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Power Quality Issues of Single Phase PFC Low Frequency Active Converter

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Abstract: *The equipment connected to an power distribution network usually needs some kind of power conditioning, typically rectification, which produces a non-sinusoidal line current due to the non-linear input characteristic. With the steadily increasing use of such electronic equipment, line current harmonics have become a major problem. Their adverse effects on the power system are well recognized. They include increased magnitudes of neutral currents in three-phase systems, overheating in transformers and motors, as well as the degradation of system waveforms. Several international standards now exist, which limit the harmonic content due to line currents of equipment connected to electricity distribution networks. As a result, there is the need for a Power Factor Correction - PFC. In this paper, we address several issues concerning the application to single-phase PFC of various high-frequency switching converter topologies. The inherent PFC properties of second order switching converters operating in Discontinuous Inductor Current Mode – DICM are well known, and Boost converters are widely used. However, their output voltage is always higher than the amplitude of the rectified-sinusoid input voltage. Methods for improving the efficiency of the PFC stage are addressed. We compare several Boost-type topologies that have lower conduction losses than the combined diode bridge and Boost converter in other words it can perform direct AC/DC conversion. Simulation results show that the topological issues related PFC in power converter.*

Index Terms: *Power quality, PFC, boost converter, current mode, current harmonics.* ***(Key words)***

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I. Nonlinear loads and their effect on the electricity distribution network

The equipment connected to an electricity distribution network usually needs some kind of power conditioning, typically rectification, which produces a non-sinusoidal line current due to the nonlinear input characteristic. The most significant examples of nonlinear loads are reviewed next. Line-frequency diode rectifiers convert AC input voltage into DC output voltage in an uncontrolled manner. Single-phase diode rectifiers are needed in relatively low power equipment that need some kind of power conditioning, such as electronic equipment (e.g. TVs, office equipment, battery chargers, electronic ballasts) and household appliances. For higher power, three phase diode rectifiers are used, e.g. in variable-speed drives and industrial equipment. In both single- and three-phase rectifiers, a large filtering capacitor is connected across the rectifier output to obtain DC output voltage with low ripple. As a consequence, the line current is non-sinusoidal. Line-frequency phase-controlled rectifiers are used for controlling the transfer of energy between the AC input and the adjustable DC output.

In most of these cases, the amplitude of odd harmonics of the line current is considerable with respect to the fundamental. As an example, a single-phase diode rectifier is presented in Fig. 1.1, together with its line current and voltage waveforms. The odd harmonics of the line current, normalized to the fundamental, are shown in the same figure. The normalized amplitudes of the 3rd, 5th, 7th and 9th harmonics are significant.

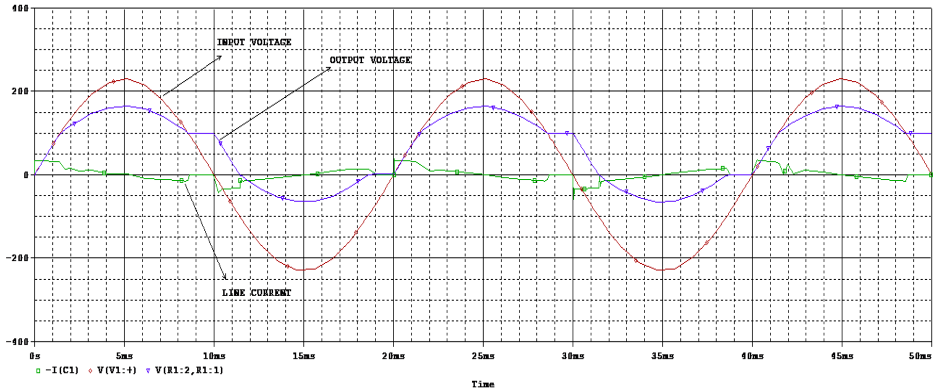


Fig. 1.1 Single-phase diode bridge rectifier: a) Schematic; b) Typical line current and voltage

While the effect of a single low power nonlinear load on the network can be considered negligible, the cumulative effect of several nonlinear loads is important. Line current harmonics have a number of undesirable effects on both the distribution network and consumers. These effects include:

1) Losses and overheating in transformers, shunt capacitors, power cables, AC machines and Switchgear, leading to premature aging and failure.

2) Excessive current in the neutral conductor of three-phase four-wire systems, caused by odd Triple-n current harmonics (triple-*n*: 3rd, 9th, 15th, etc.). This leads to overheating of the neutral Conductor and tripping of the protective relay.

3) Reduced power factor, hence less active power available from a wall outlet having certain apparent power rating.

4) Electrical resonances in the power system, leading to excessive peak voltages and RMS currents, and causing premature aging and failure of capacitors and insulation.

5) Distortion of the line voltage via the line impedance, as shown in Fig. 1.1, where the typical worst-case values, $R_{line} = 0.4\Omega$ and $L_{line} = 800\mu h$ [Red01], have been considered. The effect is stronger in weaker grids. The distorted line voltage may affect other consumers connected to the electricity distribution network. For example, some electronic equipment is dependent on accurate determination of aspects of the voltage wave shape, such as amplitude, RMS and zero-crossings.

6) Telephone interference.

7) Errors in metering equipment.

8) Increased audio noise.

9) Cogging or crawling in induction motors, mechanical oscillation in a turbine-generator Combination or in a motor-load system.

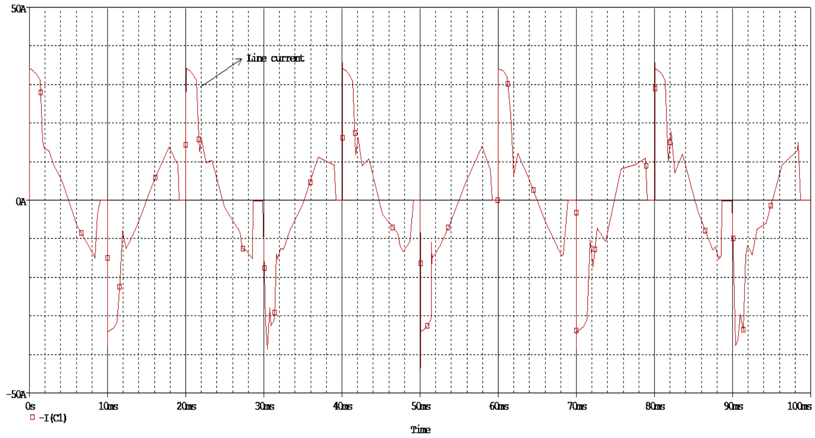
Standards regulating line current harmonics

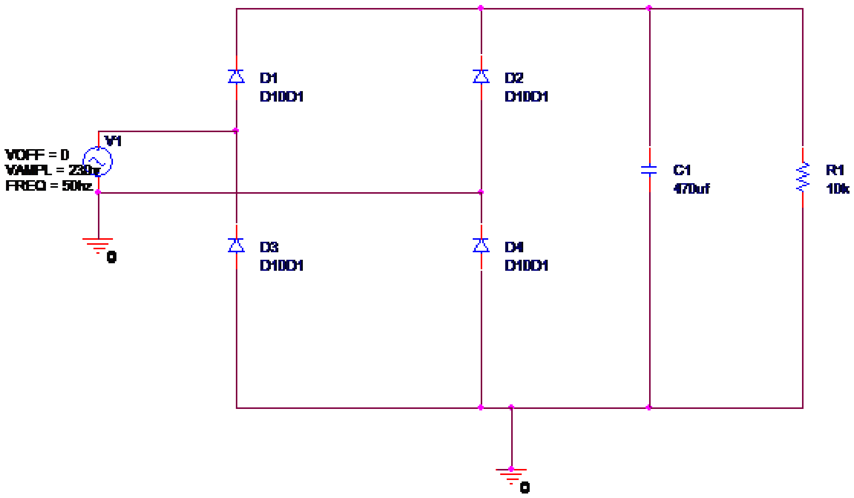
The previously mentioned negative effects of line current distortion have prompted a need for setting limits for the line current harmonics of equipment connected to the electricity distribution network. Standardization activities in this area have been carried out for many years. As early as1982, the International Electro technical Committee - IEC published its standard IEC 555-2 [IEC82], which was also adopted in 1987 as European standard EN 60555-2, by the European Committee for Electro technical Standardization - CENELEC. Standard IEC 555-2 has been replaced in 1995 by standard IEC 1000-3-2 [IEC95], also adopted by CENELEC as European standard EN 61000-3-2. Standard IEC 1000-3-2 applies to equipment with a rated current up to and including 16Arms per phase which is to be connected to 50Hz or 60Hz, 220-240Vrms single-phase, or 380-415Vrms three-phase mains.

Items of electrical equipment are categorized into four classes (A, B, C and D), for which specific limits are set for the harmonic content of the line current. The standard has been revised several times and a second edition was published in 2000 [IEC00] with an amendment in 2001 [IEC01].

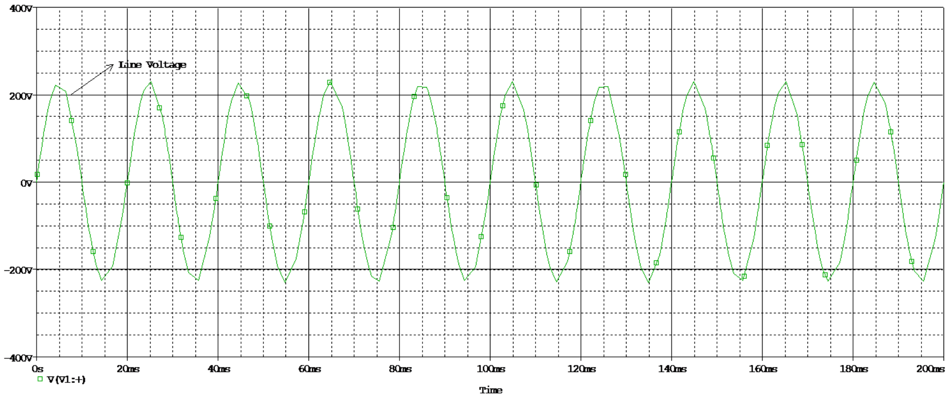
II. Overview of Methods for PFC

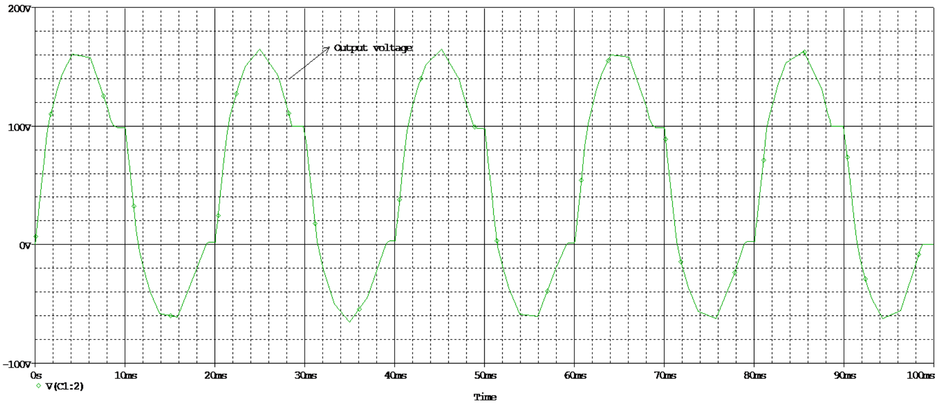
As mentioned in the previous chapter, the diode bridge rectifier, shown again in Fig. 2.1a), has non-sinusoidal line current. This is because most loads require a supply voltage V_2 with low ripple, which is obtained by using a correspondingly large capacitance of the output capacitor C_f Consequently, the conduction intervals of the rectifier diodes are short and the line current consists of narrow pulses with an important harmonic content. The simplest way to improve the shape of the line current, without adding additional components, is to use a lower capacitance of the output capacitor C_f . When this is done, the ripple of the output voltage increases and the conduction intervals of the rectifier diodes widen. The shape of the input current becomes also dependent on the type of load that the rectifier is supplying, resistive or constant power, as opposed to the case of negligible output voltage ripple where the type of load does not affect the line current. This solution can be applied if the load accepts a largely pulsating DC supply voltage and it is used, for example, in some handheld tools. The concept is highlighted by the simulated waveforms shown in Fig. 2.1b), for two values of the output capacitor and assuming constant power load. The shape of the input current is improved to a certain extent with the lower capacitance, at the expense of increased output voltage ripple, as can be seen also from the results listed in the caption of Fig. 2.1.





INPUT VOLTAGE:

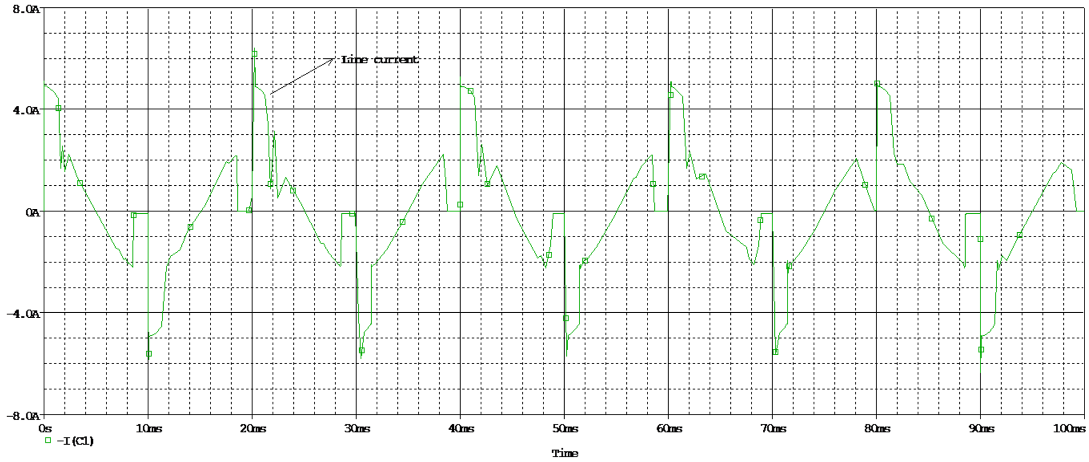




When C_f= 470µF.

When C_f =68µF.

LINE CURRENT:



OUTPUT VOLTAGE:

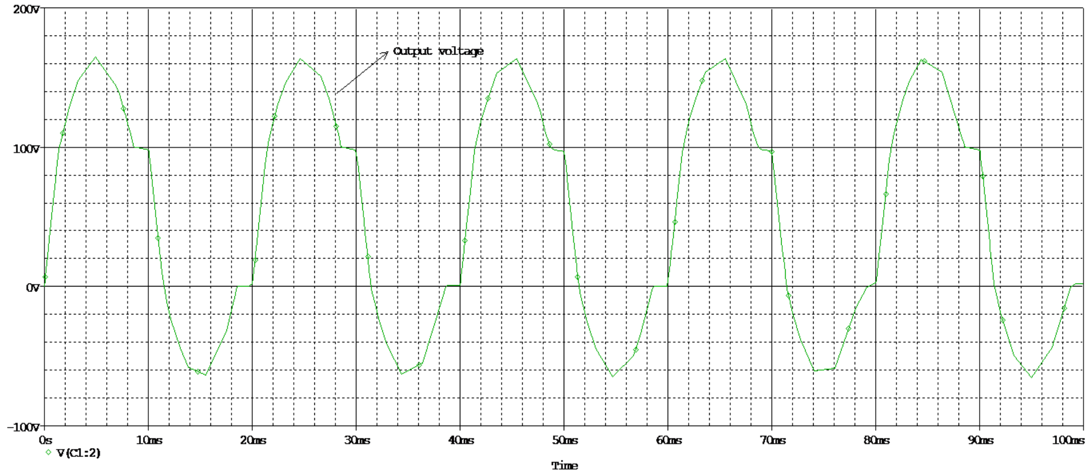


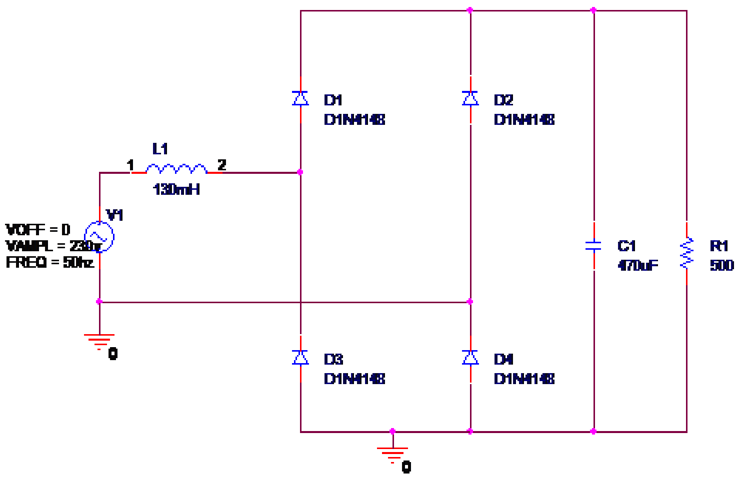
Fig. 2.1 Diode bridge rectifier: a) Schematic; b) Line voltage and line current (upper plot), and output voltage (lower plot), withV_1= 230V_{rms} and constant power load P = 200W .With C_f= 470µF, the line current has K_p= 0.415 , cosφ = 1 and PF = 0.415 , and the output voltage ripple is ΔV_2=160V . With C_f= 68 µF, the line current has K_p= 0.619 ,cos φ = 0.910 andPF = 0.563 , and the output voltage ripple is ΔV_2=165V.

We would like to clarify here that, throughout this chapter, the purity factor K_p , the displacement factor cos φ and the power factor PF , are given only as basic information on the PFC properties of the simulated circuits, and they are not relevant as such for assessing compliance with standard IEC 1000-3-2.

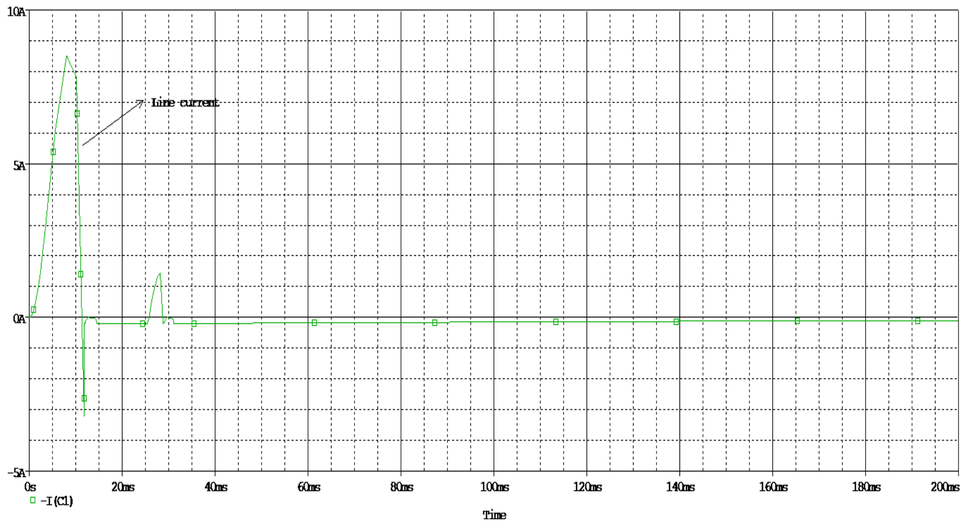
The method presented above has severe limitations: it does not reduce substantially the harmonic currents and the output voltage ripple is large, which is not acceptable in most of the cases. Several other methods to reduce the harmonic content of the line current in single-phase systems exist, and an overview of the representative ones is presented next.

2.1 Passive PFC

Passive PFC methods use additional passive components in conjunction with the diode bridge rectifier from Fig. 2.1. One of the simplest methods is to add an inductor at the AC-side of the diode bridge, in series with the line voltage as shown in Fig. 2.2a), and to create circuit conditions such that the line current is zero during the zero-crossings of the line voltage [Moh95, pp. 91-94]. The maximum power factor that can be obtained is $PF = 0.76$, with the theoretical assumption of constant DC output voltage. We should note here that in reality, as explained later on in this chapter, the DC output voltage of the PFC circuit has ripple at twice the line-frequency, ripple that is also dependent on the load current. Simulated results for the rectifier with AC-side inductor are presented in Fig. 2.2b), where the inductance L_a has been chosen so as to maximize the power factor.



LINE CURRENT:



OUTPUT VOLTAGE:

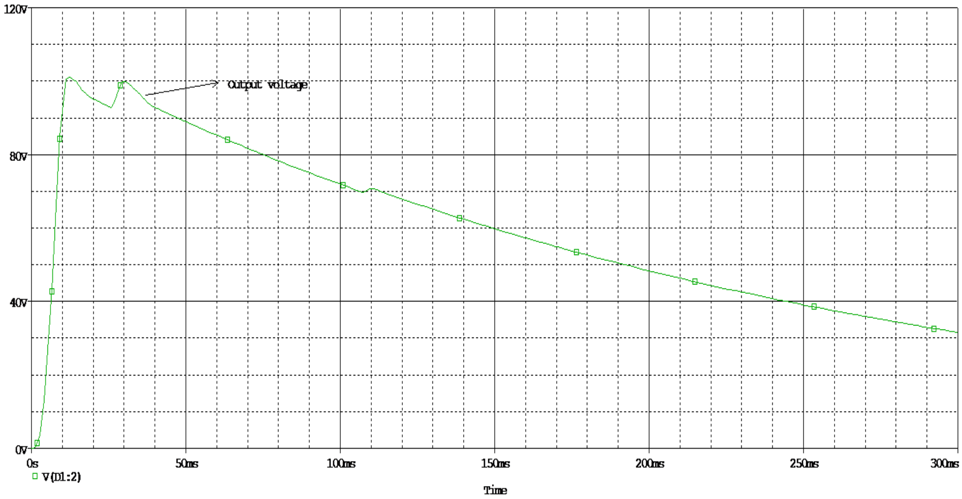
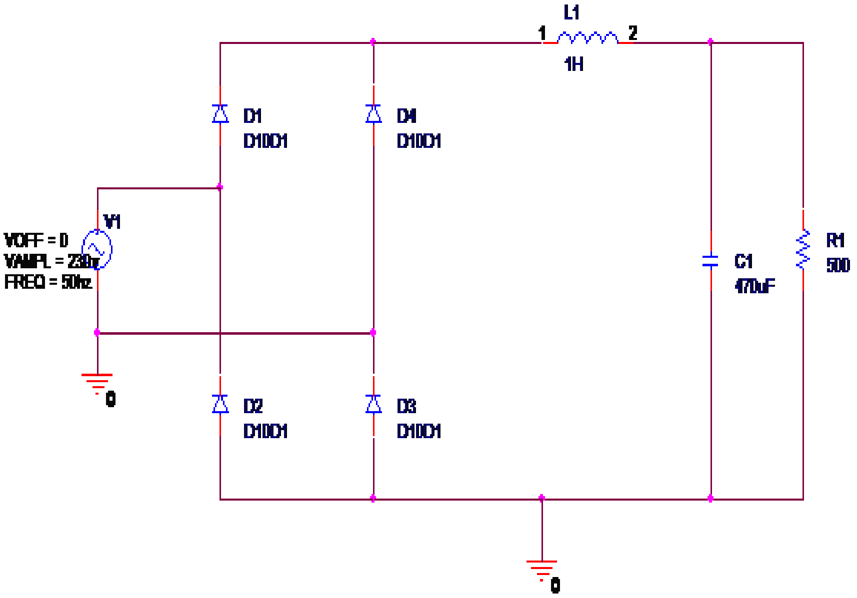
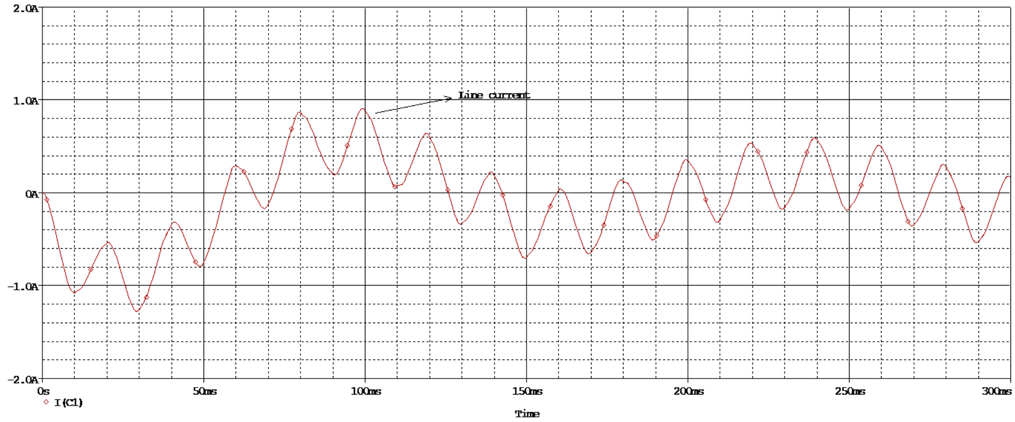


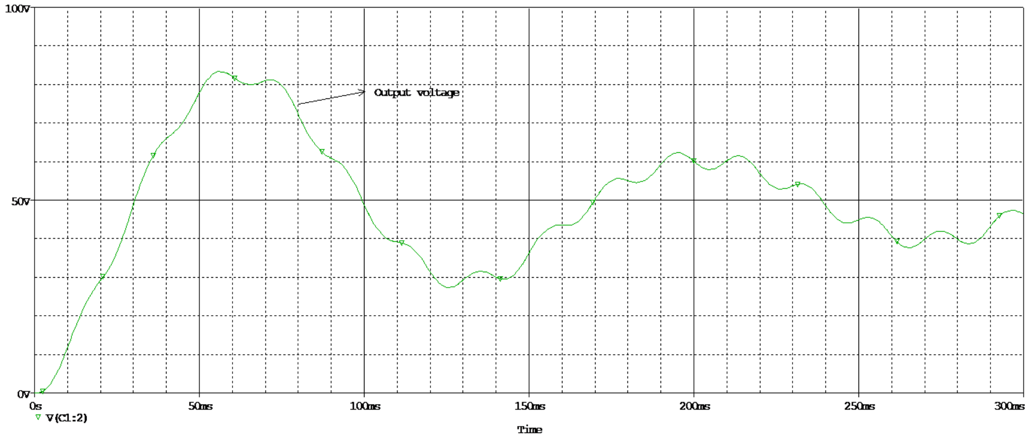
Fig. 2.2 Rectifier with AC-side inductor: a) Schematic; b) Line voltage, line current and output voltage with V_{rms}= 230V , resistive load R = 500 Ω,C_f= 470µF, andL_a=130mH
The line current has K_p= 0.143, cosφ = 0.62 and PF = 0.0886.
The output voltage is V_2= 101V.

The inductor can be also placed at the DC-side, as shown in Fig. 2.3a) [Dew81], [Kel92]. The inductor current is continuous for a large enough inductance L_d. In the theoretical case of near infinite inductance, the inductor current is constant, so the input current of the rectifier has a square shape and the power factor is PF = 0.9. However, operation close to this condition would require a very large and impractical inductor, as illustrated by the simulated line current waveform for L_d=1H (without Ca), shown in Fig. 2.3b). For lower inductance L_d, the inductor current becomes discontinuous. The maximum power factor that can be obtained in such a case is PF = 0.76, the operating mode being identical to the case of the AC-side inductor previously discussed. An improvement of the power factor can be obtained by adding the capacitor C_a as shown in Fig. 2.3a), which compensates for the displacement factor cos φ. A design for maximum purity factor K_p and unity displacement factor cos φ is possible, leading to a maximum obtainable power factor PF = 0.905 [Kel89]. This is exemplified by the simulated line current for L_d= 275mH and C_a= 4.8µF, which is shown in Fig. 2.3b).



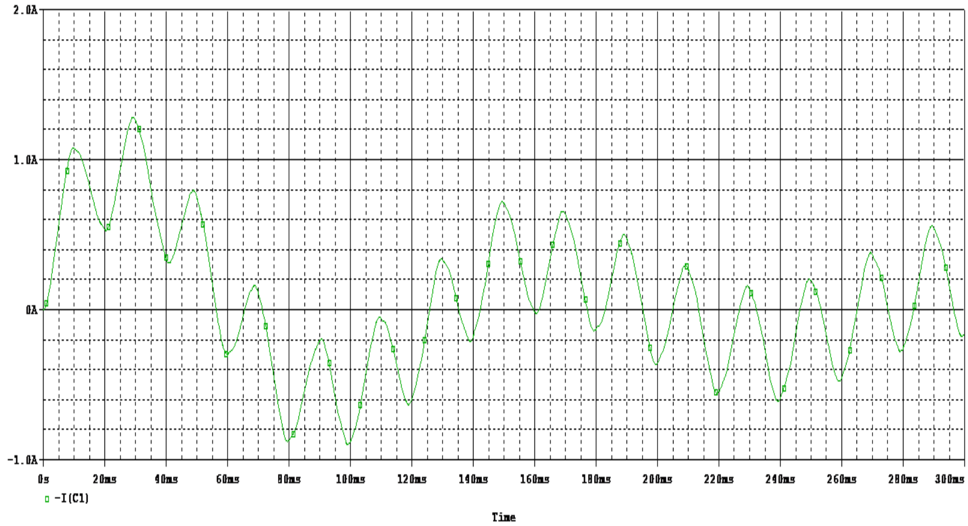
LINE CURRENT WITHOUT C_A:





OUTPUT VOLTAGE:

WITH C_a=4.8μF
LINE CURRENT:



OUTPUT VOLTAGE:

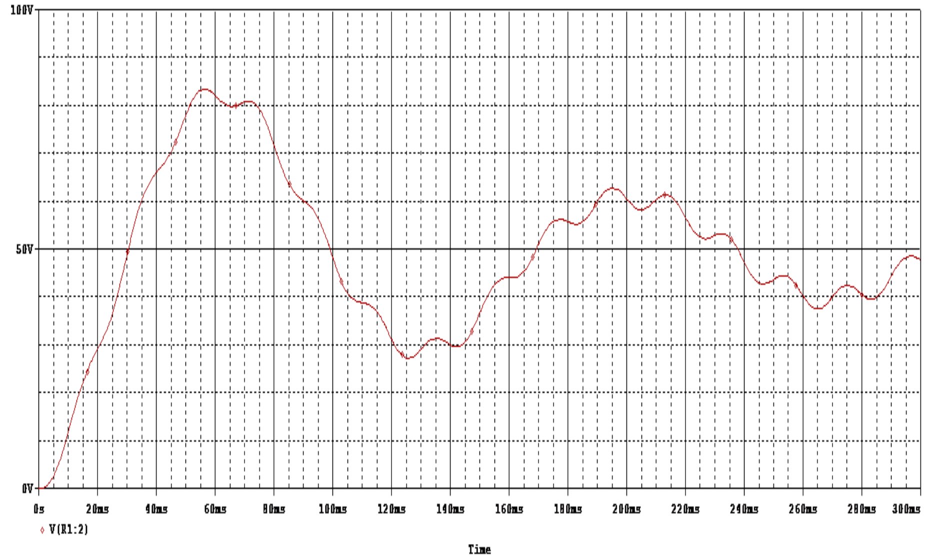
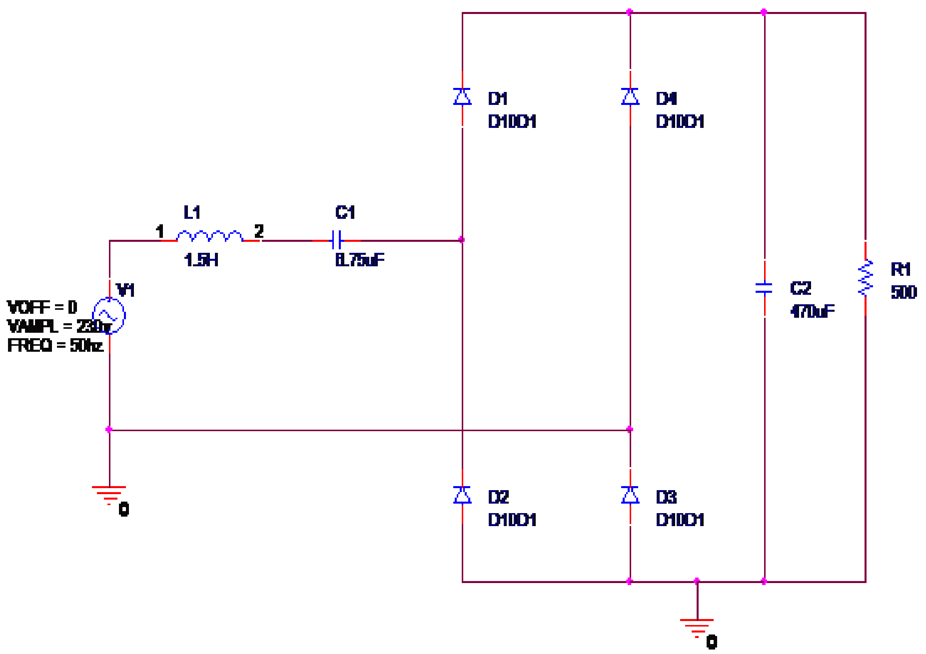


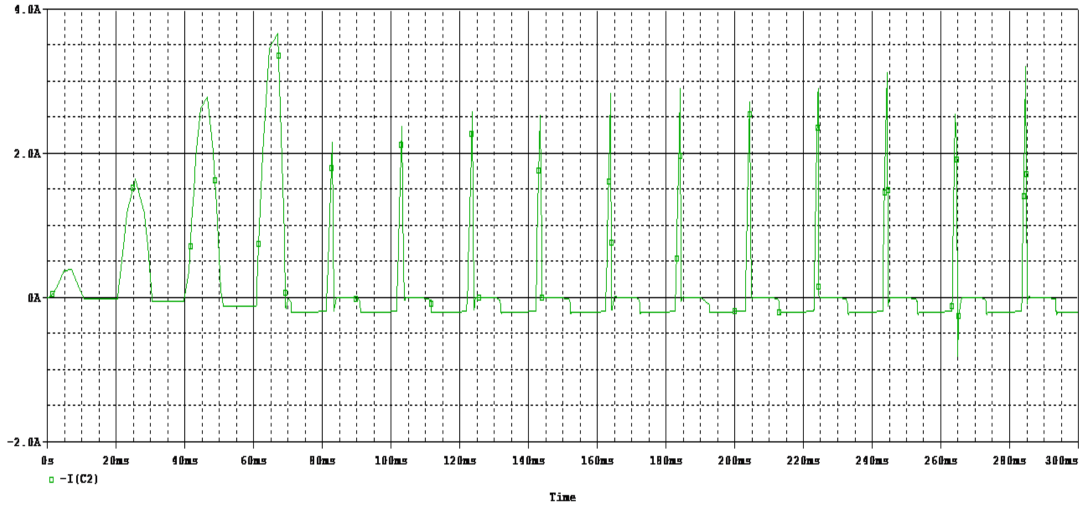
Fig. 2.3 Rectifier with DC-side inductor: a) Schematic; b) Line voltage and line current with V_{rms}= 230V , resistive load R = 500 ohms , and C_f= 470µF. With L_d=1H and without C_a, the line current has K_p= 0.435 , cos φ = 0.995 and PF = 0.433 , and the output voltage is V_2= 84V With L_d= 275mH and with C_a= 4.8 µF, the line current has K_p= 0.292 , cos φ = 0.998 and PF = 0.291 , and the output voltage is V_2= 97V.

The shape of the line current can be further improved by using a combination of low-pass input and output filters [Moh95, pp. 488-489]. There are also several solutions based on resonant networks which are used to attenuate harmonics. For example, a band-pass filter of the series resonant type, tuned at the line-frequency, is introduced in-between the AC source and the load, as shown in Fig. 2.4 together with simulated waveforms. For 50/60Hz networks, large values of the reactive elements are needed. Therefore, this solution is more practical for higher frequencies, such as for 400Hz and especially 20kHz networks [Vor90a].

The solution using a band-stop filter of the parallel-resonant type [Pra90] is presented in Fig. 2.5 together with simulated waveforms. The filter is tuned at the third harmonic, hence it allows for lower values of the reactive elements when compared to the series-resonant band-pass filter.



LINE VOLTAGE:



OUTPUT VOLTAGE:

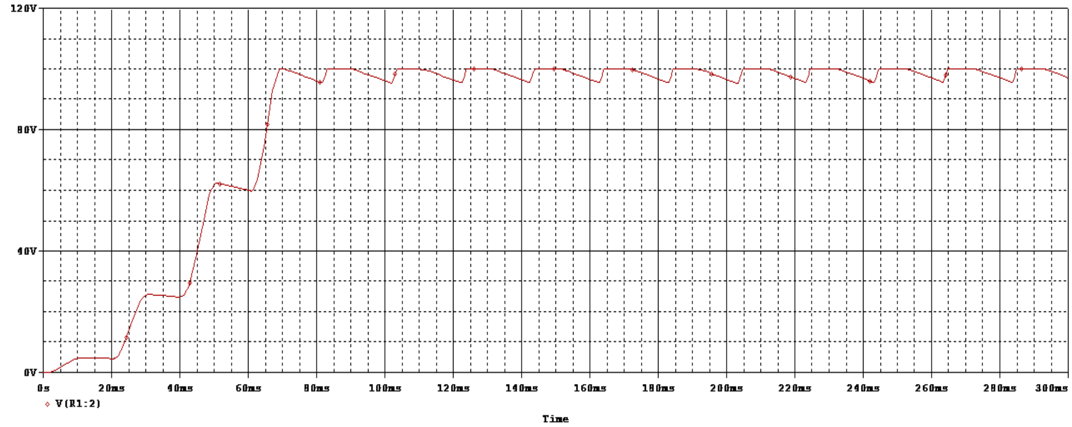
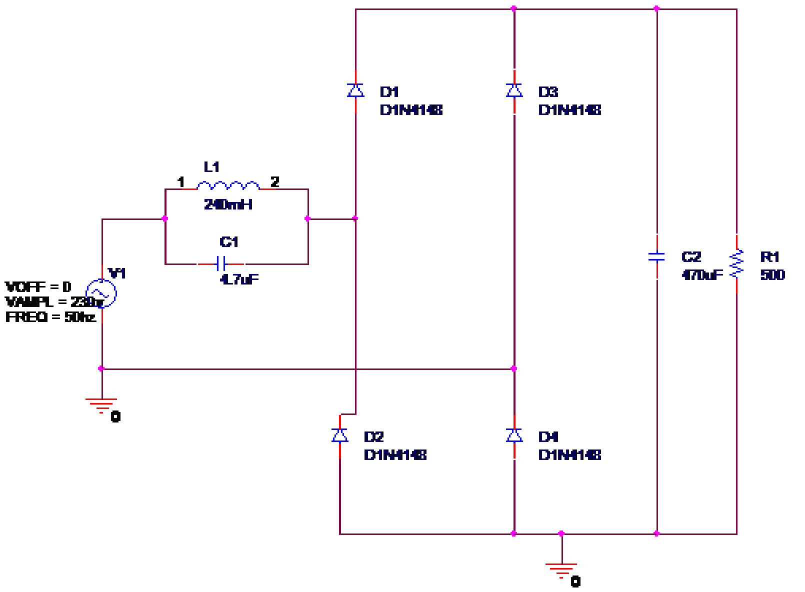
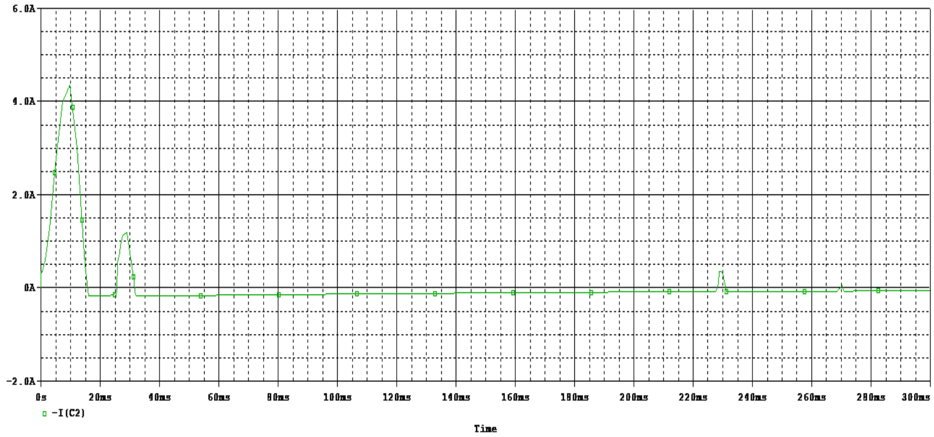


Fig. 2.4 Rectifier with series-resonant band-pass filter: a) Schematic; b) Line voltage and line current with V_1= 230V_{rms} , resistive load R = 500 ©, C_f= 470μF, L_s=1.5H and C_s= 6.75 μF. The line current has K_p = 0.250, cos φ = 0.755 and PF = 0.189. The output voltage isV_2= 100 V.



LINE CURRENT:



OUTPUT VOLTAGE:

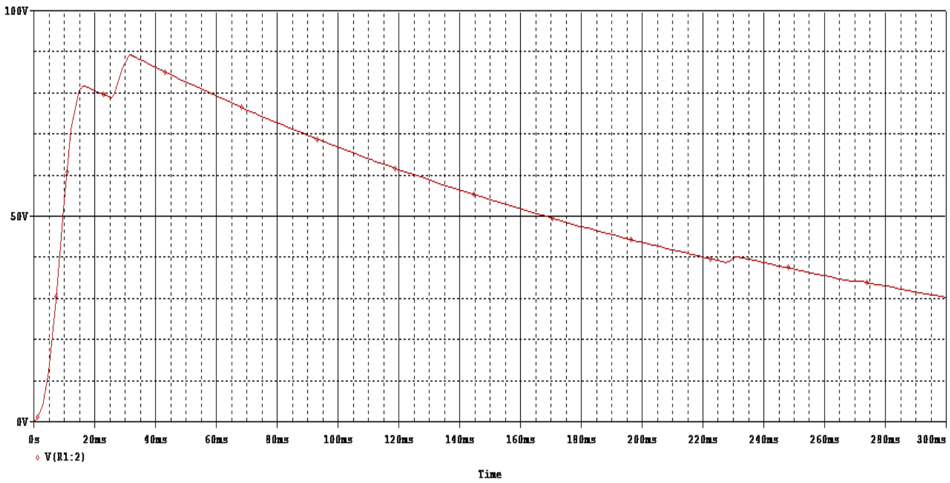
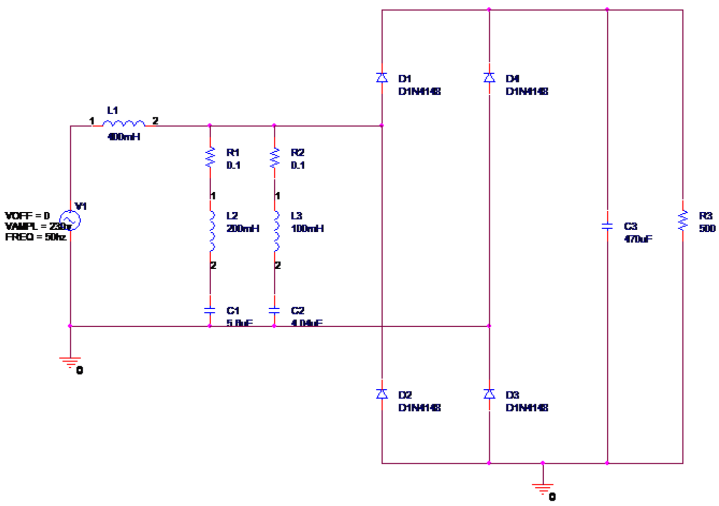
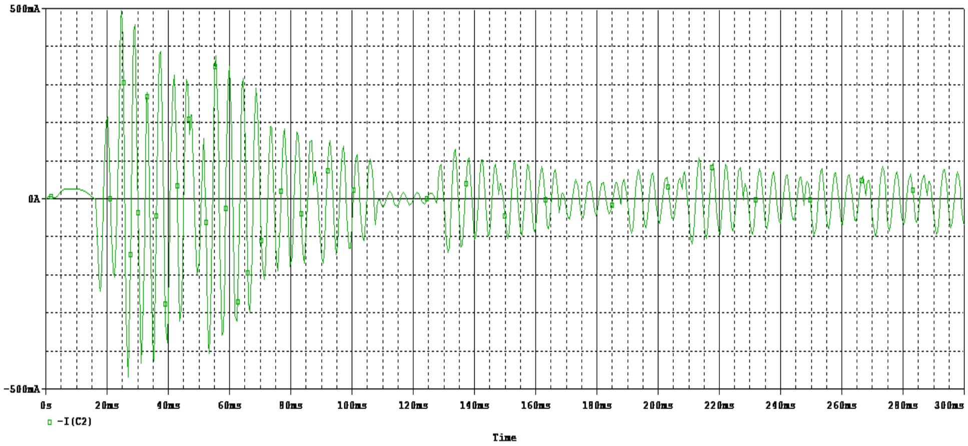


Fig. 2.5 Rectifier with parallel-resonant band-stop filter: a) Schematic; b) Line voltage and line current withV_1= 230V_{rms}, resistive load R = 500 © ,C_f= 470µF, L_p= 240mH and C_p= 4.7µF. The line current has K_p= 0.2, cos φ = 0.717 and PF = 0.143 . The output voltage is V_2= 89V.

Another possibility is to use a harmonic trap filter. The harmonic trap consists of a series resonant network, connected in parallel to the AC source and tuned at a harmonic that must be attenuated [Eri97, pp. 575-582]. For example, the filter shown in Fig. 2.6a)-b) has two harmonic traps, which are tuned at the 3rd and 5th harmonic, respectively, as shown in Fig. 2.6c). As seen from Fig. 2.6d), the line current improvement is very good, at the expense of increased circuit complexity. Harmonic traps can be used also in conjunction with other reactive networks, such as a band-stop filter [Red91].



LINE CURRENT:



OUTPUT VOLTAGE:

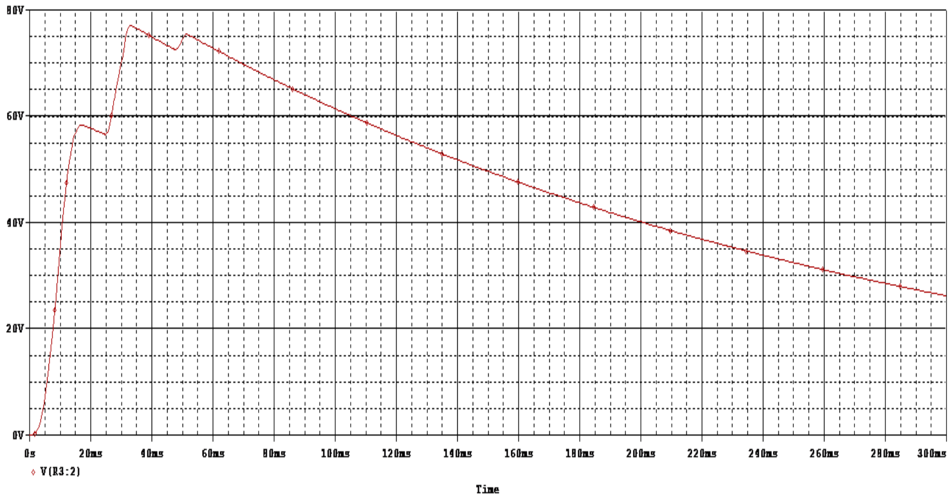
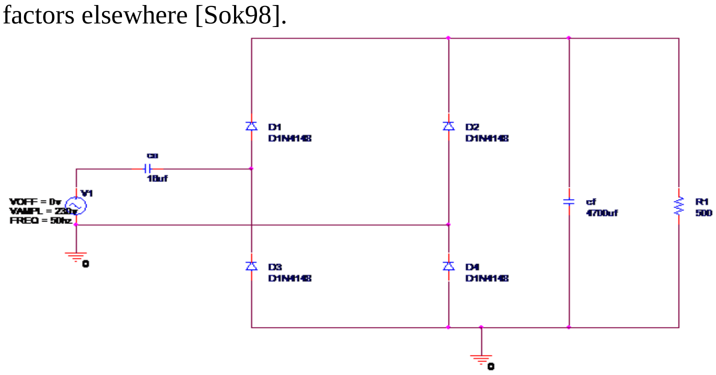
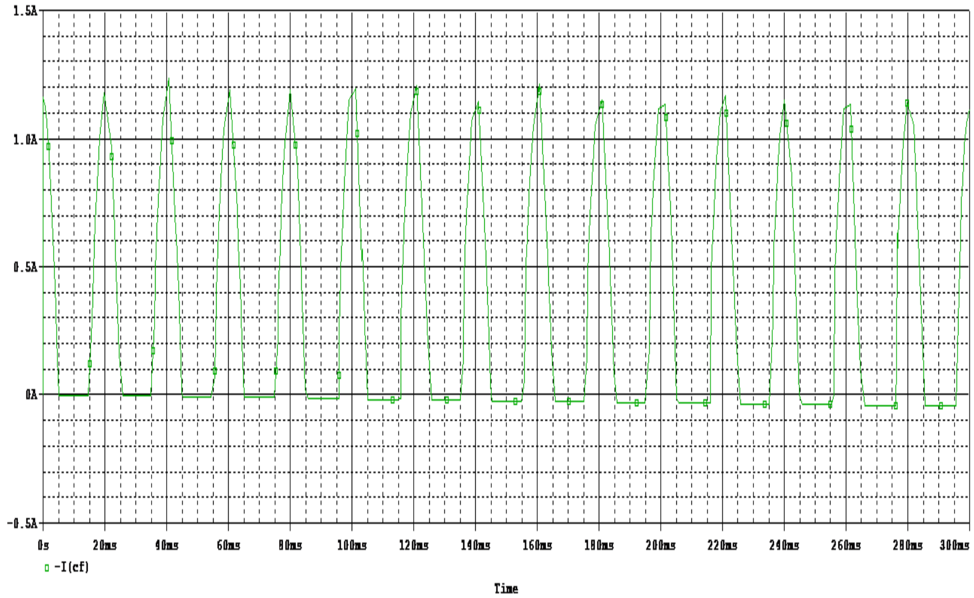


Fig. 2.6 Rectifier with harmonic trap filter: a) Schematic; b) Simulation circuit for the frequency response of the harmonic trap filter; c) Frequency response of the harmonic trap filter with L_1= 400mH,L_3= 200mH,C_3= 5.6μF,R_3= 0.1ohms, L_5=100mH, C_5= 4.04μF, and R_5= 0.1ohms; d) Line voltage and line current with V_{rms}= 230V , resistive load R = 500ohms , C_f= 470μF, and filter values from c). The line current has K_p= 0.240, cos φ = 0.651 and PF = 0.156. The output voltage is V_2= 77V.

The capacitor-fed rectifier, shown in Fig. 2.7 together with simulated waveforms, is a very simple circuit that ensures compliance with standard IEC 1000-3-2 for up to approximately 250W input power at a 230Vrms line voltage. The conversion ratio is a function of Xa/R, where $X_a = 1/(\omega_L C_a)$. Therefore, it is possible to obtain a specific output voltage, which is nevertheless lower than the amplitude of the line voltage and strongly dependent on the load. Despite the harmonic current reduction, the power factor is extremely low. This is not due to current harmonics, but to the series-connected capacitor that introduces a leading displacement factor cos φ. An advantage could be that the leading displacement factor cos φ can assist in compensating for lagging displacement factors elsewhere [Sok98].



LINE CURRENT:



OUTPUT VOLTAGE:

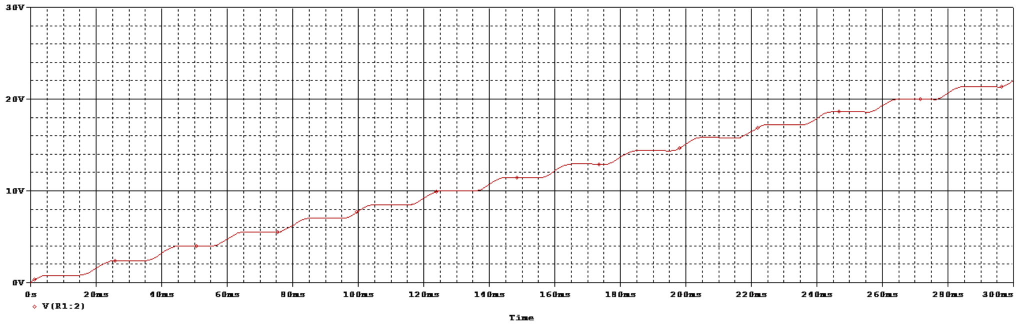
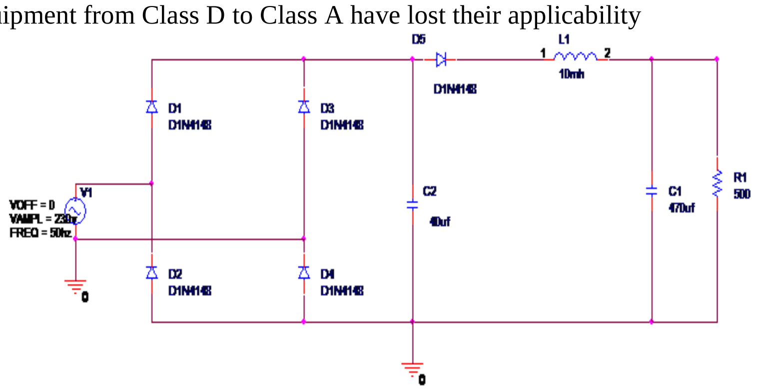
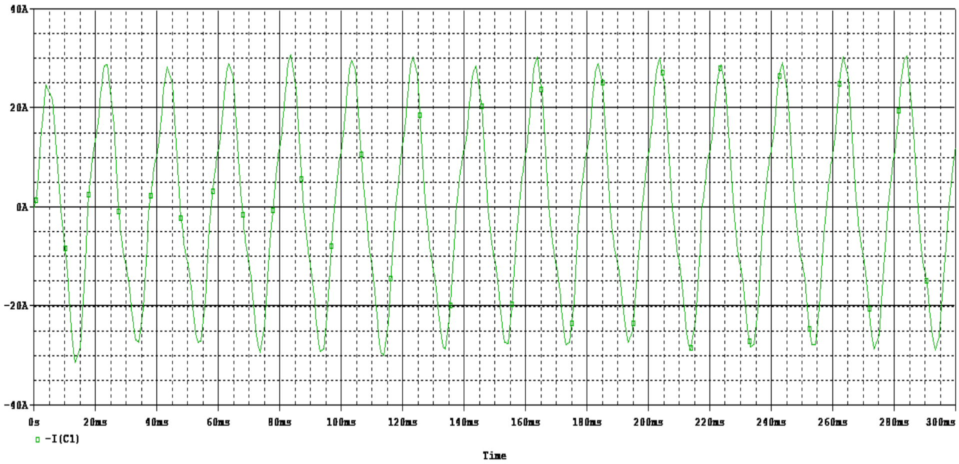


Fig. 2.7 Capacitor-fed rectifier: a) Schematic; b) Line voltage and line current with V_{rms}= 230V , resistive load R = 500ohms , C_f= 4700µF, andC_a=16µF. The line current has K_p= 0.984, cosφ = 0.483 and PF = 0.475. The output voltage is V_2=22V.

The rectifier with an additional inductor, capacitor, and diode – LCD rectifier – is shown in Fig. 2.8, together with simulated waveforms. The added reactive elements have relatively low values. The idea behind the circuit is linked to the previous definition of Class D of the IEC 1000-3- 2 standard, which was based on the envelope shown in Fig. 1.2. The circuit changes the shape of the input current and, while only a limited reduction of the harmonic currents can be obtained, it was also possible to change the classification of the circuit from Class D to Class A. The power-related limits of Class D were avoided and the absolute limits of Class A could be met for low power, in spite of the line current being relatively distorted [Red98]. However, as presented in Chapter 1, the definition of Class D has been changed and techniques aiming at changing the classification of equipment from Class D to Class A have lost their applicability



LINE CURRENT:



OUTPUT VOLTAGE:

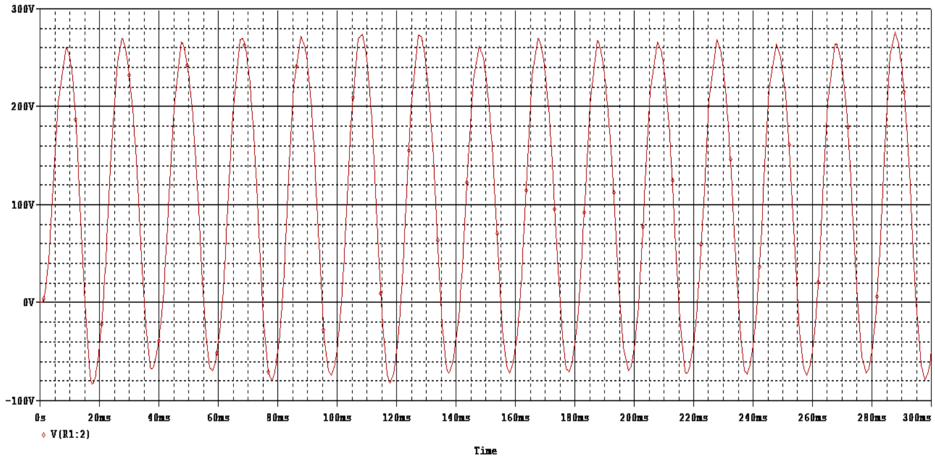
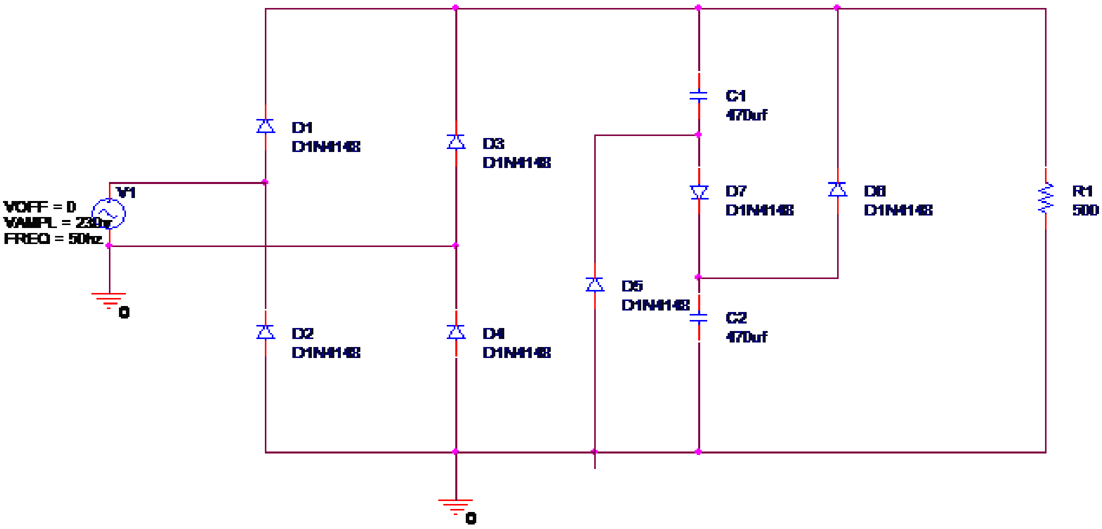
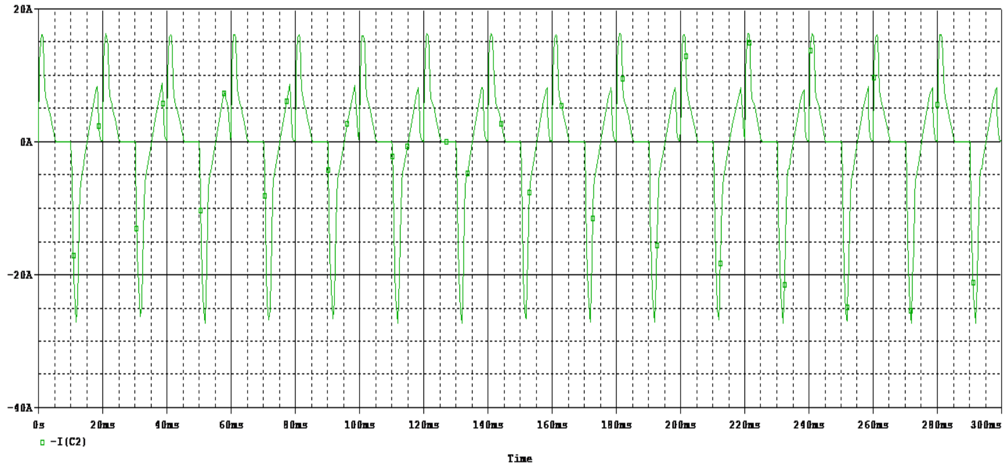


Fig. 2.8 Rectifier with an additional inductor, capacitor and diode (LCD): a) Schematic; b) Line voltage and line current with V_1= 230V$_{rms}$, resistive load R = 500ohms , C_f= 470µF, C_1= 40µF and L_d=10mH. The line current has K_p= 0.133, cos φ = 0.991 and PF = 0.132. The output voltage is V_2= 260V.

Finally, the valley-fill rectifier is shown in Fig. 2.9, together with simulated waveforms [Spa91], [Kit98]. The circuit reduces the harmonic content of the line current but the output voltage has a large variation and the load of the rectifier must be able to tolerate it.



LINE CURRENT:



OUTPUT VOLTAGE:

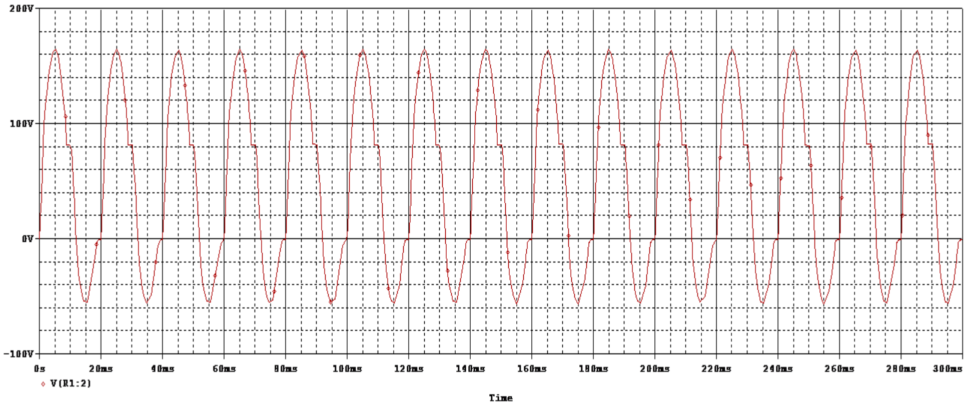


Fig. 2.9 Valley-fill rectifier: a) Schematic; b) Line voltage and line current (upper plot), and output voltage (lower plot), withV_1= 230V_{rms}, constant power load P = 200W, and C_1= C_2= 470μF. The line current has K_p = 0.458, cos φ = 0.982 and PF = 0.450 . The output voltage ripple is ΔV_2=164V.

Passive power factor correctors have certain advantages, such as simplicity, reliability and ruggedness, insensitivity to noise and surges, no generation of high-frequency EMI and no high frequency switching losses. On the other hand, they also have several drawbacks. Solutions based on filters are heavy and bulky, because line-frequency reactive components are used. They also have poor dynamic response, lack voltage regulation and the shape of their input current depends on the load. Even though line current harmonics are reduced, the fundamental component may show an excessive phase shift that reduces the power factor. Moreover, circuits based on resonant networks are sensitive to the line-frequency. In harmonic trap filters, series-resonance is used to attenuate a specific harmonic. However, parallel-resonance at different frequencies occurs too, which can amplify other harmonics [Eri97, pp. 575-582].

2.2 Low-frequency active PFC

Three representative solutions are presented in Fig. 2.10. The phase-controlled rectifier is shown in Fig. 2.10a), and its control signals in Fig. 2.10b). It is derived from the rectifier with a DC-side inductor from Fig. 2.3, where diodes are replaced with thyristors. According to [Kel90], depending on the inductance L_d and the firing-angle α , a near-unity purity factor K_p *or* displacement factor cos Æ can be obtained. However, the overall power factor PF is always less than 0.9. In [Kel91], the inductance L_d and firing angle αare chosen to maximize K_p.

This implies a lagging displacement factor cos Æ that is compensated for by an additional input capacitance C_a. This approach is similar to that used in [Kel89] for the diode bridge rectifier with a DC-side inductor, and discussed in the previous subchapter. This solution offers controllable output voltage, is simple, reliable, and uses low-cost thyristors. On the negative side, the output voltage regulation is slow and a relatively large inductance L_d is still required.

Second-order switching converters are introduced in the next subchapter, as they are mainly used at high switching frequencies. However, it is also possible to use them at low switching frequencies, as explained next. The low-frequency switching Boost converter is shown in Fig. 2.10c). The active switch S is turned on for the duration T_{on}, as illustrated in Fig. 2.10d), so as to enlarge the conduction interval of the rectifier diodes

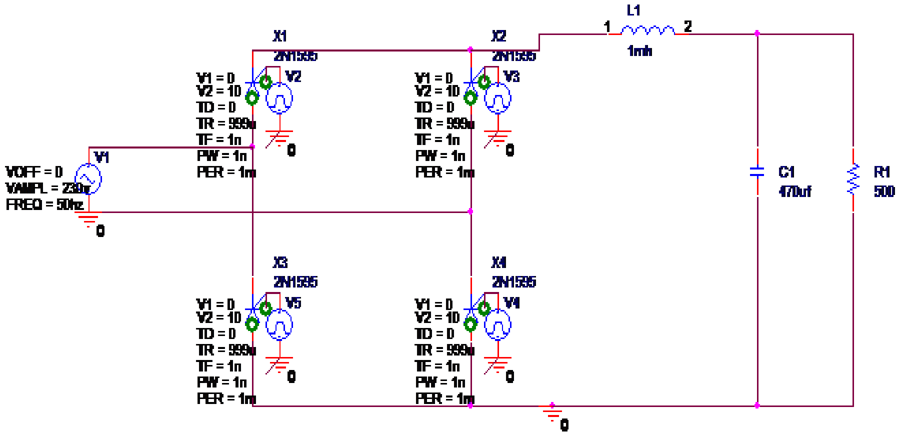
[Zuc97]. It is also possible to have multiple switching's per half line-cycle, at low switching frequency, in order to improve the shape of the line current [Red91]. Nevertheless, the line current has a considerable ripple.

The low-frequency switching Buck converter is shown in Fig. 2.10e) [Red91]. Theoretically, the inductor current is constant for a near-infinite inductance L_d .The switch is turned on for the duration *T*on and the on-time intervals are symmetrical with respect to the zero-crossings of the line voltage, as illustrated in Fig. 2.10f). The line current is square with adjustable duty-cycle. For a lower harmonic content of the line current, multiple switching per line-cycle can be used.

However, the required inductance *L*d is large and impractical.

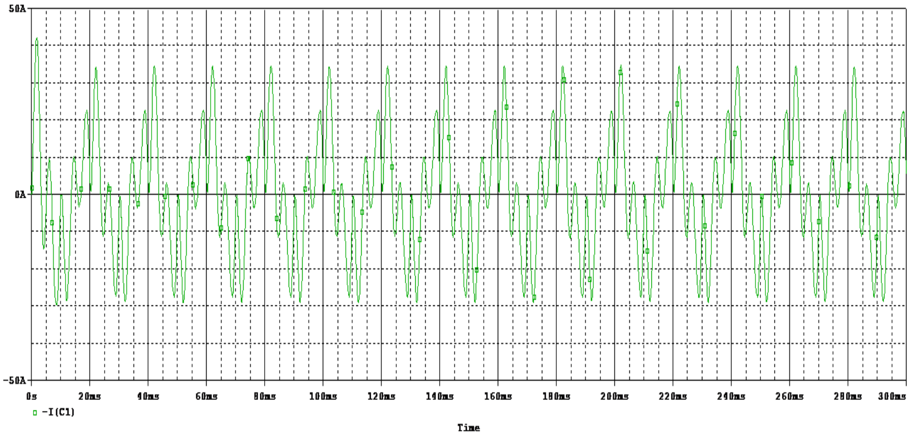
To conclude, low-frequency switching PFC offers the possibility to control the output voltage in certain limits. In such circuits, switching losses and high-frequency EMI are negligible. However, the reactive elements are large and the regulation of the output voltage is slow.

a)

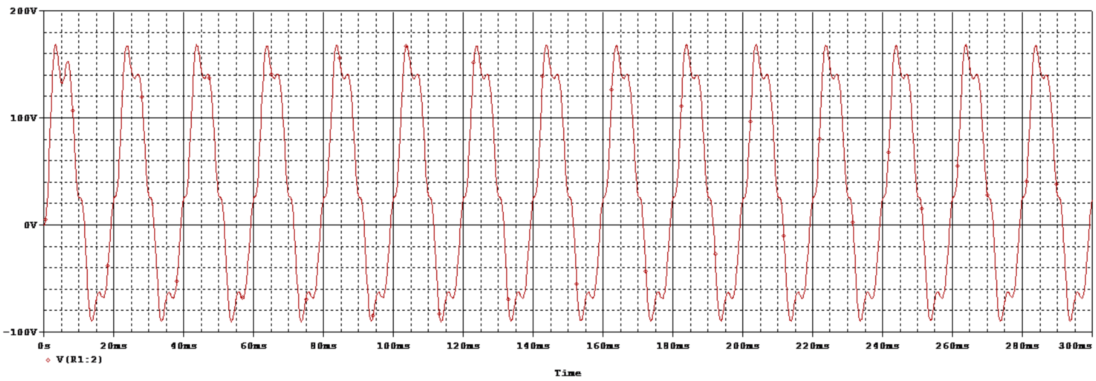


b)

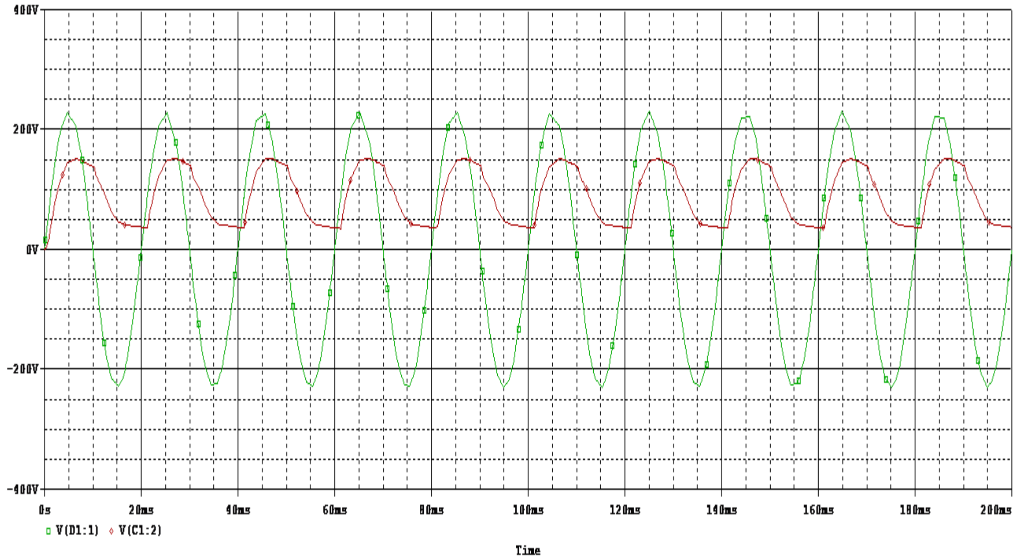
LINE CURRENT :

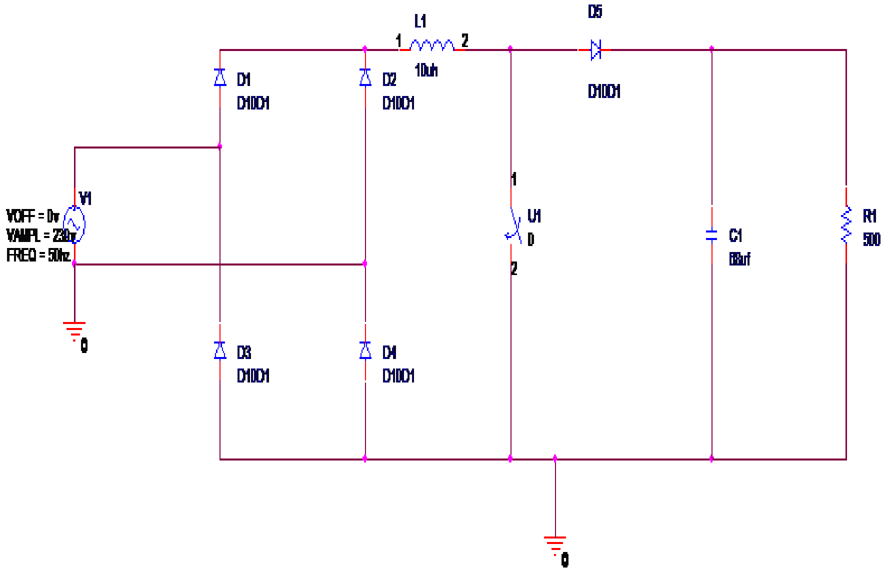


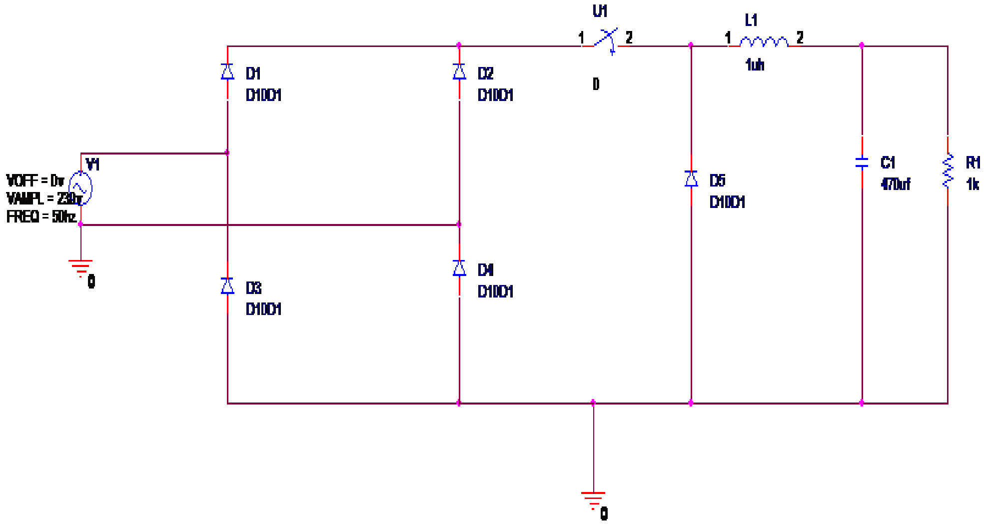
OUTPUT VOLTAGE:



When the diode are replaced with the thyristor and the inductor value L_d= 1mH,C_a=470μF,while giving the pulse signal to the gate of the thyristor and the line current and output voltage are shown in the above figure.


400V
200V
0V
-200V
-400V
0s
20ms
40ms
60ms
80ms
100ms
120ms
140ms
160ms
180ms
200ms
V(D1:1)
V(C1:2)
Time


L1
10uh
D5
D1001
D1
D2
D3
D4
V1
VOFF = 0v
FREQ = 50hz
U1
C1
R1
500
0


U1
L1
1uh
D1
D2
D3
D4
D5
D1001
V1
VOFF = 0v
FREQ = 50hz
C1
470uf
R1
1k
0

f)

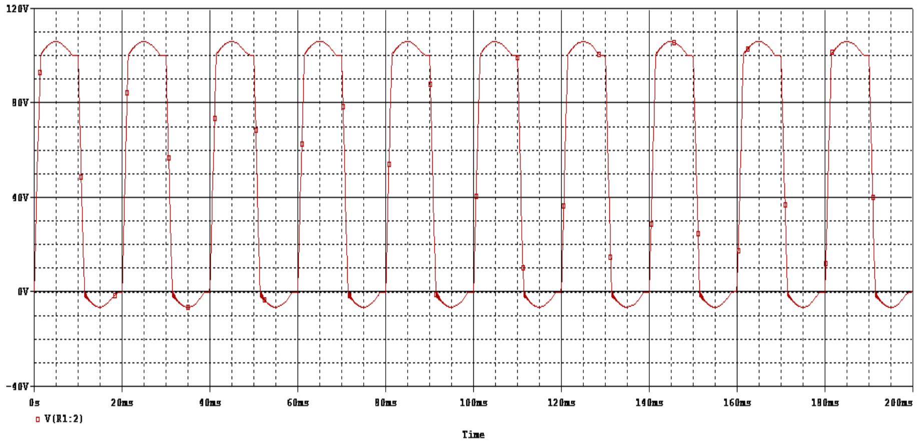


Fig. 2.10 Low-frequency active PFC: a) Controlled rectifier with DC-side inductor, with b) phase-control; c) Boost converter, with d) one commutation per half line-cycle; e) Buck converter, with f) one commutation per half line-cycle.

S. No.	Name of the circuits	Components used	Line current (I_L)	Output Voltage (V_2)	Purity Factor (K_p)	Power Factor	Efficiency
Passive PFC							
1	Diode Bridge Rectifier	R = 500 Ω C_f = 470µF	6.5 A	165 V	0.415	1.000	71.7%
2	Rectifier with AC-side inductor	R = 500 Ω L_a = 130mH C_f = 470µF	8.4 A	101 V	0.143	0.602	43.9%
3	Rectifier with DC-side inductor (without C_a)	R = 500 Ω L_d = 1H C_f = 470µF	1.2 A	84 V	0.435	0.995	42.2%
	Rectifier with DC-side inductor (with C_a)	R = 500 Ω L_d = 275mH C = 4.8µF, 470µF	3.6 A	97 V	0.292	0.998	36.5%
4	Rectifier with series-resonant band-pass filter	R = 500Ω L_s = 1.5H C_f = 470µF C_s = 6.75µF	3.6 A	100 V	0.250	0.755	43.5%
5	Rectifier with parallel-resonant band-stop filter	R = 500Ω L_p = 240mH C_p = 4.7µF	4 A	89 V	0.200	0.717	38.7%
6	Rectifier with harmonic trap filter	R = 0.1Ω, 0.1Ω, 500Ω L= 400mH, 200mH, 100mH C = 5.6µF, 4.04µF, 470µF	3 A	77 V	0.240	0.651	33.5%
7	Capacitor-fed rectifier	R = 500Ω C = 470µF, 16µF	1.23 A	22 V	0.984	0.483	9.5%
8	Rectifier with additional inductor, capacitor & diode (L,C,D)	R = 500Ω C = 470µF, 40µF L = 10mH	50 A	220 V	0.133	0.991	95.6%
9	Valley-fill rectifier	R = 500Ω C_1 = C_2 = 470µF	16.27 A	164 V	0.458	0.982	71.3%

S. No.	Name of the Circuits	Components used	Line Current (I_L)	Output Voltage (V_2)	Purity Factor (K_P)	Power Factor	Efficiency
Low-frequency Active PFC							
10	Controlled rectifier with DC-side inductor	R = 500 Ω L = 1mH C = 470μF	42 A	168.6 V	0.525	0.999	73.3%
11	Boost Converter	R = 500 Ω L = 10μH C = 68μF	1.25 A	81 V	0.108	0.980	35.2%
12	Buck Converter	R = 1 K Ω L = 1μH C = 470μF	1.2 A	82 V	0.108	0.992	35.7%

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