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Harmonic reduction based on active solutions

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Most electronic systems use one or more switch mode power converter that will tend to draw current from the power line in a non sinusoidal shape. This input current characteristic results in current distortions that can contribute as well to the degradation of the supply voltage as to the negative disturbance effects of any connected equipment on the same line (interference, heating, noises, etc.). These problems have led to the creation of design standards and to develop interface systems which improve the power quality. Due to the high harmonic distortion of the wave of the current, it is necessary to develop solutions for their possible reduction. Consequently, the Power Factor Correction (PFC) stage of the front-end converter has become an important accessory. Operating principles, simulations and features of active solutions are discussed in this paper.

INTRODUCTION

In order to improve the power quality i.e. harmonic content of the input current and power factor, a great effort has been made to develop efficient interface which provides compliance with the international standards like IEC 1000-3-2, and others.

To ensure this operation, several techniques have been used. Conventional way is realized by installing a passive filter. Unfortunately, the effects of passive filters are sensitive to temperature and parameter changes; also this approach is only cost effective in high power applications [1].

In low and medium power applications, it is preferable to use the active correction.

Before, specifying how active correction acts on the efficiency of the converter, it is useful to understand the power factor (PF), the inconvenient of low PF; because it causes the input current degradation and then all other problems.

1. POWER FACTOR DEFINITION

The power factor values measures how much the mains efficiency is affected by both phase lag ϕ and harmonic content of the input current.

The power factor (PF) is defined by

$$PF = \frac{P}{S} = \frac{\text{Real Power}}{\text{Total Apparent Power}} = \frac{V_{rms} \times I_1 \times \cos\varphi_1}{V_{rms} \times I_{rms}} = \frac{I_1}{I_{rms}} \cos\varphi_1, \tag{1}$$

where V_{rms} is the root mean square input voltage, I_{rms} is the root mean square input current, $\cos\varphi_1$ is the displacement factor, I_1 is the fundamental component.

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1.1. For the linear load case (*ideal sinusoidal wave forms*)

The power factor can be determined by the rate of the real power to the apparent, or alternatively, by measuring the phase shift between the input voltage and current waveforms and taking the cosine of this angle (displacement angle), fig. 1:

$$PF = \frac{P}{S} = \cos\phi . \tag{2}$$

In a classical sense, PF means compensation of the displacement factor.

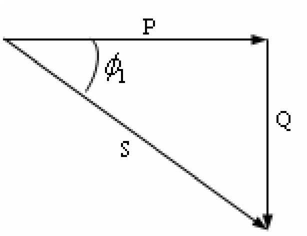

Fig. 1. Power factor for linear load

1.2. For the non linear load case

In the case, things get more complex. The current has a periodic non ideal sinusoidal waveform:

$$I_{rmsTotal} = \sqrt{I_0^2 + I_{1rms}^2 + I_{2rms}^2 + \dots\dots + I_{nrms}^2} , \tag{3}$$

Therefore, the classical definition of the power factor does not apply.

This adds another type of power, which we will refer to as distortion power (fig. 2).

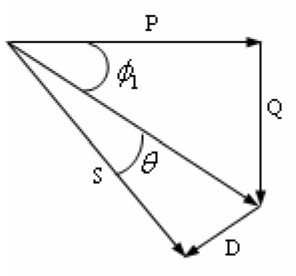

Fig. 2. Power factor for nonlinear load

Distortion power does not contribute directly to the useful power dissipated in the load, but rather adds to the reactive power to create a higher value of apparent power.

Than the power factor can be calculated as

$$PF = \frac{P}{S} = \frac{V_{rms} \times I_{1rms} \times \cos\phi_1}{V_{rms} \times I_{rmsTotal}} = \frac{I_{1rms}}{I_{rmsTotal}} \times \cos\phi_1 = k_d \times k_\phi , \tag{4}$$

where k_d and k_ϕ are both factors between 0 and 1, $k_d = \frac{I_{1rms}}{I_{rmsTotal}} = \cos\theta$ is distortion factor or purity factor, $k_\phi = \cos\phi_1$ is the displacement factor.

Finally PF can be expressed by

$$PF = k_d \times k_\varphi = \cos\theta \times \cos\phi_1 . \tag{5}$$

Consequently, for improving PF, we have to improve the two factors:

$\phi_1 \to 0 \;\Rightarrow\; \cos\phi_1 \to 1 \;\Rightarrow$ reduce lag between current and tension,

$\theta \to 0 \;\Rightarrow\; \cos\theta \to 1 \;\Rightarrow$ reduce harmonic content of current.

A useful measure of the severity of harmonics in the voltages or currents is the distortion factor [2]. The term "THD" for total harmonic distortion is often used, usually as percentage. It is the same as the distortion factor.

THD is defined as

$$THD = \sqrt{\frac{I_{rms}^2 - I_{1rms}^2}{I_{1rms}^2}}\,. \qquad (6)$$

2. WHAT'S ACTIVE CORRECTION?

PFC solutions can be categorized as passive or active.

In passive PFC, the output voltage is not controllable, and they have the demerits of fixed compensation, large size, and resonance.

The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power engineers to develop dynamic and adjustable solutions to the power quality problems [2, 3].

For active PFC, active switches are used in conjunction with reactive elements in order to increase the effectiveness of the line current shaping and to obtain controllable output voltage.

Active approaches utilize feedback circuitry along with switch mode converters to synthesise input current waveforms consistent with high power factor [4]. On the other hand, they employ controlled switches to remove the limitations of the passive solutions.

3. PASSIVE PFC

Simulation is illustrated in Fig. 3, 4 and 5 for a simple conventional rectifier and in Fig. 6 and 7 for the rectifier with AC side inductor.

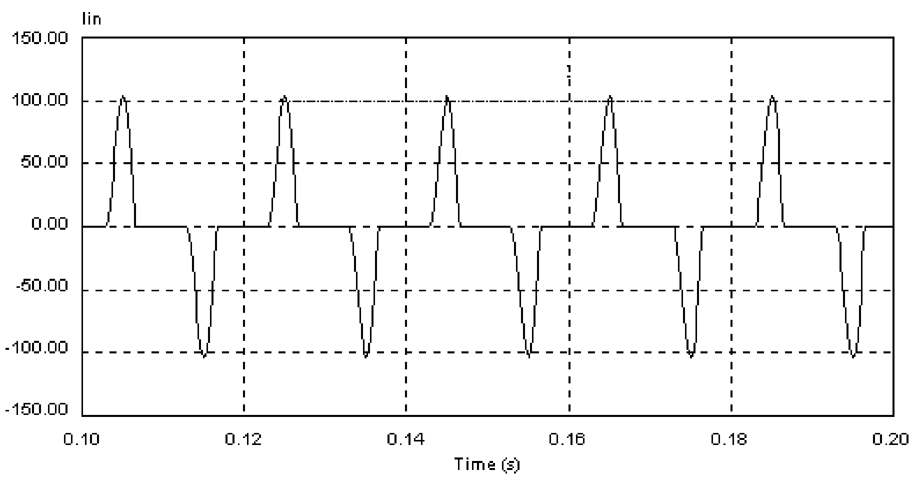

Fig. 3. Line current of single phase

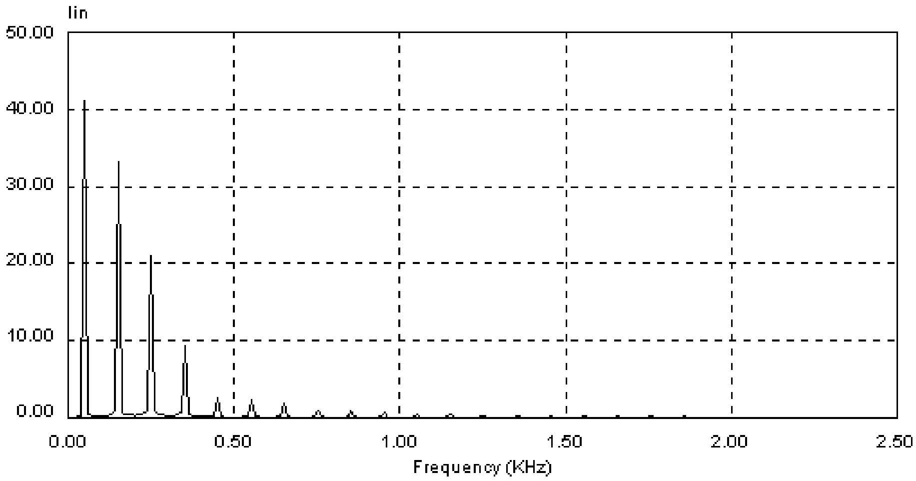

Fig. 4. The spectrum analysis of the current

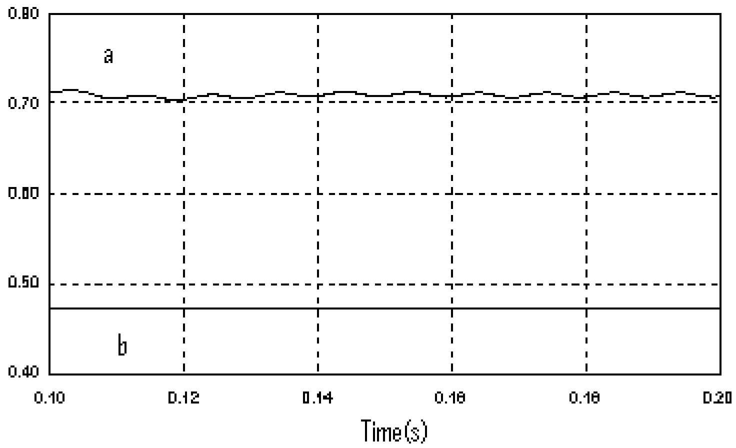

Fig. 5. The conventional rectifier: a – Nonlinear Displacement factor, b – Nonlinear PF

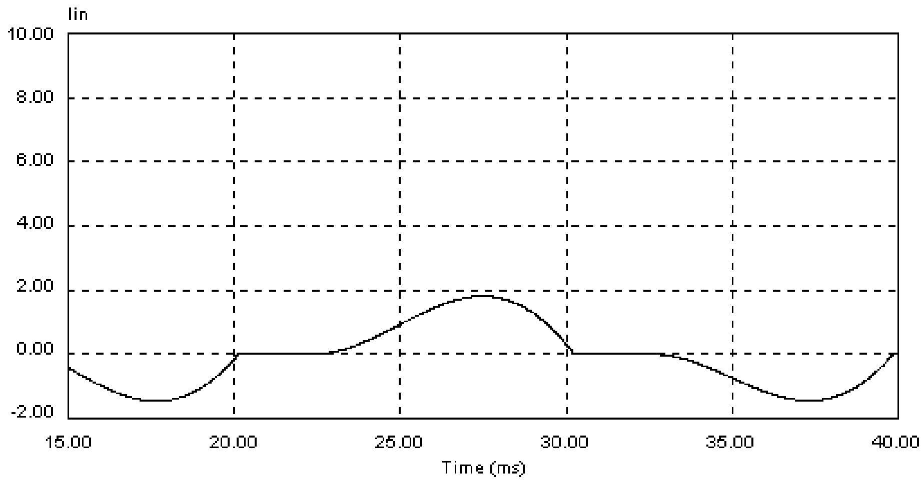

Fig. 6. The line current for the AC side inductor rectifier

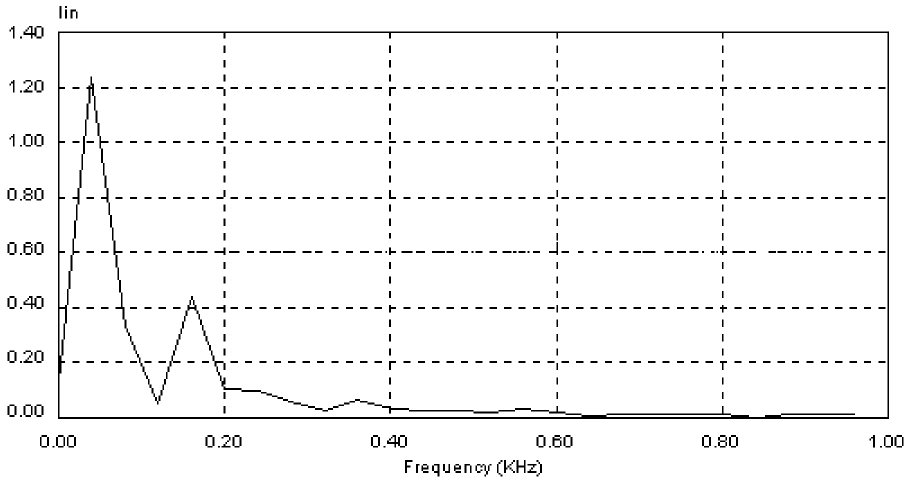

Fig. 7. The analysis spectral of the line current

The inductor can also be placed at the DC-side, Fig. 8 [4, 5].

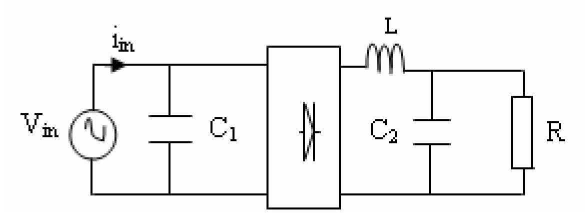

Fig. 8. The bridge rectifier with the DC side inductor

For lower inductance, the inductor current becomes discontinuous. The inductor current is continuous for large enough inductance. However, this operation would require a very large and impractical inductor.

An improvement of the power factor can be obtained by adding the capacitor (Fig. 8) as illustrated by the simulated line current waveform in Fig. 9 and 10.

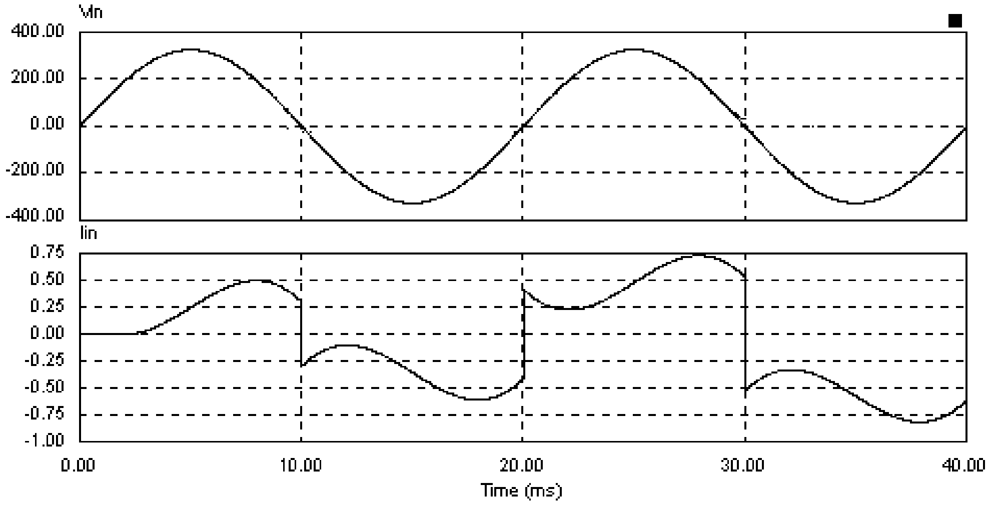

Fig. 9. Line voltage and current line with C_1

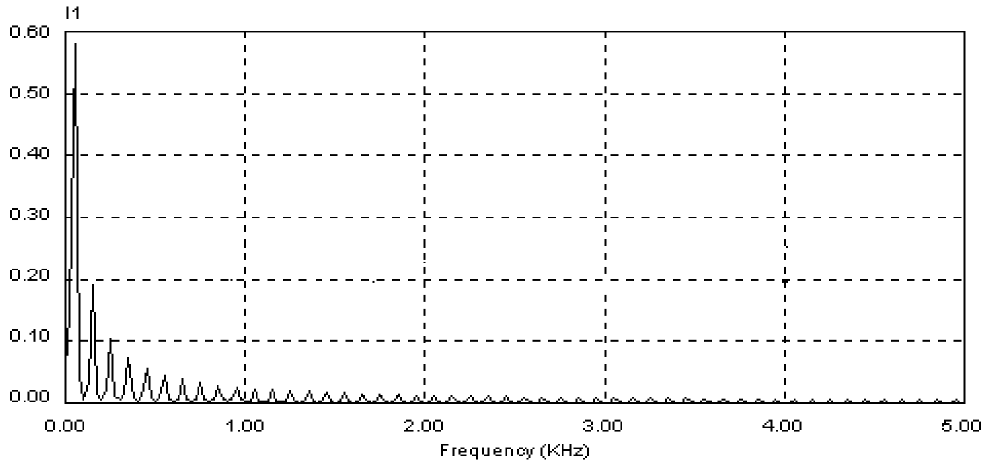

Fig. 10. Analysis spectral

The shape of the line current can be further improved by using a combination of low-pass input and output filters [6], Fig. 11.

There are also several solutions based on resonant networks that are used to attenuate harmonics yet, another possibility is to use harmonic trap filter, Fig. 12.

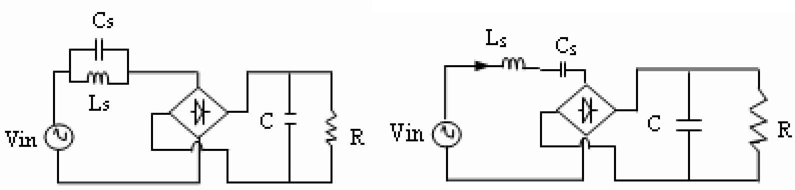

Fig. 11. Bridge rectifier with filters

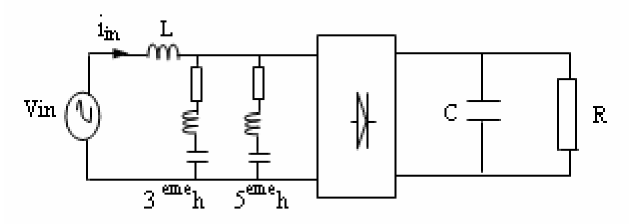

Fig. 12. Bridge rectifier with filter (Trap filter)

4. ACTIVE PFC

The switching frequency further differentiates the active PFC solutions into two classes:

- In low-frequency active PFC, switching takes place at low-order harmonics of the line-frequency and it synchronized with the line voltage.
- In high-frequency active PFC, the switching frequency is much higher than the line-frequency.

4.1. Low-frequency active PFC (slow switching topologies)

The slow switching approach can be thought of as a mix of passive and active techniques, both in complexity and performance.

The low-frequency type operation is illustrated on two examples:

- controlled rectifier,
- boost converter.

According to the choice of the inductance, and the firing angle α, a near-unity purity factor or displacement factor can obtain for a controlled rectifier. However, the power factor is less than unity. The inductance and the firing angle are chosen to maximize k_d [7]. This implies a lagging displacement factor that is compensated by an additional input capacitance.

This solution is simple, reliable and offers a regulation of the output voltage. Unfortunately, the output voltage regulation is slow and relatively large inductance is still required.

The boost converter is mainly used at high switching frequencies. However, it also used for the low frequencies.

In the low-frequency switching, the switch is turned on for the duration T_{on}, Fig. 13, so as to enlarge the conduction interval of the rectifier diodes. It is also possible to have multiple switching per half line-cycle, at low switching frequency, in order to improve the shape of the line current [8]. Nevertheless, the line current has a considerable ripple.

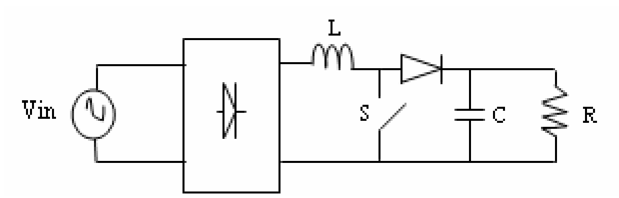

Fig. 13. Boost converter

4.2. High-frequency active PFC (high frequency topologies)

In this operation, PFC stage can be realized by using a diode bridge and DC/DC converter with a switching frequency much higher than the line frequency. Generally, any DC/DC converter can be used for this purpose, if the suitable control method is used to shape its input current or if it has inherent PFC properties. Regardless of the particular converter topology that used, the output voltage carries a ripple on twice the line frequency. This is because, on the one hand, in a single-phase system the available instantaneous power varies from zero to a maximum, due to the sinusoidal variation of the line voltage. On the other hand, the load power is assumed to be constant. The output capacitor of the PFC stage buffers the difference between the instantaneous available and consumed power, hence the low-frequency ripple.

We will focus on the boost topology since it is the most popular implementation.

5. BOOST ACTIVE PFC CONVERTER

In this operation the goal is to keep the line current approximately sinusoidal, in this case the boost converter is called PFC. In comparison to the boost converter, the PFC is controlled in a different way. The output voltage is higher than the input voltage as for the boost converter, but the switch is turned on and off in a way that a sinusoidal input current is achieved instead of an exact constant output voltage. The switch is driven in such a way, that the inductor current $I_L(t)$ follows the shape of the rectified mains $V_{in}(t)$.

A general topology of active PFC converter consists on a diode bridge rectifier, an input inductor L_{in}, an output capacitor and a network of switches, capacitors and inductors. For the boost converter the switching network consists of single transistor and diode. During the on-time of the transistor, the voltage across inductor L is equal to V_{in} and the current I_L (input current) increases linearly. When the switch is open, the current (I_L) flows through the diode and charges the output capacitor.

The function of the boost converter can also be described in terms of energy balance. During the on-time of the switch, the inductance is charged with energy and during the off-time of the switch, this energy is transferred from the inductor to output capacitor through the diode. This is repeated each switching cycle.

6. CONTROLLING PFC

The control circuit usually consists of a cascade of two feedback circuits, Fig. 14:

- The voltage loop controller is used to keep the output voltage of the PFC constant, which means keeping it independent from the load power consumption.
- The current loop regulates the input current so that it follows the reference current acting on the duty ratio of the switch (to control the input current to be sinusoidal).

The input current control loop is lead by the input voltage. In this case the input current acquires the same shape as the input voltage and consequently the power factor of the mains current will be unity [9].

The output voltage is controlled by comparing it to a constant reference voltage.

A multiplier is used to provide a reference I_{ref} which is proportional to the error signal v_e and which has a modulating signal with the desired shape for the input current.

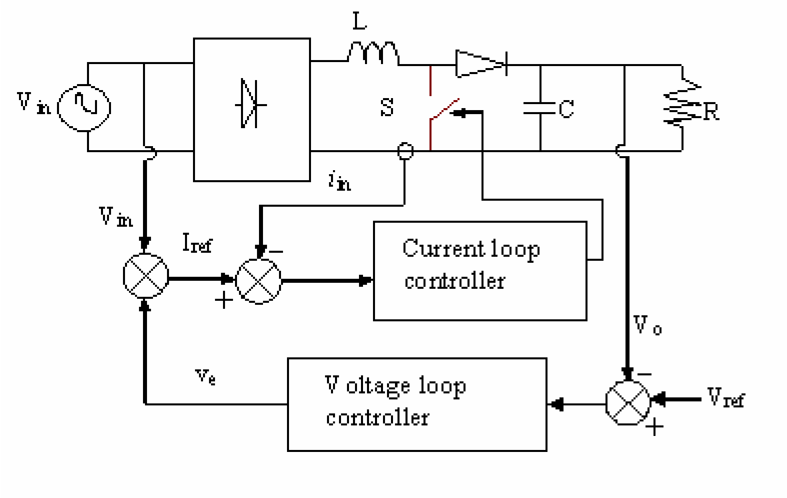

Fig. 14. The control circuit for PFC

Other control techniques are used:

1. Peak current mode control.

In this strategy, well-known from DC/DC converters, the switch is tuned on with constant switching frequency, and tuned off when the upslope of the inductor current reaches a level set by the outer loop.

2. Average current mode control.

In this method, the inductor current, instead of the peak, is compared to the current program level. This offers better noise rejection and stability, when compared to peak current mode control. Consequently, average current mode control is widely used in PFC applications [10, 11].

3. Hysteretic control.

The inductor current is kept within a regulation band [12]. Its main advantage is its simple implementation. However, the variable switching frequency associated with it is a drawback.

4. Charge non-linear control (Non-linear-carrier control).

This control is an approach where the integral of the current trough the switch is compared with a non-linear carrier voltage generated by the controller [13, 14].

Simulation results are given in Fig. 15 and 16 (Line voltage, line current, and analysis spectral) for a PFC boost. The following parameters are used in the simulation: $V_{in} = 200$ V, $f = 50$ Hz, $L = 0.001$ μH, $C = 0.002$ μF, $R = 144$ Ω.

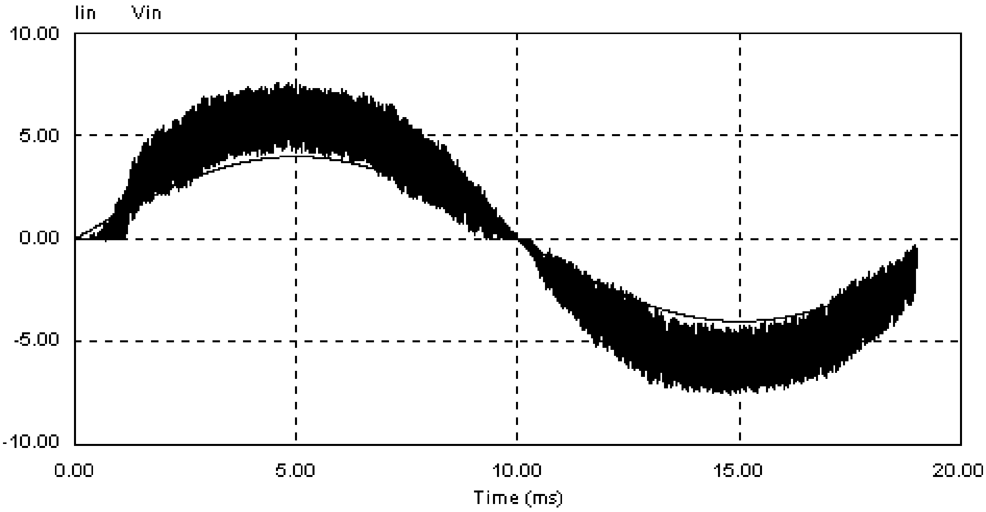

Fig. 15. The input current and voltage of the boost rectifier

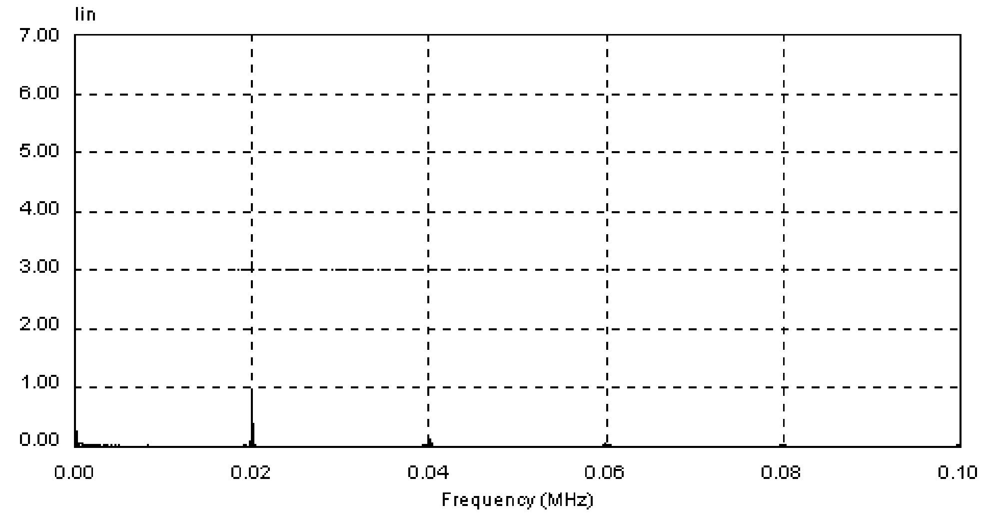

Fig. 16. The spectrum of the line current

CONCLUSIONS

As we have seen, conventional AC rectification is a very inefficient process, resulting a waveform distortion of the current drawn from the power line. It produces large spectrum of harmonic signals that may disturb with other equipment.

The effects of high harmonic distortion and low power factor have been discussed along with the tradeoffs involved in correcting them.

This paper discusses how the harmonic may be reduced and the supply from the mains made more efficient by additional circuits at the input of the converter.

Examples have been provided of passive technique.

Active power factor correction is introduced to avoid mains disturbances caused by the increasing number of mains rectifiers, supplying all kinds of electrical devices.

The mode of operation of single phase rectifier with active power factor correction has been described and simulated.

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