced by the type of the load. The principal circuit operations of the various configurations of rectifier circuits are similar, whether half or full wave, single-phase or three phase. Such circuits are said to be uncontrolled since the rectified output voltage and current are a function only of the applied excitation, with no mechanism for varying the output level. In such circuits, regardless of the configuration, diodes are almost always used to achieve rectification.

3.1.1 Single Phase Full-wave Bridge Rectifier

This bridge configuration of diodes provides full-wave rectification because at any time two of the four diodes are forward biased while the other two are reverse biased. Thus there are two diodes in the conduction path instead of the single one for the half-wave rectifier. Therefore there will be a difference in voltage amplitude between V_{IN} and V_{OUT} due to the two forward voltage drops of the serially connected diodes. Here as before, for simplicity of the math we will assume ideal diodes.

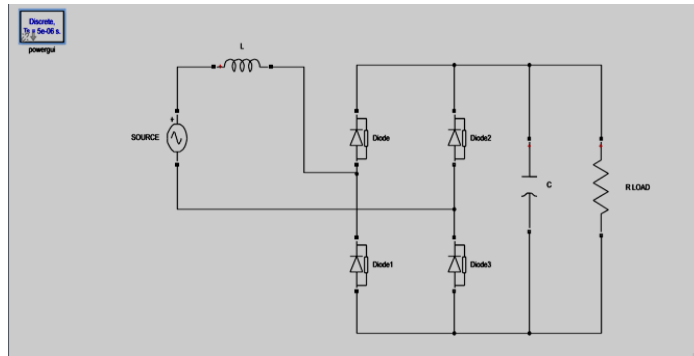The average output voltage is given by $V_{Oavg} = \dfrac{2Vm}{\pi}$

Fig 3.1 Single Phase Full Wave Bridge Rectifier

3.2 SCR Based Controlled Bridge Rectifier

In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle.The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load. By controlling the phase angle or the trigger angle 'α' (delay angle), the output RMS voltage across the load can be controlled.
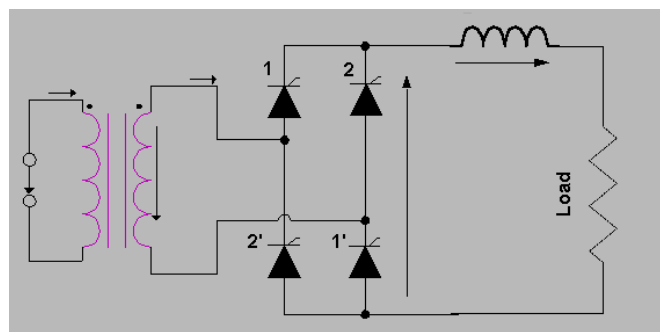

Figure.3.2 SCR based phase controlled full wave bridge rectifier

3.3 Buck-Boost Converter

The buck boost converter is a DC to DC converter. The output voltage of the DC to DC converter is less than or greater than the input voltage. The output voltage of the magnitude depends on the duty cycle. These converters are also known as the step up and step down transformers and these names are coming from the analogous step up and step down transformer.

In the fig.3.3 operation of a buck-boost converter can be understood. An AC supply is given to a diode bridge rectifier whose output is a dc voltage which is further input to the buck boost converter for stepping up/down the output dc voltage. Output voltage is given by
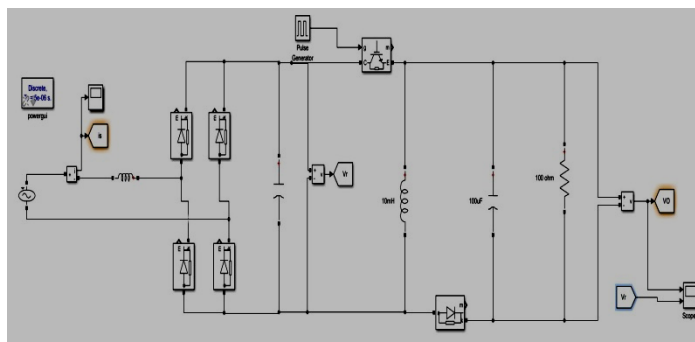
$$v_0 = \frac{D}{1-D} v_{in}$$

Figure .3.3: Buck-boost converter (ac-dc)

3.4 Three-Phase Boost Derived Rectifier Topologies

Three-phase boost PFC power rectifier have traditionally been the preferred topology for high power applications due to their symmetric current drawing characteristics. A disadvantage to any boost derived topology is the inability to control startup inrush currents and output short circuit conditions, unless bi-directional power flow is possible. The following subsections describe various boost derived topologies.

3.4.1 Three-Phase Six Switch Boost Rectifier

A common six switch boost rectifier topology has the ability to operate as a rectifier as well as an inverter due to the bidirectional power flowing capabilities
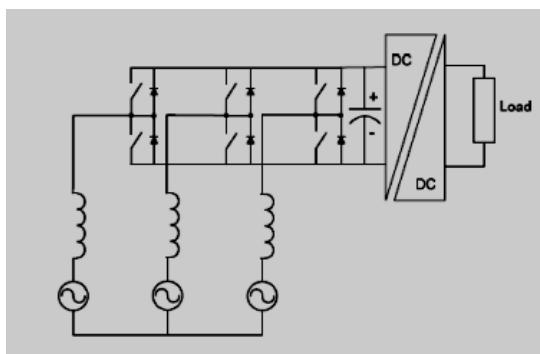

Figure 3.4.1: Three-Phase Six Switch Boost Rectifier

It also has good current quality and low EMI emissions [V. Blasko, V.Vaura and W. Niewiadomski ,1998] . The converter is controlled by an output voltage loop for output regulation, and inner current loops which shape the input currents according to their sinusoidal references. The input inductors form part of the boost topology and, as such, work at the switching frequency. As a result, input inductors operating at switching frequencies are smaller in size compared with line frequency input inductors.

3.4.2 Three Switch Boost Power Converter

The three switch boost derived converter proposed in [S. Zheng and D. Czarkowski,2007] works on the principle of current control. When two switches are conducting, the phase with the larger supply voltage is connected to the positive rail, while the phase with the smaller supply voltage is connected to the negative rail (Figure3.4.2). This topology suffers from startup inrush currents and, also, uncontrolled negative half cycles on all phases and fluctuations in the DC bus voltage. DC-DC converter stage is still needed to provide isolation, voltage transformation and ripple reduction.
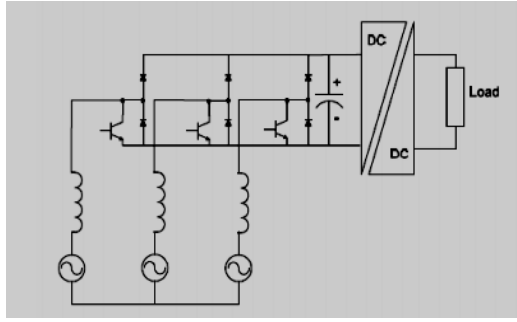
Figure 3.4.2 : Three Switch Boost Power Converter System

3.4.3 Three-Phase Four Switch Boost Rectifier

The boost derived rectifier shown in Figure 3.4.3 , and proposed in [Abraham Pressman,1991] , has three boost inductors in them AC lines, four active switches and two series connected capacitors. The boost derived rectifier is capable of bi-directional power flow and, thus, is able to control the output voltage down to zero. The converter performs PFC by taking advantage of the fact that if two of the three line currents in a balanced three-phase system are controlled, the third is automatically constrained. This removes the need for a third converter leg. A disadvantage is that even with a slight imbalance in the supply system, the converter performance may deteriorate considerably. DC-DC converter stage is still needed to provide isolation, voltage transformation and ripple reduction.
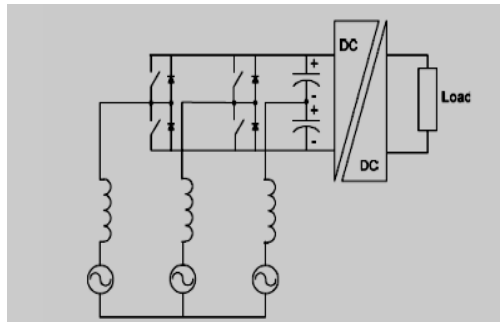

Figure.3.4.3: Four Switch Boost Power Converter System

3.4.4 Single Switch Boost Power Converter

The single switch boost converter topology proposed in [T. Nussbaumer, M.L. Heldwein, G. Gong, S. Round, and J. Kolar,2008] has an LC type input filter and, with the boost switch turned on at a constant frequency, the duty cycle is controlled such that the input current is always discontinuous (Figure 3.4.4). During the on-period of the boost switch, all three input phases become shorted through the input inductors, the six rectifier diodes and the boost switch. The input currents begin to increase at a rate proportional to the instantaneous values of their respective phase voltages. The peak current values during each on-interval are proportional to the average values of their input phase voltages during the same on-interval. The result is that each AC line current is a discontinuous waveform made up of a train of triangular pulses bounded by a sinusoidal envelope.
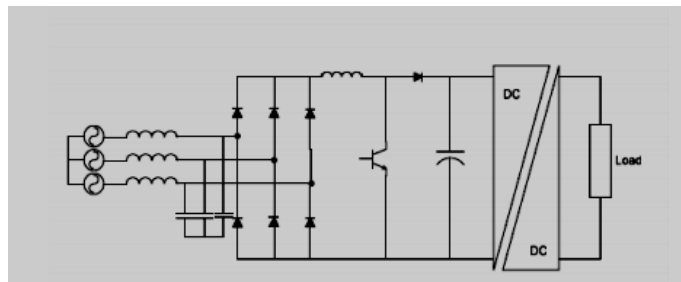

Figure 3.4.4 : Single Switch Boost Power Converter

3.4.5 Vienna Rectifier

Another three-switch boost derived converter, also called the Vienna rectifier, is a unidirectional three-level PWM converter (Figure 3.5.5) and, as a result, suffers from startup inrush currents. The input stage creates a DC voltage across the two switches connected to the transformer primary. These two switches, in turn, regulate the voltage being applied to the primary of the transformer. Accordingly, they are able to control the output voltage generated [D.M. Mitchell ,1980] The Vienna rectifier has a complex control system and requires special semiconductor module fabrication.
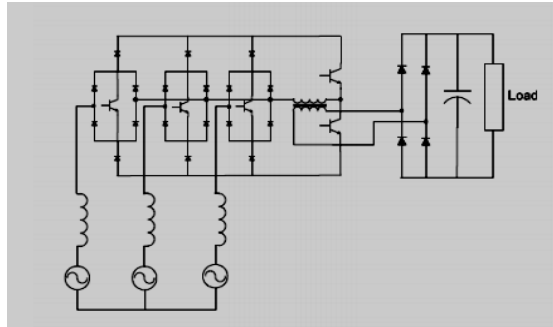

Figure 3.4.5: Vienna Rectifier

3.5.1 Three-Phase, Single Switch Boost Rectifier

The single switch boost rectifier proposed in [Q. Huang and F. C. Lee,1996] to reduce the magnitude of the 5th harmonic in the input current. The fifth-order-harmonic trap filter, which consists of inductances and capacitance place at the input of the power stage. The harmonic-trap inductance can be utilized as a part of the differential-mode input filter formed by the addition of filter. One problem in using a harmonic trap in a harmonic generating power system is the possibility to excite harmonic resonances. Both series and parallel resonances may occur in a power system due to the existence of the filter and power line reactive components.

The harmonic-injection method does not increase the voltage stress of the boost switch. In the technique presented in [Y. Jang and M. M. Jovanovic,1997] , a voltage signal which is proportional to the inverted ac component of the rectified three-phase line-to-line input voltage is injected into the output-voltage feedback loop to vary the duty cycle of the rectifier within a line cycle in order to reduce the fifth-order harmonic and improve the THD of the rectifier input currents.

3.6 Modulation Techniques

There are two different types of modulation techniques applied for pulse width modulation (PWM)
[P. Wood, 1981]

3.6.1 Sinusoidal PWM

Technique employed where the sinusoidal waveform or modulation signal is compared with a very high frequency triangle or carrier signal to obtain the switching pulses for the device. The modulation and the carrier signals are compared such that when the sine wave is higher in magnitude the corresponding value of the switching pulse is high (has a value = 1) and when the sine wave is lower than the carrier, the pulse is low (has a value = 0). This is shown graphically in figure 3.6.1.
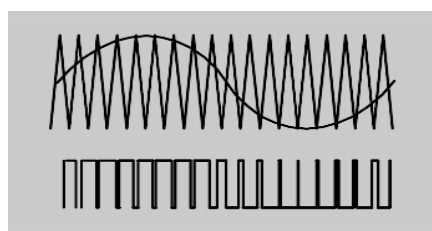

Figure 3.6.1: Sinusoidal PWM

3.6.2 Generalized Discontinuous pulse width modulation (GDPWM).

Technique is represents the ac side voltages of the converter as a space vector. Each active state is represented as a vertex of a hexagon, while the null vectors are represented at the centre of the hexagon. Depending on the sector in which the reference vector lies, the switching times are calculated to generate the desired reference vector.

3.6.3 Hysteresis Control Technique:

Among hysteresis control methods, the most well-known is the hysteresis current control. Every time the error between control references and control variables crosses either the positive or negative hysteresis band's boundary, a significant change in the controller's output (switch) occurs as shown in Figure 2.3. Thus the controller quickly reacts to any deviation from control references, which are the reason of the high gain behaviour of these controllers. Hysteresis current control is the easiest control method to be implemented. How- ever, the disadvantage is that there is no limit to the switching frequency. On the other hand, hysteresis band can be used to limit the maximum switching frequency. The maximum error is the difference between the upper and lower limit, and this hysteresis tolerance bandwidth is mostly equal to two times of the error. If the error signal is within the tolerance band, there will be no switching action for the filter. However, when the error leaves the tolerance band, switching pulses will be gener- ated and the driver will produce signals to be injected into the supply line.Figure 2.3 illustrates the ramping of the current between the two limits. The upper hysteresis limit is the sum of the reference current and the maximum error or the difference between the upper limit and the reference current. The lower hysteresis is defined by the subtraction of the reference current and the minimum error. If the values of the minimum and maximum errors are the same, then the hysteresis bandwidth is equal to two times of error.

3.7 Active Power Filter

There are various types of active power filters and these active power filters can be classified into different categories based on the system configuration, the power circuit, the control strategy and techniques. Normally, active power filters can be classified into shunt, series or hybrid active passive power filter.

The series active power filter show as figure 3.7.1 is connected in series with the utility by a matching transformer. The compensation voltage VC* is used to cancel the voltage harmonics of the load with high capacitance in the DC side.
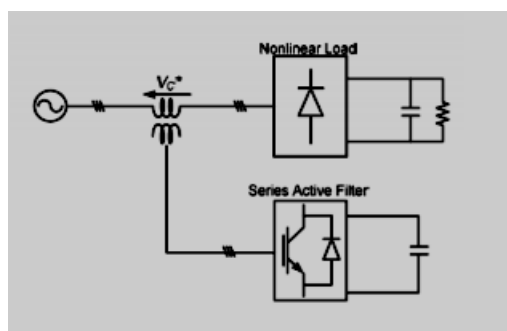

Figure 3.7.1:Series active power filter

. The shunt active filter shown in figure (3.7.2) is the most fundamental system configurations where the shunt active power filter is controlled to draw and inject compensating current, Ic * to the power system and cancel the harmonic currents on the AC side of a general purpose rectifier. Thyristor or diode rectifier normally used in shunt active power filter.
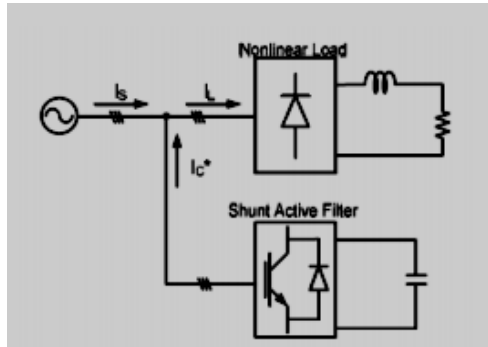
Figure 3.7.2:Shunt active power filter

The advantages of the active filtering process over the passive one caused much research to be performed on active power filters for power conditioning and theirpractical application. [Hirofumi Akagi,1994] By implementing the active power filters for power conditioning; it provides functions such as reactive power compensations, harmonic compensations, harmonic isolation, harmonic damping, harmonic termination, negative-sequence current or voltage compensation and voltage regulation. Active power filter consists of an inverter with switching control circuit. The inverter of the active power filter will generate the desired compensating harmonics based on the switching gates provided by the controller. The total harmonic distortion (THD) of a current or voltage is equal to the effective value of all the harmonics divided by the effective value of fundamental.

The equation of a distorted current is:

$$\text{Total Harmonic Distortion (THD)} = \frac{IH}{IF} \tag{1}$$

The equation of a distorted voltage is:

$$\text{Total Harmonic Distortion (THD)} = \frac{VH}{VF} \tag{2}$$

The IEEE Standard 519-1992 specifies the maximum percentage THD permitted for both current distortion and voltage distortion. [Theodore R.Bosela]. The THD in voltage and current are defined as:

$$\text{THD} = \frac{\sqrt{\sum Vn^2}}{V_1} \times 100\% \qquad (N = 2,3,4,..\infty) \tag{3}$$

$$\text{THD} = \frac{\sqrt{\sum In^2}}{I_1} \times 100\% \tag{4}$$

Where Vn an In = the amplitide of that harmonic relative to the fundamental; n = harmonic number

3.8 PWM Rectifier

A PWM rectifier is a new member of rectifier family which can overcome the short- comings of conventional phase controlled rectifiers. In all inverter controlled drive applications and in wind power conversions, the use of two stage power conversion i.e. power conversion from AC-DC and DC-AC is unavoidable. For such applications this PWM rectifier can be used for primary AC-DC conversion and hence in literature it is also called as front end converter. In Present days for AC-DC conversion we use SCR based phase controlled rectifier. This method is simple as we do not re- quire any closed loop control and the required output voltage can be controlled. But looking at the source

side, the phase controlled rectifier is drawing non sinusoidal current from the supply. In previous days we do not have any alternative method to handle this problem, but now using PWM rectifier we can be able to control both input side AC source current and the output side load voltage.
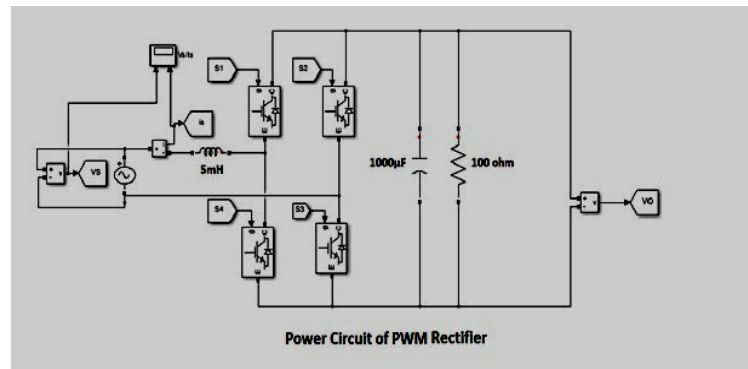

Power Circuit of PWM Rectifier

Figure 3.8: Single Phase Pwm Rectifier

4. Conclusion

PWM Rectifier with Hysteresis Current Control is suitable converter for converting AC supply into controlled DC. It provides THD on source side as prescribed under IEEE limits as current is almost sinusoidal and follows source voltage. Regenerating in case of DC Motor loads is also possible with this converter. As this converter provides output voltage more than input supply, this can be considered as an additional advantage.Output voltage of this converter can be varied over a wide range to get desired output but it cann ot go below the input supplied. Experimental results are provided to confirm the improvement in the efficiency

However, this converter does not have any significant disadvantage but the cost for this kind of converter is more in comparision to other AC to DC converter as it operates in closed loop which requires sensors and controllers.

As the high speed microprocessors are evolving, these kind of converters have possibility to be made cheap, compact and light weight for using them in industries as well as in domestic applications.

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