CONTROL TECHNIQUES AND POWER FACTOR CORRECTION METHODS: A REVIEW

Authors' contributions

This work was carried out in collaboration between all authors. Author GAA designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors OA and AOR managed the analyses of the study. Author AOR managed the literature searches. All authors read and approved the final manuscript.

Abstract.

The ratio of real power flowing into the load to the apparent power in a circuit is referred to as the power factor (PF). It has no unit as its values lie between 0 and 1. Power factor correction (PFC) leads to a reduction in apparent power drawn from the ac source which in turn saves energy and minimizes the transmission losses. This paper reviews various methods used for PFC as well as the various control measures for power factor. The correction methods include distributed PFC, group PFC, centralized PFC and combined PFC. Distributed PFC is applicable to large electrical equipment with constant load and power with long connection times. Combined PFC is the hybrid between a distributed and a centralized correction method. Peak current control technique makes use of constant switching frequency even though, the presence of sub-harmonic oscillations at a duty cycle greater than 50% is a disadvantage. The presence of constant switching frequency and better input current waveforms are some of the applications of average current control. In the discontinuous current pulse width modulation (PWM) control, the internal current loop is completely eliminated so that the switch is at a constant frequency. In nonlinear carrier controllers, the duty ratio is determined by comparing a signal derived from the main switch current with a periodic nonlinear carrier waveform. Therefore, combined PFC and nonlinear carrier controllers are more accurate PFC methods for the power plant because they employ a high power factor boost converter with low total harmonic distortion for installations of large equipment with a constant load. This research paper forms a basis for power system planning as it assists in recommending the appropriate and adequate technique(s) for correcting and controlling the pf of the factory.

Keywords: Power factor correction, Control techniques, Capacitor bank, Compensation system, Peak current control, Communication noises, Hysterisis control.

1. Introduction

Power factor correction (PFC) is a technique used in the power supply to reduce the amount of reactive power generated by the power system. The overall power is the power supplied through the power mains to produce the required amount of real power.PFC takes the form of a new front end of power supplies, adding circuitry to shape the input current into an image of the input voltage. In addition, PFC makes the power supply input look resistive to the source [1]. A high power factor is generally desirable in a power system to reduce system losses and improve voltage regulation at the load. In most cases, it is desirable to adjust the power factor of a system to near 1.0. However, increased use of non-linear loads such as televisions, computers, faxes, adjustable speed drives has increased the harmonic distortion level in the system. Increased harmonic distortion results in voltage distortion, low efficiency and poor power quality which in turn reduces the reliability and causes deregulation of the power system. Therefore, it is necessary to improve the power factor (quality) of the supply system so that the electrical equipment operates correctly and reliably without being damaged or stressed and to increase the efficiency of supply system [2, 3].

When reactive elements supply or absorb reactive power near the load, the apparent power reduced thus power factor correction (PFC) is applied by an electric power utility to improve the voltage stability and efficiency of the power network. Electrical customers who are charged by their utility for low power factor may install correction equipment to reduce those costs [1, 4]. PFC is a technique that promotes efficient energy consumption from the power grid. PFC is employed inside common electrical and electronic equipment that is powered from the ac outlet, also it enables the equipment to maximize the active power drawn and minimizes the reactive power drawn from the ac outlet. PFC reduces the harmonics in the system currents, reduce customer's utility bill and hence increases the efficiency and capacity of power systems. PFC systems make a major contribution to achieving energy efficiency and reducing CO_2 emissions and are thus an indispensable component of modern electrical installations [5, 6, 7].

Many methods have been proposed to improve power factor which can be categorized as passive and active methods. Passive power factor correction methods involve shaping of line current using passive elements such as inductor and capacitor while active power factor correction methods involve shaping of line current using semiconductor switches such as metal oxide semiconductor field effect transistors (MOSFETs) and IGBTs [8].

Passive methods of power factor correction have some advantages such as simplicity, reliability and ruggedness, insensitivity to noise and surges and no switching losses. They possess a poor dynamic response, lack of voltage regulation, sensitive to changes in load. Hence for low power applications (less than 50 W) passive methods are preferred and for high power applications (above 50W) active methods are preferred because of the following [5, 7, 9]:

i. Close to Unity Power Factor (UPC) operation.
ii. Less than 10 % Total Harmonic Distortion (THD) in line current
iii. Reduced number of feedback signals for controller implementation

2. Power Factor Correction techniques:

These are the strategies employed to adjust and vary the power flowing in a typical load in power systems. The essence of such is to ensure an optimal performance of the plant. These correction technologies include the following [9, 10]:

i. Automatic power factor correction
ii. Centralized power factor correction
iii. Combined power factor correction
iv. Distributed power factor correction
v. Group power factor correction

a. Automatic Power factor correction:

In this technique, there is no constant absorption of reactive power due to working cycles for which machines with different electrical characteristics are used. In such installations, there are systems for automatic power factor correction which allow the automatic switching of different capacitor banks, thus following the variations of the absorbed reactive power and keeping the power of the installation constant.

An automatic compensation system is formed by [11]:

i. a set of sensors directing current and voltage signals.
ii. an intelligent unit which compares the measured power factor with the desired one and operates the connection and disconnection of capacitor banks with the necessary reactive power (power factor regulator).
iii. electric power board comprising switching and protection devices and capacitor banks.

b. Centralized power factor correction:

In this technique, not all loads function simultaneously since there is load shedding as some loads are connected for just a few hours a day. It is now obvious that even though this is an economic advantage and it is inefficient since many of the installed capacitors stay idle for a period. The consequence of this is the use of compensation systems located at the origin of the installation which allows a remarkable reduction of the total power of the installed capacitors. This leads to optimization cost of the capacitor bank, leading to the absorption of full reactive power by the loads connected to the distribution lines [11, 12].

c. Distributed power factor correction:

When a properly sized capacitor bank is connected directly to the terminals of a load that needs reactive power, distributed PF correction is obtained. The installation is easy and they are usually inexpensive; capacitor and load can use the same protective devices against over currents and are connected and disconnected simultaneously. This type of power factor correction has a wide application in the case of large electrical equipment with constant load and power with long connection times and it is generally applicable to motors and fluorescent lamps [2, 9].

d. Combined power factor correction:

The approach is a hybrid of distributed and centralized power factor correction and it utilizes the advantages they offer. In the distributed compensation, it is used for high power electrical equipment and the centralized technique is used for the remaining part. Combined power factor correction is used in installations where large equipment is frequently used. In this situation, the power factor is corrected individually [13].

e. Group power factor correction:

By installing a dedicated capacitor bank, the power loads having similar functioning characteristics can be improved. A compromise is reached between the inexpensive solution and the proper management of the installation since the benefits of the power factor is as a result of the location of the capacitor bank [14].

3. Power Factor Control Techniques:

To operate converter as power factor corrector, a PFC circuit is required to maintain a dc output voltage of constant value and also maintains input current wave shape as pure sinusoidal. In order to obtain a constant dc output voltage, a voltage control loop is used to ensure that the input power from ac side is equal to output power demand plus losses [4, 14]. The voltage control loop senses the output voltage increases the current drawn from the line. However, a voltage control loop cannot shape the current drawn from the input or the current through the inductor. It can only decide the amplitude of the full wave rectified current wave that is to be made to flow through the inductor. In order to shape the inductor current as a full wave rectified wave, a control current loop is used [15, 16].

Thus, in power factor control techniques there is:

i. outer voltage loop which monitors output voltage and decides the amplitude of full wave rectified current that should flow through the inductor and

ii. an inner current loop which shapes the inductor current.

a. Voltage Control Loop:

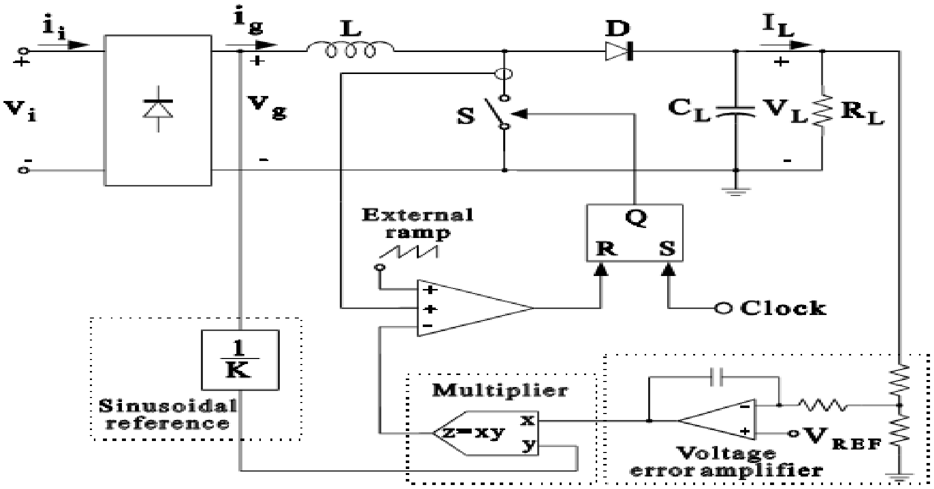
In this case, the output dc is sensed and compared with a set reference in the error amplifier. The amplified error is converted into a current reference waveform by multiplying it with a waveform template, which represents the desired current wave shape in the boost inductor. This desired shape is that of the full wave rectified shape and is readily available at the output of the rectifier bridge. The reference current waveform is then given to the pre-regulator block. The pre-regulator block consists of the boost switch, boost inductor and the current control loop [16]. The current control loop monitors the actual inductor current and compares it with the reference current. It makes the inductor current to track the reference current wave generated by the voltage control loop with minimum tracking error. In case of variations in the input line voltage, the amplitude of the waveform template also changes which in turn changes the output voltage. The main disadvantage of this technique is that in case of load throw off, the output voltage rises to a very high value which may damage the load and the PFC, since the output voltage rise is sensed slowly by the feedback system due to its low bandwidth. It is difficult to bring down the capacitor voltage once it rises to a very high value due to the unilateral flow of current [12, 14]].

b. Current Control technique:

There are five current control methods for power factor correction in order to monitor the inductor current and to track the desired wave shape. This includes peak current control, average current control, hysteresis current control, borderline current control and discontinuous current control [16].

i. Peak current control:

In this technique, the switch is turned on the constant frequency by a clock signal and is turned off when the sum of the positive ramp of the indicator current (i.e. the switch current) and an external ramp (compensating ramp) attains the sinusoidal current reference. This reference is usually obtained by multiplying a sealed replica of the rectified line voltage times the output of the voltage error amplifier which sets the current reference amplitude. In this way, the reference signal is naturally synchronized and always proportional to the line voltage, which is the condition for attaining unity power factor. The circuit diagram is depicted in Figure 1 [7, 17, 18, 19].



Figures 1: Peak current control circuit

Merits: This control technique offers the following merits [18]:

- Constant switching frequency
- Only the switch current must be sensed and this can be accomplished by a current transformer, thus avoiding the losses due to the sensing resistor
- No need of current error amplifier and its compensation network
- The possibility of a true switch current limiter

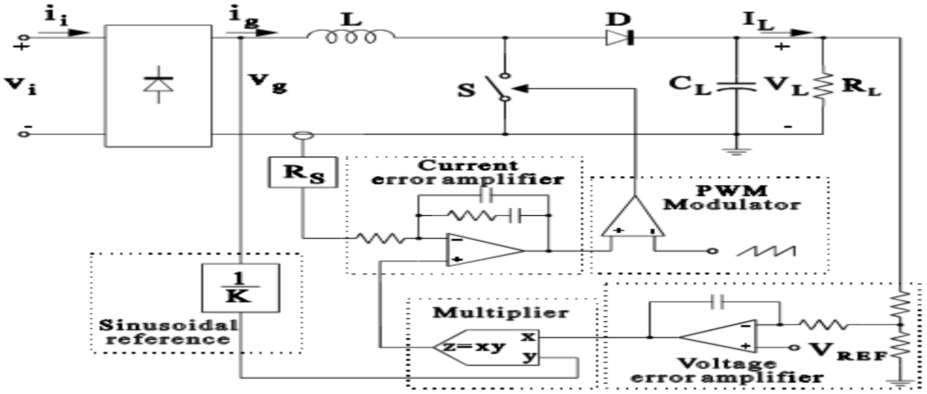
Demerits: The demerits include the following [17]:-

- Presence of sub-harmonic oscillation at duty cycles greater than 50%.
- Input current distortion which increases at high line voltages and light load and is worsened by the compensation ramp.
- Control more sensitive to communication noises.

By changing the current reference wave shape, for example by introducing a soft clamp, the input current distortion can be reduced. Moreover, if the PFC is not intended for universal input operation, duty-cycle can be kept below 50% thereby avoiding the compensation ramp. Available commercial IC's for peak current control are ML4812 (Micro Linear) and TK84812 (Toko) [19, 20].

ii. Average current control

In most of the power electronic converter applications, the output variable is the voltage and is involved in the outer loop. The variable within the inner loop is current and also allows a better input current waveform, this is the reason why this technique is called average current control technique [20]. The average current control interleaved boost PFC converter is designed to operate in continuous current mode (CCM) and transit to discontinuous current mode (DCM) when the load becomes light as shown in Figure 2.Here the inductor current is sensed and filtered by a current error amplifier whose output drives a PWM modulator. The inner current loop tends to minimize the error between the average input current i_g and its reference [19, 21].



Figures 2: an Average current control circuit

Merits: The following are some of the merits [21]:-

- Constant switching frequency;
- No need for compensation ramp;
- Control is less sensitive to commutation noises, due to current filtering;
- Better input current waveforms than for the peak current control since, near the zero crossing of the line voltage, the duty cycle is close to one, so reducing the dead angle in the input current.

Demerits: The shortcomings of this technique include the followings [22]:-

- Inductor current must be sensed;
- A current error amplifier is needed and its compensation network design must take in to account the different converter operating points during the line cycle.

iii. Hysteresis Current Control

Out of the various control methods, hysteresis current control is the extensively used technique owing to its noncomplex implementation, enhanced system stability, fast response, less distortion in input current waveform and regulating the output voltage [23]. This technique is believed to exhibit greater stability. According to this control technique, when the inductance current is less than the lower current reference, two sinusoidal current references are generated, one for the peak and the other for the value of the induction current. According to this control technique, the switch is turned on when the inductor current goes above the upper reference giving rise to a variable frequency control. The main circuit and control block diagram of hysteresis current control is shown in Figure 3 [11, 23].

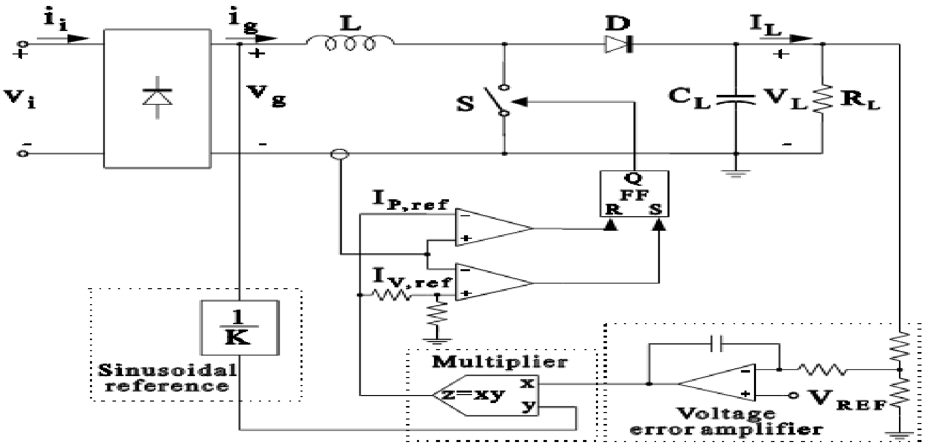


Figure 3: Hysteresis control circuit

Merits: Some of the merits of this control technique are as follows [24]:

- No need of compensation ramp.
- Low distorted input current waveforms.

Demerits: The demerits include the following [24]:-

- Variable switching frequency;
- Inductor current must be sensed;
- Control sensitivity to commutation noise.

In order to avoid too high switching frequency, the switch can be kept opened near the zero crossing of the line voltage. A control IC which implements this control technique is the CS3810 [25].

iv. Borderline Control

In this control approach, the switch is held constant during the line cycle and is turned on when the inductor current falls to zero. At this instance, the converter operates at the boundary between continuous and discontinuous induction current mode. In this way, freewheeling-diode is turned off softly (no recovery losses) and the switch is turned on at zero current, hence the commutation losses are reduced [26].

The instantaneous input current is constituted by a sequence of triangles whose peaks are proportional to the line voltage. Thus, the average input current becomes proportional to the line current. This characterizes this control as an automatic current shaper technique and the circuit diagram is shown in Figure 4 [22].

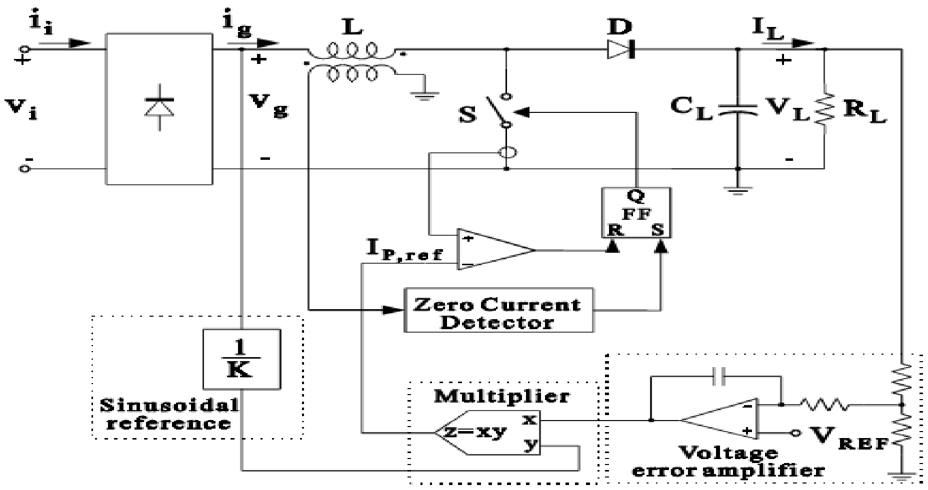


Figure 4: Borderline control circuit

Merits [27]:

- No need for a compensation ramp;
- No need of a current error amplifier;

Demerits [28]:

- Variable switching frequency;
- Voltage must be sensed in order to detect the zeroing of the inductor current;
- For controllers in which the switch current is sensed, control is sensitive to commutation noise.

v. Discontinuous Current Control

This control technique allows unity power factor when used with converter topologies like fly back with the converter working in discontinuous condition mode (DCM). In addition, with the boost PFC, this technique causes some harmonic distortion in the line current. The circuit diagram is depicted in Figure 5 [29, 30].

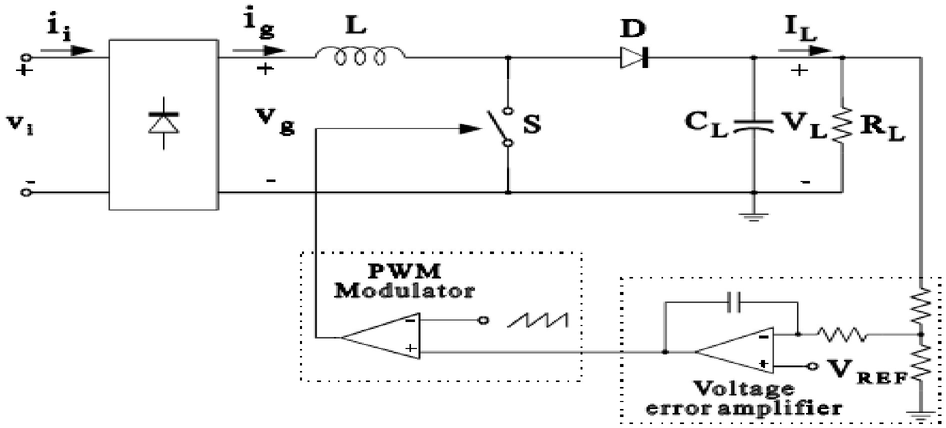


Figure 5: Discontinuous current control circuit

Merits: The following are some of the merits of the technique [31]:-

- constant switching frequency;
- no need of current sensing;
- simple PWM control;

Demerits: The demerits include the following [30]:

- higher device current stress than for borderline control;
- input current distortion with boost topology.

A control IC specifically developed for this type of control is the ML4813 (Micro Linear).

c. Non-linear Carrier Control:

Nonlinear carrier controllers are employed for high power factor boost rectifiers with low total harmonic distortion. In this type of controllers, the duty ratio is determined by comparing a signal derived from the main switch current with a periodic nonlinear carrier waveform. This technique is desirable for boost converters operating in the continuous conduction mode [4]. The controller obtains the duty ratio in each switching period from the comparison of the negative ramp carrier waveform and the sensed inductor current signal as shown in Figure 6. The input voltage sensor, the error amplifier in the current feedback loop and the multiplier as used in the other control techniques are not required [31, 32, 33].

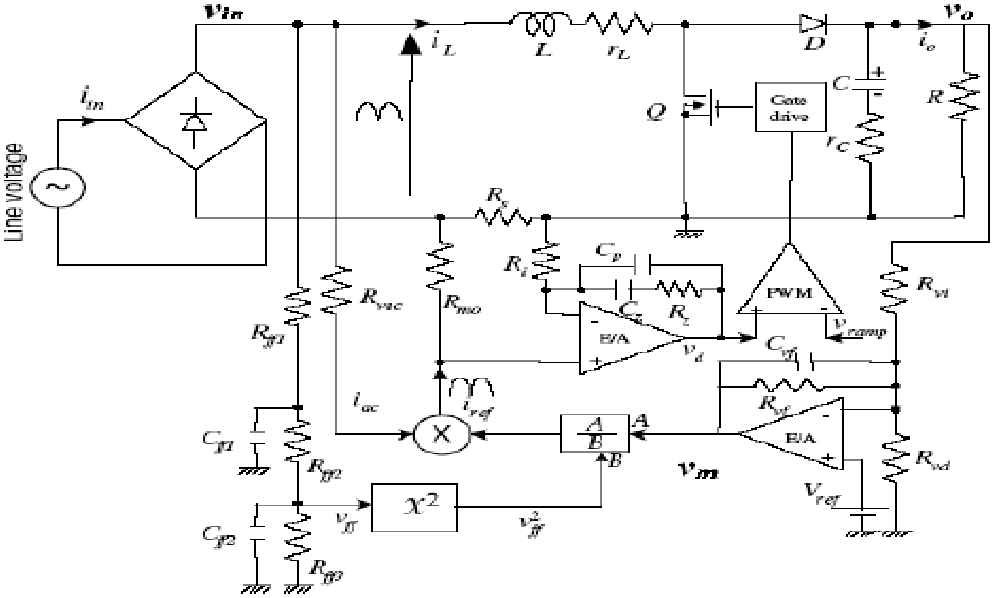


Figure 6: Non-linear current control circuit

4. Effects of Harmonics on the PFC Techniques

Harmonics are the phenomenon which affects power factor correction. The presence of harmonics in the electrical network causes malfunctioning of the equipment, such as overloading of the neutral conductor, an increase of losses in the transformers and disturbances in the torque of motors [2, 33]. In addition, due to the growth of nonlinear loads, such as power electronics converters, switching mode power supplies, computer, serious power pollution is produced and reflected into the distribution and transmission networks [7, 34]. Several PFC techniques have been applied for current or voltage harmonics elimination and power factor improvements such as power factor correctors (control rectifier) and active power filters. The controlled rectifier is used to produce a sinusoidal current on the ac side while the active power filters compensate current harmonics generated by nonlinear loads in the power system [34, 35].

However, low power factor and high pulsating current from the ac mains are the main disadvantages of the diode rectifier and phase controlled rectifier. These circuits generate serious power pollution in the transmission or distribution system. The power pollutants such as reactive power and current harmonics result in line voltage distortion, heating of core of transformer and electrical machines, and increasing losses in the transmission and distribution line. In addition, a passive filter is often used to improve the power quality because of its simple circuit configuration. Bulk passive elements, fixed compensation characteristics, and series and parallel resonances are the main drawbacks of this scheme [36, 37].

5. New Power Factor Technique

Several circuit topologies and control strategies of power factor correctors and active power filters have been applied to perform current or voltage harmonics reduction and increase the power factor. However, in order to meet the IEEE Std 519 requirements on the quality of the input current that can be drawn by low-power equipment, a PFC circuit is typically added to an existing circuit as a front end stage (i.e. Boost converter). The boost converter is a new power factor correction technique used nowadays because of its simplicity and excellent performance [38]. This PFC technique is employed with one full-bridge diode rectifier, which is examined as a non-linear load as a source of harmonics and one Boost PFC converter. The boost PFC circuit operate in continuous conduction mode (CCM) because the continuous nature of the boost converter's input current results in low conducted electromagnetic interference (EMI) compared to other active PFC techniques [37, 39].

The Boost converter acts as a current source connected in parallel with the nonlinear load and controlled to produce the harmonic currents required for the load as shown in Figure 7. This technique employs hysteresis current control technique to trace the line current directive so that the configuration draws nearly sinusoidal current from the source [39]. Power switch in the converter is controlled in order to standoff a nearly sinusoidal line current with low distortion and low total harmonic distortion (THD) of supply current output and also regulate the DC bus voltage [40]. The inductor current is forced to fall within the hysteresis band by proper switching the power switch [41, 42, 43, 44].

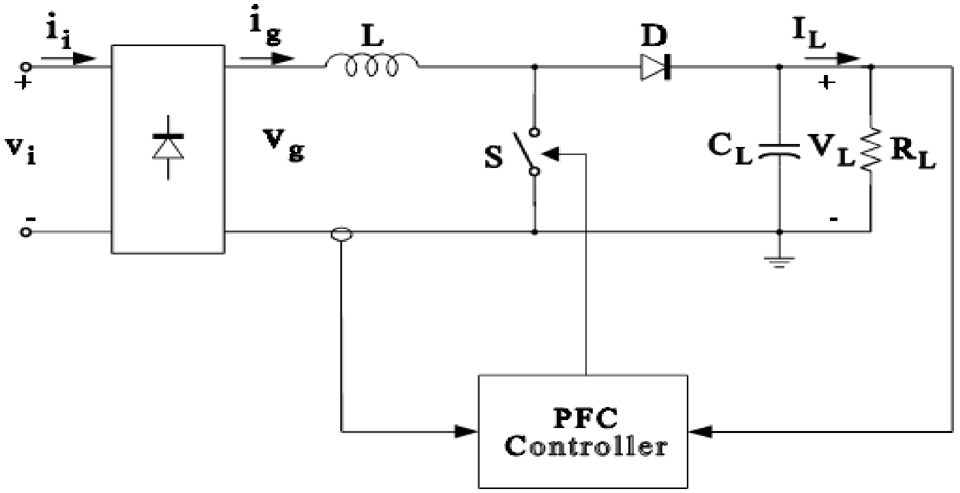


Figure 7: Boost converter circuit

This technique comprises of the conventional boost converter, bridgeless boost converter and interleaved boost as explained below [42, 45, 46, 47].

- Conventional boost converter contains a rectifier circuit and boost converter. In addition, the converter is excellent for low and medium power range loads; however, the main disadvantage of this converter is the size and volume of the circuit.
- Bridgeless boost converter has no rectifier circuit and the solution for power level is greater than 1kW. It solves the disadvantages of the conventional method but elevates the noise. The loss of conduction can be minimized by paralleling the semiconductor components. The disadvantages of this converter are the floating input line with respect to the PFC stage, and also, the diode and MOSFET failed to identify the flow of current during each of the half-line cycles.
- Interleaved boost converter consists of two Boost converters and both of them are connected in parallel. The current input is the total current flow throughout the two inductors. This converter is able to reduce the ripple in the current waveform and indirectly reduces the total harmonics distortion or error especially at high frequency and it also minimizes the conduction losses by paralleling the semiconductor components.

6. Benefits of Power Factor Correction

There are many benefits to be gained through power factor correction. These range from reduced demand charges on power system to increased load carrying capabilities in existing circuits and overall reduced power system loses. Other benefits of power factor correction are the improved voltage, reduced power system losses and reduced carbon footprint [48, 49, 50, 51].

Benefits achieved by the installation of PFC include [48, 51]:

- Electricity tariff savings.
- Avoidance of Network Service Provider (NSP) penalties for low power factor, including restricted access to more suitable tariffs.
- Reduced losses
- Reduce power drawn from distribution systems and optimum sizing of electrical infrastructure.

- Stabilized site voltage levels by reducing the inductive effect of the connected load.

7. Conclusion

A comprehensive review of control techniques and PFC methods has been presented. The correction methods include distributed PFC; group PFC, centralized PFC, combined PFC and automatic PFC. In automatic PFC, there is no constant absorption of reactive power owing to the working cycle for which machines with different electrical characteristics are used. There is load shedding in centralized PFC because not all loads function simultaneously. The combined PFC is a hybrid of distributed and centralized PFC. Distributed PFC is achieved when a correctly sized capacitor bank is directly connected to the terminals of a load that needs reactive power. PF control techniques include the voltage control loop, current control technique and non-linear carrier control. Therefore, combined power factor correction and nonlinear carrier controllers are more accurate PFC methods for the power plant because they make use of high power factor boost converter with low total harmonic distortion for installations where large equipment is frequently used with a constant load.

The research paper provides a basis for power system planning in order to recommend appropriate and adequate PF techniques and controls for power plants.

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