Analysis of Rectifier Circuits with Power Factor Correction

(Passive Methods of Power Factor Correction)

A Thesis submitted to the
Dept. of Electrical & Electronic Engineering, BRAC University
in partial fulfillment of the requirements for the
Bachelor of Science degree in Electrical & Electronic Engineering

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January 2014

Declaration

We do hereby declare that the thesis titled " Analysis of Rectifier Circuits with Power Factor Correction (Passive Methods of Power Factor Correction)" is submitted to the Department Of Electrical and Electronics Engineering of BRAC University in partial fulfillment of the Bachelor of Science in Electrical and Electronics Engineering. This is our original work and was not submitted elsewhere for the award of any other degree or any other publications.

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Letter of Transmittal

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Dear faculty,

It is our great pleasure to submit our project report as a part of our thesis paper to you that we are assigned to prepare under your direct supervision. We have got the opportunity to make a report on Analysis of Rectifier Circuits with Power Factor Correction (Passive Methods of Power Factor Correction).

We have tried to show our best skills on this thesis report. We would like to assure you that we will remain standby for any clarification or explanation when required. Thank you in advance for your overwhelming assistance.

Yours sincerely,
M. M. Emran Hassan
Afrin Sultana
Sunjida Akther

Student of
BRAC, EEE DEPARTMENT

Acknowledgement

We have benefited a lot from this thesis work. This project has been a rewarding knowledge. We have get into the various aspects of Rectifier Circuits with Power Factor Correction by analyzing various information sources on the labs , internet as well as in practical fields.

We take this opportunity to acknowledge invaluable assistance of those people who helped us in successful completion of this project and also express our special thanks to Amina Hasan Abedin (Assistant Professor) who provided us an opportunity with suggestions and format of making this thesis report.

Last but not list we express our thanks to all the person and friends who always encourage us and provide us support at all times.

M. M. Emran Hassan

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Abstract

Power Factor, the ratio between the real power and the apparent power forms a very essential parameter in power system. It is indicative of how effectively the real power of the system has been utilized. With rapid development in power semiconductor devices, the usage of power electronic systems has expanded to new and wide application range that include residential, commercial, aerospace and many others. Power electronic interfaces have proved to be superior. However, their non-linear behavior puts a question mark on their high efficiency. The current drawn by the interfaces from the line is distorted resulting in a high Total Harmonic Distortion(THD) and low Power Factor(PF).

Individually, a device with harmonic current does not pose much serious problem however when used on a massive scale the utility power supply condition could be deteriorated. Other adverse effects on the power system include increased magnitudes of neutral currents in three-phase systems, overheating in transformers and induction motors etc.

Hence, there is a continuous need for power factor improvement and reduction of line current harmonics. Development of new circuit topologies and control strategies for Power Factor Correction (PFC) and harmonic reduction has become essential. This project aims to develop a circuit for PFC using passive filters.

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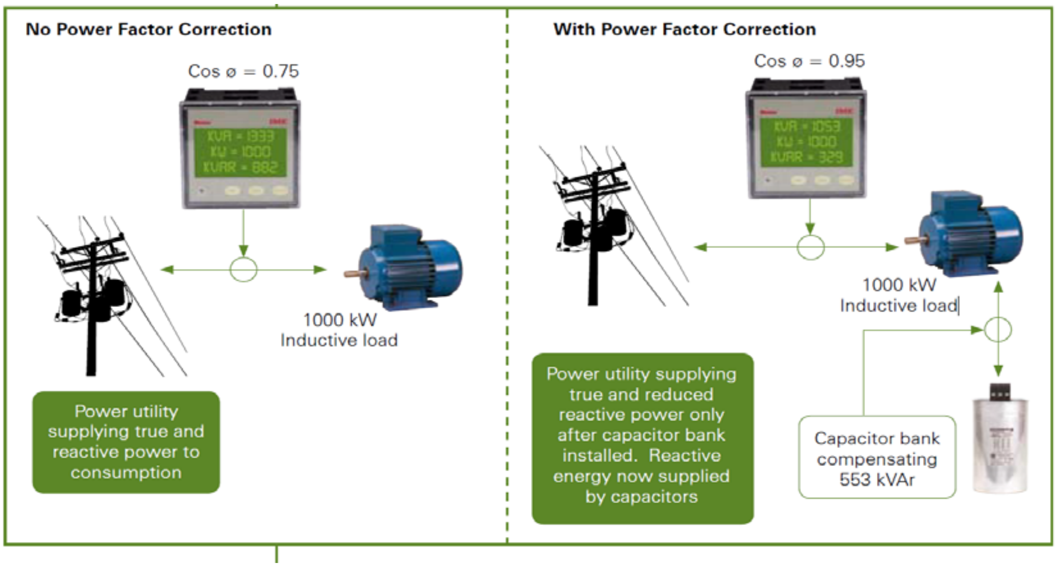
Chapter : 1

Introduction:

In today's world where the supply of electrical energy becomes competitive between the supply utilities the private or public distribution companies who are obligated to run a profitable and successful business. They are also committed to maintain the quality of supply at a high level. Competition in an open electricity market creates new opportunities for even better quality of supply of electricity. One very important aspect of improving quality of supply is the control of power factor by reducing the harmonic contents. Low power factor generally refers as a poor electrical efficiency; lower the power factor, the higher is the apparent power drawn from the distribution network. Which represents that the supply company must install larger generation capacity, larger sized transmission lines and cables, transformers and other distribution system devices, which otherwise would not be necessary. This obviously results in a much higher capital expenditures and operating costs for the Electricity Supply Company, which in most cases is passed on to the consumer in the form of higher tariff rates.

This is the main reason behind why the Electricity Supply Companies in modern economies demand reduction of the reactive load in their networks via improvement of the power factor. In most cases, special reactive current tariffs penalize consumers for poor power factors. Power factor is a technique of counteracting the undesirable effects of electric loads that create a power factor that is less than 1, (or unity). In an electric circuit, if the load is resistive, the voltage and current waveforms are in phase. This is called unity power factor. If the load is inductive, current lags behind voltage and if the load is capacitive then current leads voltage. Motors, fluorescent lighting fixtures, etc. are normally inductive loads; hence power factor is always less than unity in most factories. In this report, we will design and analyze different passive filters and attempt to achieve a near unity power factor. We will focus on power factor correction and harmonic reduction techniques.



1.1 Power Factor Correction (PFC):

If we would like to discuss the power factor correction (PFC) then, it is generally defined as the ratio of the real power to apparent power (S), or the cosine (for pure sine wave for both current and voltage) that represents the phase angle between the current and voltage waveforms *[1]*. The power factor can vary between 0 and 1, and can be either inductive (lagging, pointing up) or capacitive (leading, pointing down). In order to reduce an inductive lag, capacitors are added until PF equals 1. When the current and voltage waveforms are in phase, the power factor is 1 (cos (0°) = 1). The whole purpose of making the power factor equal to one is to make the circuit look purely resistive (apparent power equal to real power). Real power (watts) produces real work; this is the energy transfer component (example electricity-to-motor rpm). Reactive power is the power required to produce the magnetic fields (lost power) to enable the real work to be done, where apparent power is considered the total power that the power company supplies *[1]*. This total power is the power supplied through the power mains to produce the required amount of real power *[1]*. The previously-stated definition of power factor related to phase angle is valid when considering ideal sinusoidal waveforms for both current and voltage; however, most power supplies draw a non-sinusoidal current. When the power factor is not equal to 1, the current waveform does not follow the voltage waveform. This results not only in power losses, but may also cause harmonics that travel down the neutral line and disrupt other devices connected to the line. The closer the power factor is to 1, the closer the current harmonics will be to zero since all the power is contained in the fundamental frequency.

1.2 Passive Method of PFC:

Although vastly inferior to active power factor correction (PFC), passive systems are still used in some cases. The passive approach has the advantage of simplicity, but is comparatively large and heavy, and cannot approach the performance of an active PFC scheme. These circuits are based on the bridge rectifier configuration. In this filter system, the line current takes the form of pulse instead of the sinusoidal property that should follow the line voltage. At this stage the presence of harmonics create a devastating drop in power factor. Passive PFC mostly relies on the use of an inductor or capacitor or both together. For economic reasons, the inductor will almost always be smaller than desired, but by using a small inductance there is little or no reactive component and an additional PFC capacitor is not needed. The results can be better than expected, but the overall power factor is generally limited to around 0.7 - it's possible to get it better, but the cost of the filter increases disproportionately. For a large industrial machine, the extra cost can be justified but the same can never be said for (usually cheap) consumer items. There are many enhancements that can be made if the cost is justified, including harmonic traps and series and parallel resonant filters. These are seriously expensive to implement, and will not be found in any consumer goods. For a large, high power machine, the additional cost becomes very small compared to the cost of the machine itself and (perhaps more importantly) the on-going costs incurred because of the otherwise poor power factor. Resonant filters can become very expensive, largely because of the amount of capacitance needed. In some configurations, the capacitor and inductor will also have to carry a significant current, and this demands much larger (and more expensive) parts. There are many different ways that passive PFC can be incorporated, but only a few are common enough to warrant discussion. The correction scheme depends heavily on the load, the type of equipment and customer expectations. For an industrial power supply, reliability and performance are the most important, with cost and size/weight somewhere lower on the scale.

For this discussion, we have simulated the seven circuits that we considered to be effective at power factor correction. We achieved the accurate values of THD for each circuit from the simulation directly and used those values to calculate the power factor.

We know

$$\text{THD} = \sqrt{\frac{I_{rms}^2 - I_{1\,rms}^2}{I_{1\,rms}^2}} \quad \text{.. Eqn (1)}\textit{[5]}$$

From this equation, we calculated $I_{1\,rms}$ (the non-sinusoidal RMS current value in 50Hz), as we already knew the values of THD and I_{rms} from the simulation directly.

There is a relation between power factor and THD. Power factor can be expressed by

$$\text{PF} = \frac{V_{rms} I_{1rms} \cos\varphi}{V_{rms} I_{rms}} = \frac{I_{1rms} \cos\varphi}{I_{rms}} = K_d \cos\varphi = K_d\, K_\theta$$

K_d is the distortion factor given by $\frac{I_{1rms}}{I_{rms}}$ and K_θ is displacement factor given by $\cos\varphi$.

THD (%) = $100 \times \sqrt{\left(\frac{1}{K_d^2} - 1\right)}$ or, $K_d = \frac{1}{\sqrt{1+\left(\frac{THD\,(\%)}{100}\right)^2}}$

When fundamental current is in phase with the voltage, $K_\theta = 1$, then we have PF = K_d . Therefore, we can relate THD and PF as below:

$$PF = \frac{1}{\sqrt{1+\left(\frac{THD\,(\%)}{100}\right)^2}}$$

This is an inverted relationship. Whenever THD is high the value of PF goes low. So, our aim is to minimize the input current distortion and thus improving PF to near unity.

Chapter : 2

Power Factor Correction Circuits:

2.1. Rectifier with AC-side inductor

Passive methods of PFC use additional passive components in conjunction with the diode bridge rectifier [Figure Shown]. *[1]*

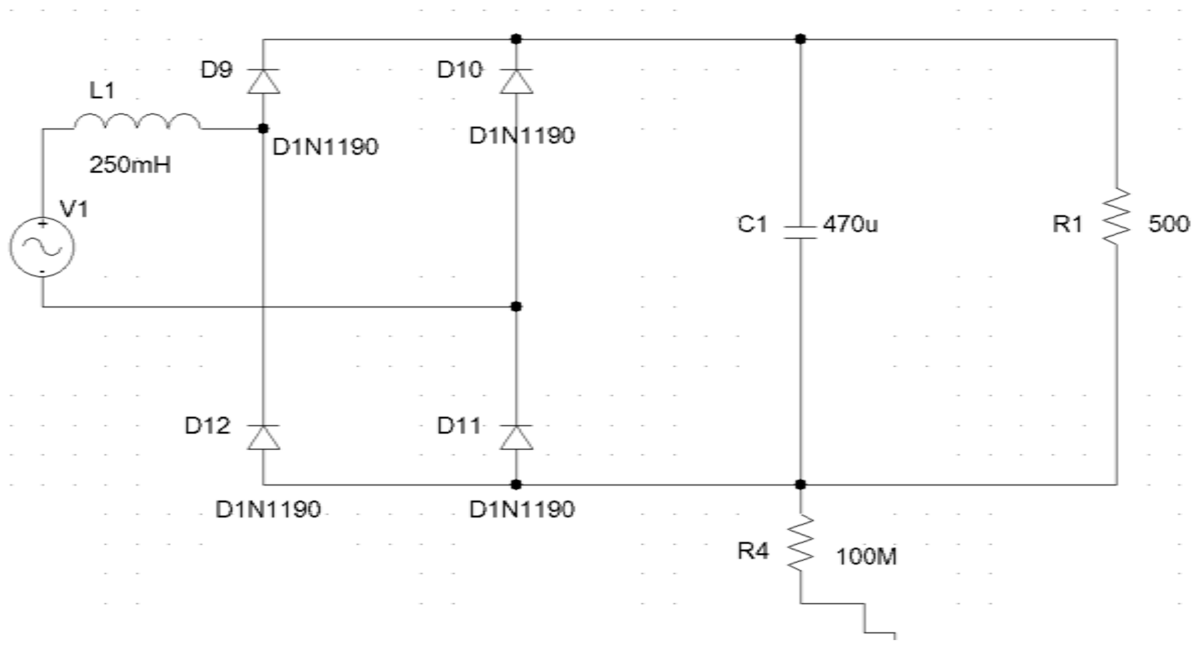


Figure: 2.1 (a) Rectifier with AC-side inductor. Here L=250mH, and C= 470µF. V1=220 V, 50Hz.

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 figure: 2.1(a). The maximum power factor that can be obtained by the configuration is 0.77. Simulated results of the rectifier with AC-side inductor are presented in the figure, where the inductance *L1* has been chosen to maximize the power factor. During the simulation we have also calculated the values of harmonics up to the tenth.

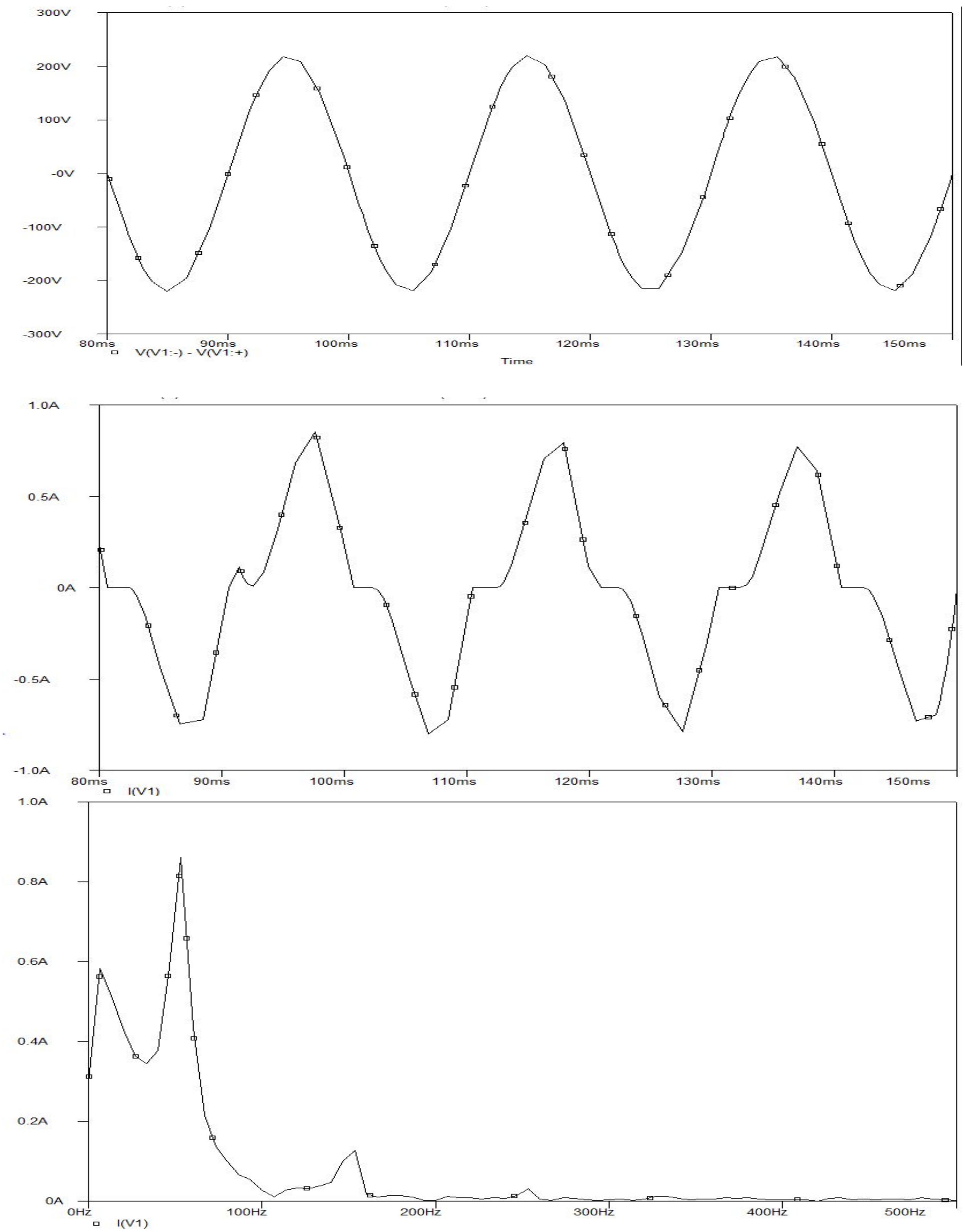


Figure: 2.1 (b): The Input voltage, current shapes and Fourier spectrum obtained in the simulation.

In the above figure: 2.1(b), the line current is slightly becoming sinusoidal as the line voltage. Yet it is discontinued and distorted during the voltage transition from positive to negative and negative to positive. The THD for this circuit is 33% and I_{rms} = 0.6A. The Fourier spectrum shows the significant amount of harmonic contents present in the line current.

2.2. Rectifier with DC-side inductor

The inductor can be also placed at the DC-side (right after the bridge), as shown in Fig 2(a). *[1]*

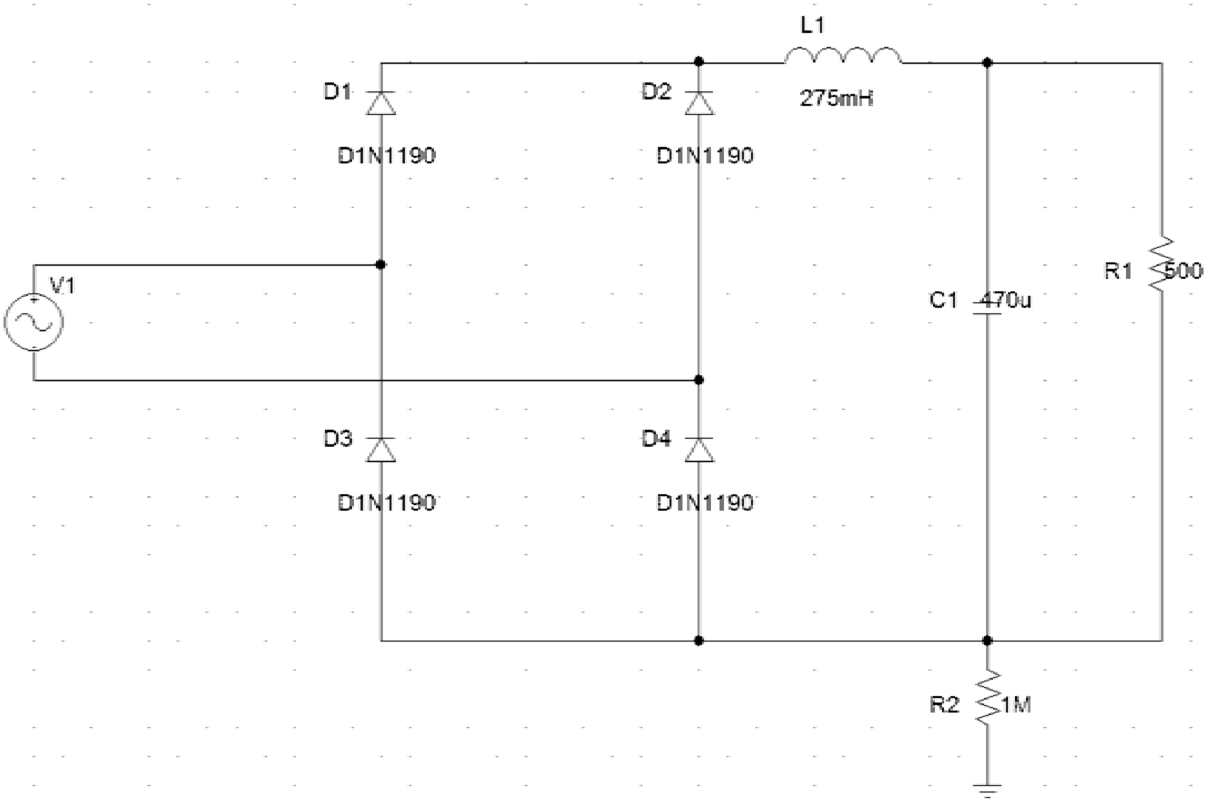


Figure: 2.2.(a): Rectifier with DC-side inductor. L1 = 275mH, C1 = 470µF, V1 = 220V, 50Hz.

The inductor current is continuous for a large enough inductance *L1* . 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 0.9. However, operation close to this condition would require a very large inductor, as illustrated by the simulated line current waveform, for *L*1 = 1H (without input capacitor Ca), shown in Figure: 2.2(b).

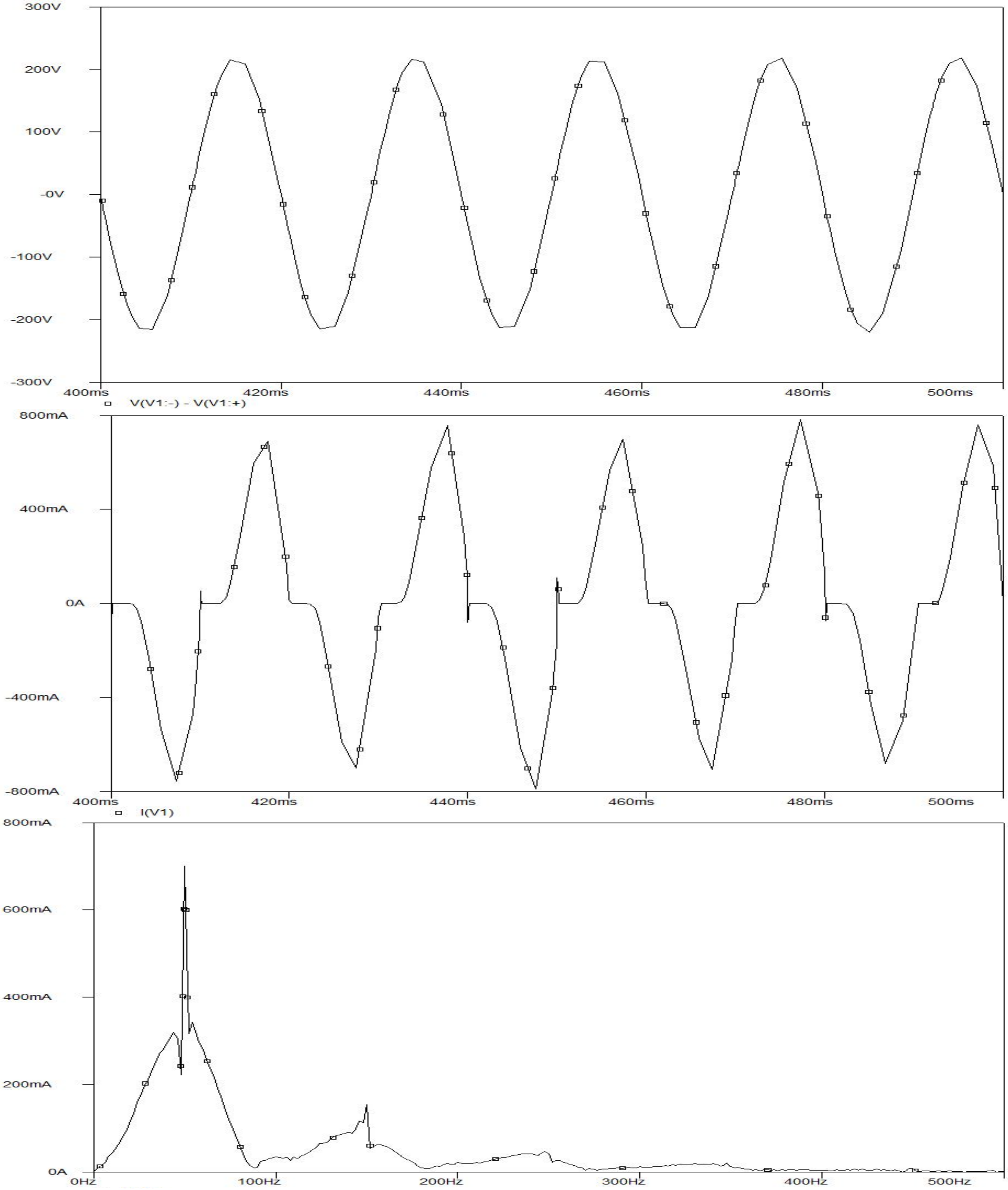


Figure: 2.2(b): Line current, voltage and Fourier spectrum (Without input capacitor)

For lower inductance $L1$ = 275mH, the inductor current becomes discontinuous. The maximum power factor that can be obtained in such a case is 0.774, the operating mode being identical to the case of the AC-side inductor, which is previously discussed. THD for this circuit is 34.16% and I_{rms} = 1.7A.

An improvement of the power factor can be obtained by adding the input capacitor Ca as shown in Figure: 2.2(c),

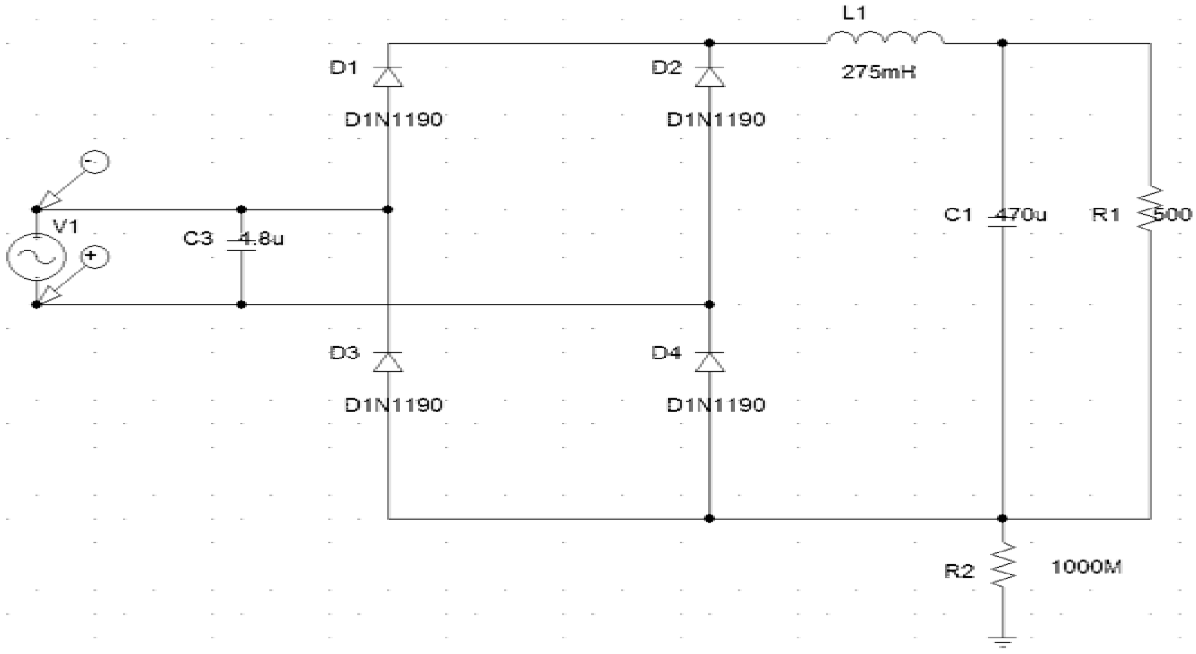


Figure: 2.2(c): DC-side inductor with input capacitor Ca.

which compensates the displacement factor, cos ϕ. A design unity displacement factor cos ϕ is possible, leading to a maximum obtainable power factor 0.90. THD value after adding the capacitor is 42%. I_{rms} = 1.7A. The simulated wave shapes are as below.

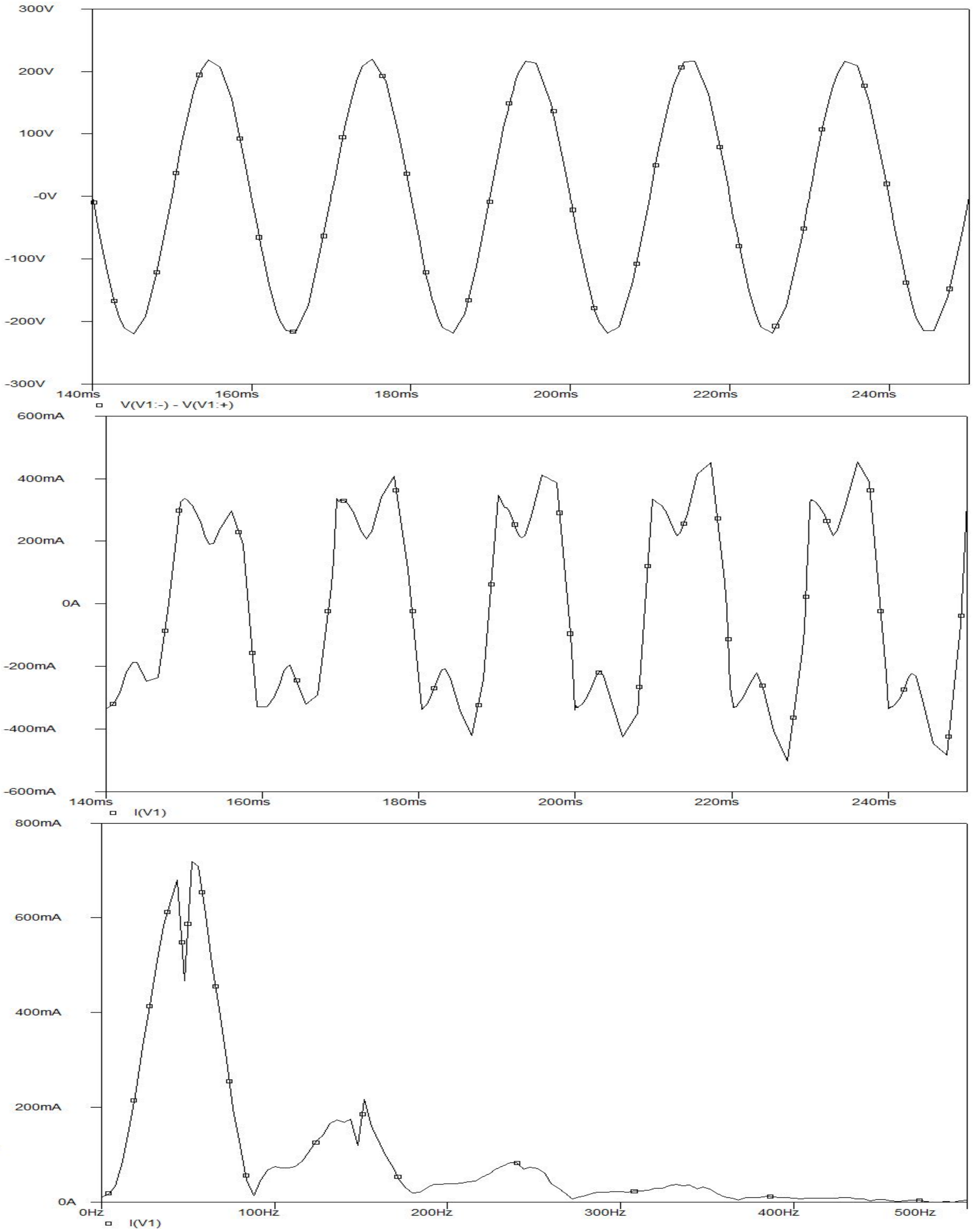


Figure: 2.2(d): As we can see from the simulated results, the line current is following the voltage in the same periodic manner. The peak of the line current is distorted. The Fourier Spectrum marks the presence of harmonics.

The power factor obtained by this circuit is promising. Yet the line current is still distorted which indicates the presence of harmonics. Though it is almost in phase with the line voltage, the distortions near the peak of the current wave is troublesome. These distortions are likely to be caused by the slight increase of the values of the harmonic contents than the previous circuit.

2.3. Rectifier with series-resonant band-pass filter

The shape of the line current can be further improved by using a combination of low-pass input and output filters. There are also several solutions based on resonant networks which are used to attenuate harmonics. For example, in this report we analyzed a band pass filter of the series resonant type, tuned at the line frequency, is introduced in-between the AC source and the load. *[1]*

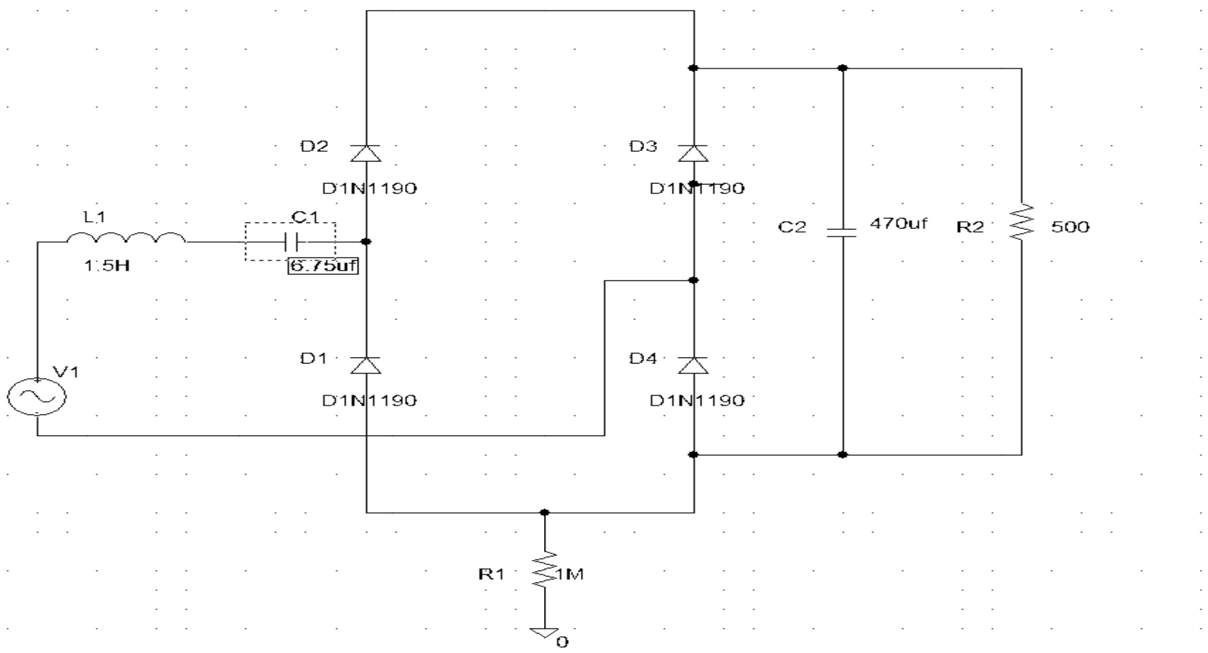


Figure: 2.3(a): Series-resonant Band-pass filter. L1 is introduced in a very high value for the sake of stable current wave. L1 = 1.5H, C1 = 5.75μF. V1 = 220V, 50Hz.

At first we simulated the circuit using a lower value of L1 more or less 250mH. After simulating several times, we tuned the values of L1 and C1 to see the results. After the final tuning we achieved a stable waveform of line current as shown in Figure: 2.3(b).

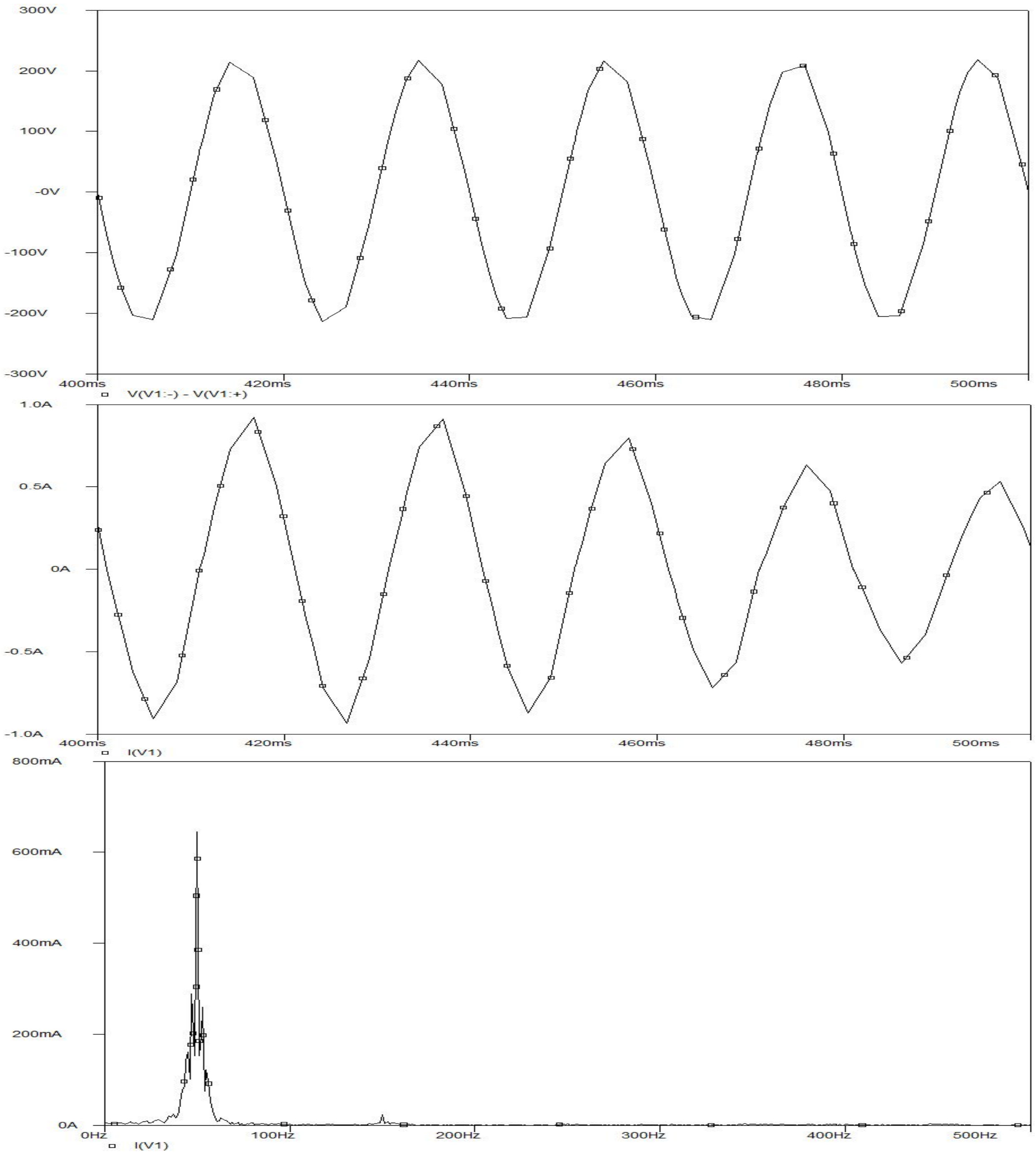


Figure: 3(b): figure shows the simulated results. For 50Hz networks, large values of the reactive elements are needed.

The THD we have in this circuit is 42.722% and I_{rms} = 0.65A. This led us to the power factor of 0.85 which is almost as good as the DC-side inductor circuit with the input capacitor. And additionally, this time the wave shape is sinusoidal. However, we have detected a very clear variation the current amplitude. This variation is caused by the large inductance of 1.5H. Also if we look at the Fourier Spectrum, we can see the harmonic content of the fundamental frequency.

2.4. Rectifier with parallel-resonant band-stop filter

This circuit uses a band-stop filter of the parallel resonant type. Figure: 2.4(a) shows the schematic diagram. *[1]*

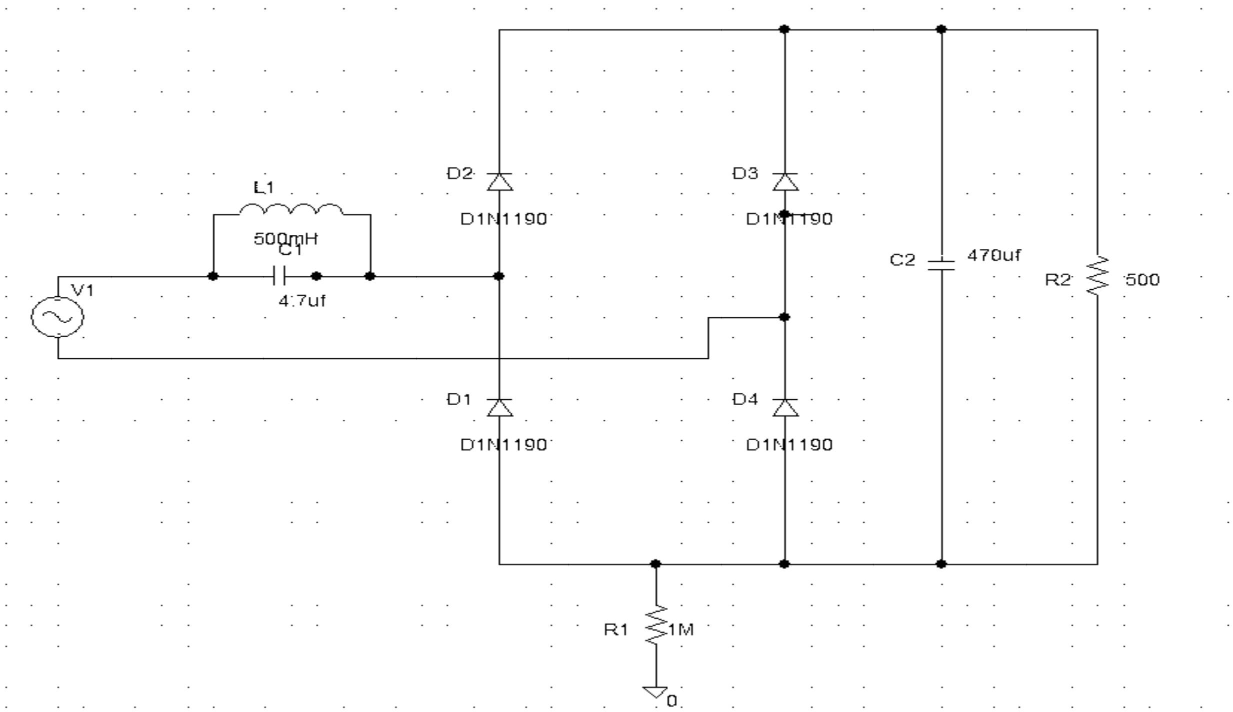


Figure: 2.4(a): Parallel-resonant Band-stop Filter. L1 = 500mH, C1 = 4.7µF. V1 = 220V, 50Hz

In this circuit, we introduced the band-stop filter. This filter requires less value of inductor. It yielded the THD value of 34%. And from the simulation we get the value I_{rms} = 0.7A. This led to a more stable and desired power factor 0.90. Even if we achieved a desired value of power factor, the wave shape of the line current is very much distorted and discontinuity can be detected. Even though the line current and line voltage are in phase, the spike in the peak of the current wave indicates the presence of higher harmonic contents. The wave shapes are shown in Figure: 2.4(b).

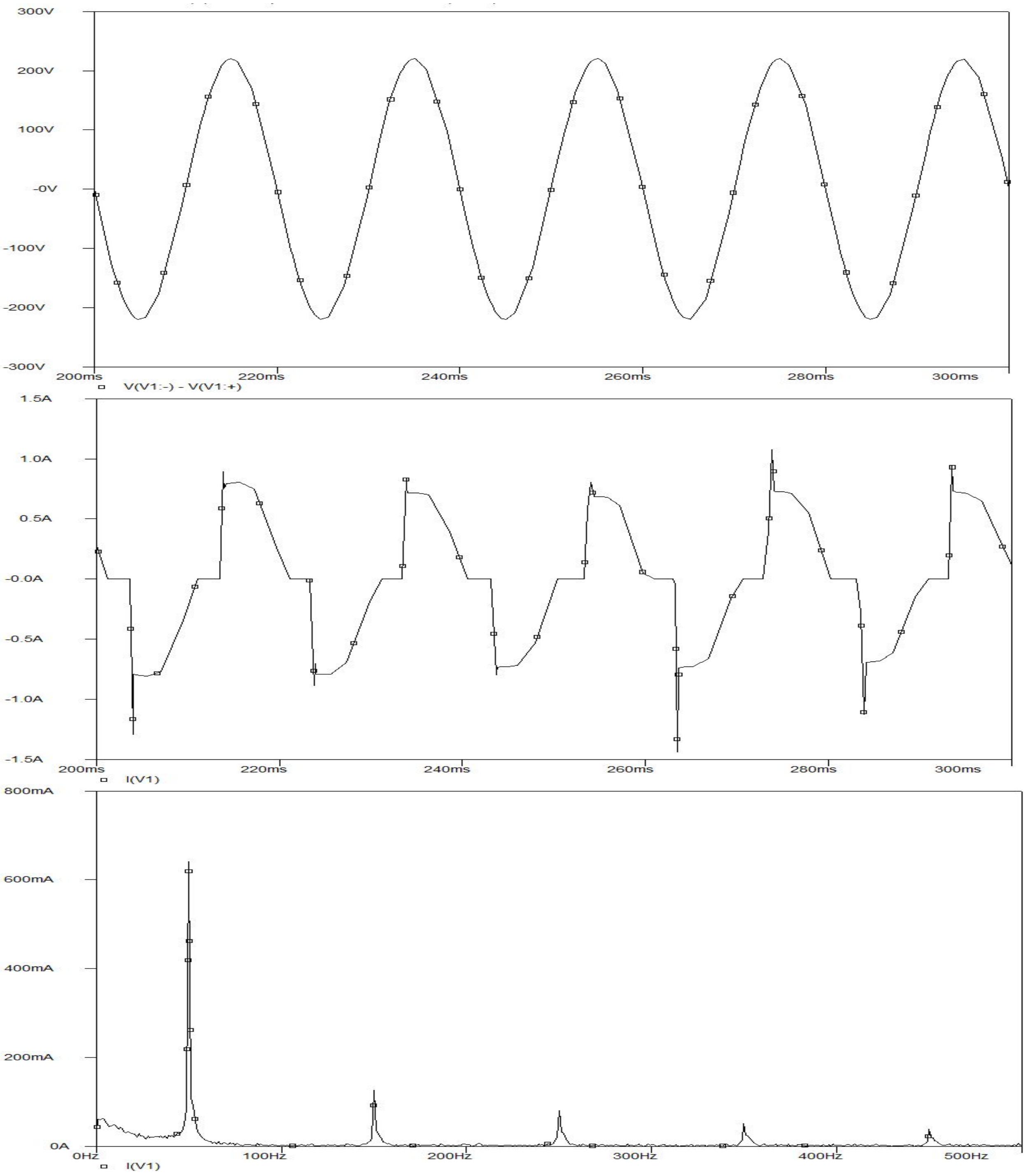


Figure: 2.4(b): The distorted current wave, the sinusoidal voltage wave and the presence of harmonics.

This 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. Though it lowers the values of the reactive components, the line current still remains distorted and discontinuous. As we can see in the Fourier spectrum, there are other harmonics present that are causing the distortions.

2.5. Rectifier with harmonic-trap filter

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. In our analysis, the filter shown in Figure: 5(a) has two harmonic traps, which are tuned at the 3rd and 5th harmonic, respectively. *[1]*

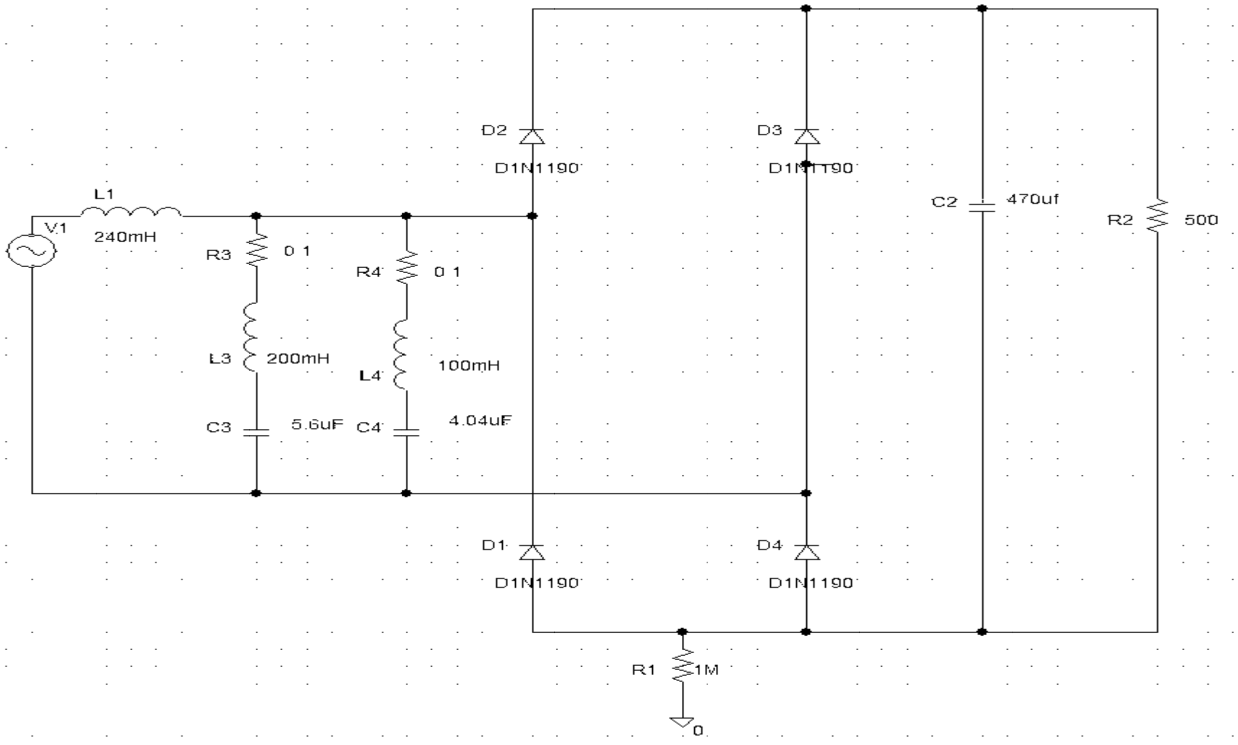


Figure: 2.5(a): Rectifier with harmonic-trap filter. L1 = 240mH, C2 = 470µF, V1 = 220V, 50Hz.

3rd Harmonic Trap: L3 = 200mH, C3 = 5.6µF; 5th Harmonic Trap : L4 = 100mH, C4 = 4.04µF

This trap filter configuration has a THD of 4.5% which is the lowest among the other circuits. I_{rms} = 1.0002A. And thus this circuit has a power factor of 0.95, which is very much close to unity. The wave shapes are given in Figure: 2.5(b).

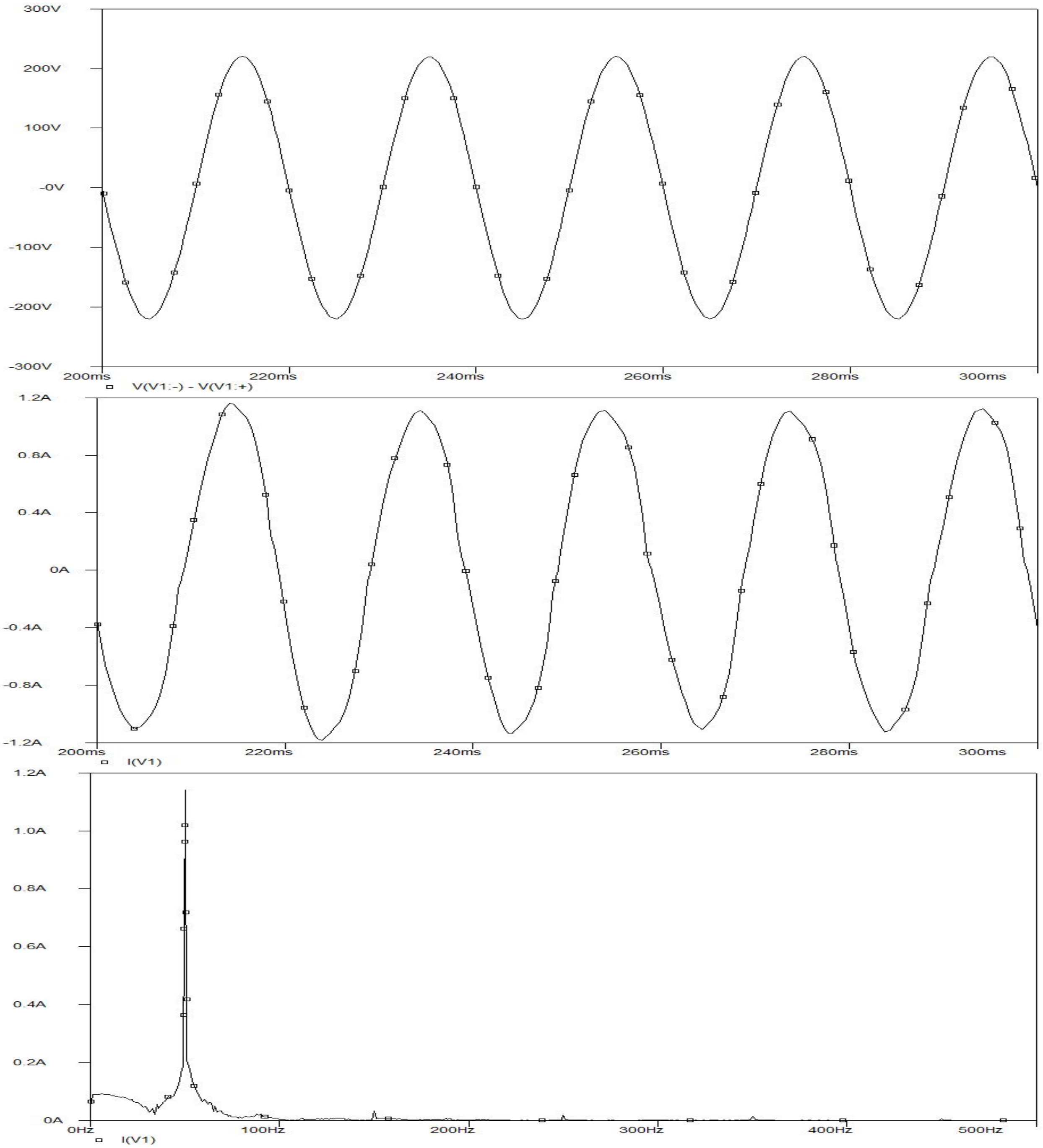


Figure: 2.5(b): The sinusoidal line current , voltage and Fourier Spectrum.

As seen in the Figure, the line current is dramatically improved, at the expense of increased circuit complexity. It is very much sinusoidal and continuous. The phase difference is very small, therefore, negligible. The THD is very low and indicates a successful attenuation of 3rd and 5th harmonic contents from the line current. The Fourier Spectrum in this case confirms our achievement. Harmonic traps can be used also in conjunction with other reactive networks, such as a band-stop filter.

2.6. Rectifier with an additional inductor, capacitor and diode (LCD)

The rectifier with an additional inductor, capacitor, and diode – LCD rectifier – is shown in the Figure: 2.6(a). *[1]*

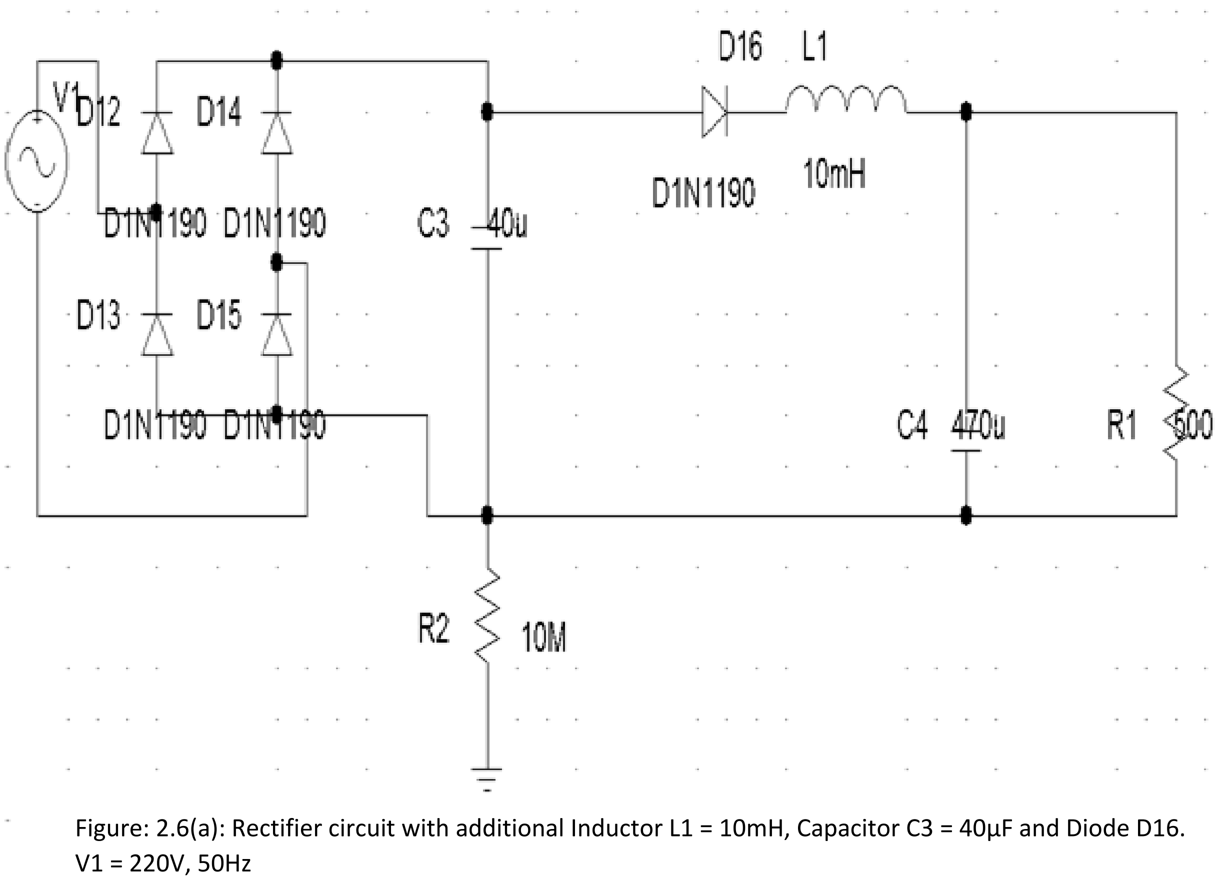


Figure: 2.6(a): Rectifier circuit with additional Inductor L1 = 10mH, Capacitor C3 = 40µF and Diode D16. V1 = 220V, 50Hz

Here the concept is to increase power factor without the complexity of the harmonic trap filter or resonant type filters. The result, however, was not satisfactory. The THD bumped up to 78.61%. There was also a significant amount of current flow through the circuit, I_{rms} = 3.7A. This led us to a rather lower power factor of 0.78. Figure: 2.6(b) illustrates the wave shapes. The added reactive elements have relatively low values. The circuit changes the shape of the input current, while only a limited reduction of the harmonic currents can be obtained. The distortion and discontinuity of the current wave shape indicates the lesser effectiveness of the circuit. If we look at the Fourier spectrum, the peaky presence of the 3rd and 5th harmonics are the reasons for the discontinuous current wave shape.

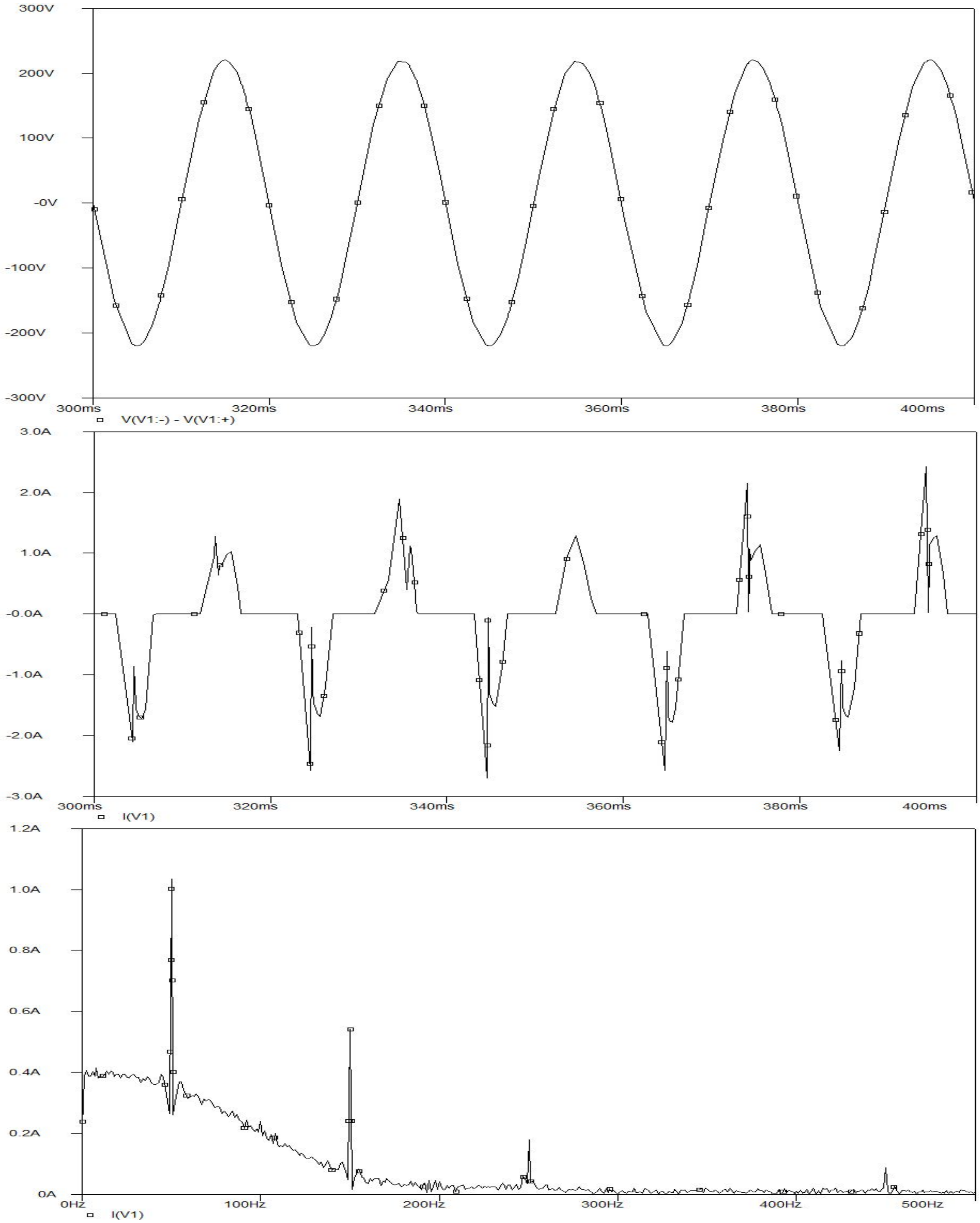


Figure: 2.6(b): Distorted line current.

Chapter : 3

Alternative Methods:

3.1 Controlled Rectifier:

There is a way to control the output with a cost to Power factor and THD using a silicon controlled rectifier or SCR. These types of controlled rectifiers are called phase controlled AC-DC converters. This however gives a higher possibility for near 100% efficiency of the circuit where the passive filters alone can give a lower efficiency in the range of 40% to 60%. A SCR schematic is given below along with the voltage, current and Fourier analysis.

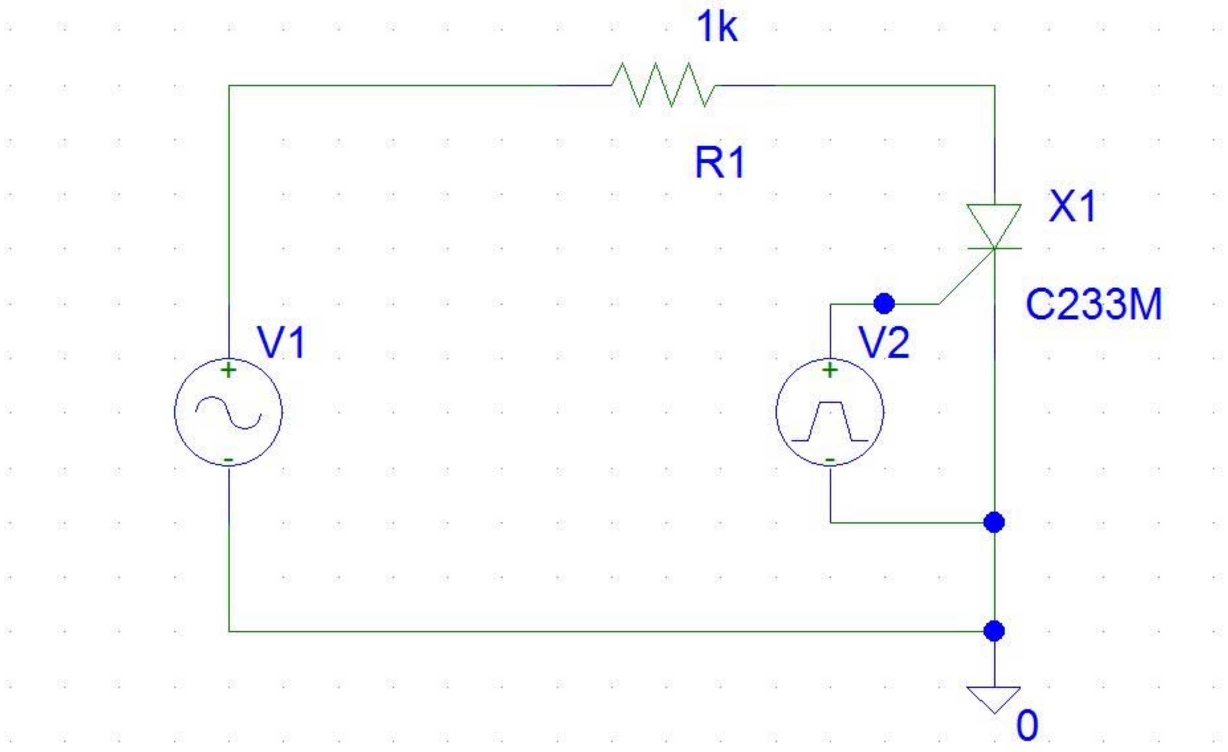


Figure: 3.1(a): SCR half wave rectifier.

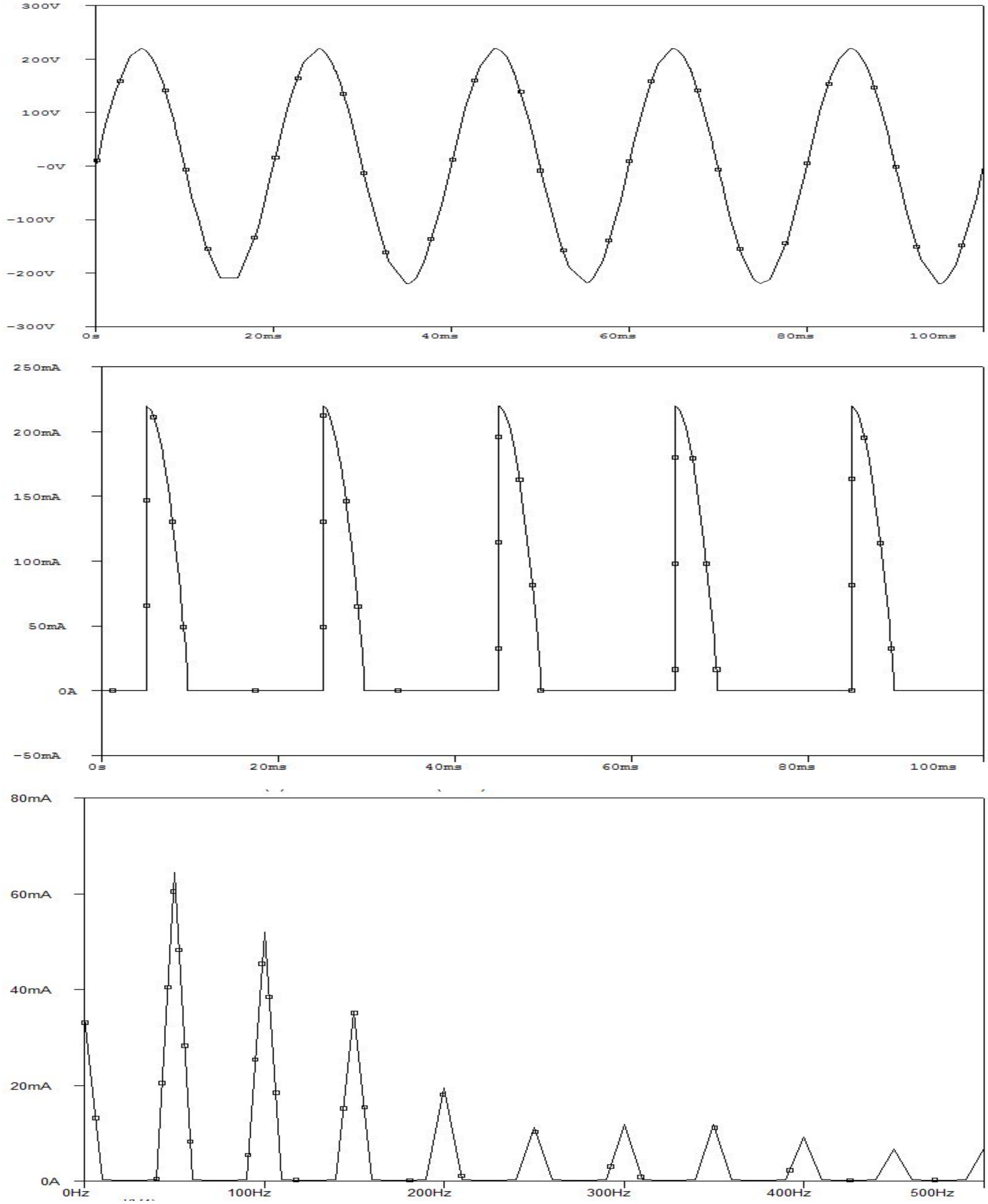


Figure: 3.1(b): SCR half wave rectifier. Input voltage, input current and Fourier analysis

From the above figures we can see that the current is like a pulse and the harmonic contents are present. Though we can fully control the output, these harmonics calls for PFCs to be applied along with the rectifier. In this case, the components for the passive PFCs will be simpler and lighter.

3.2 Active Method of PFC:

The above method takes us to the idea of low frequency active method of PFC. In this case the diodes are replaced with Thyristors.

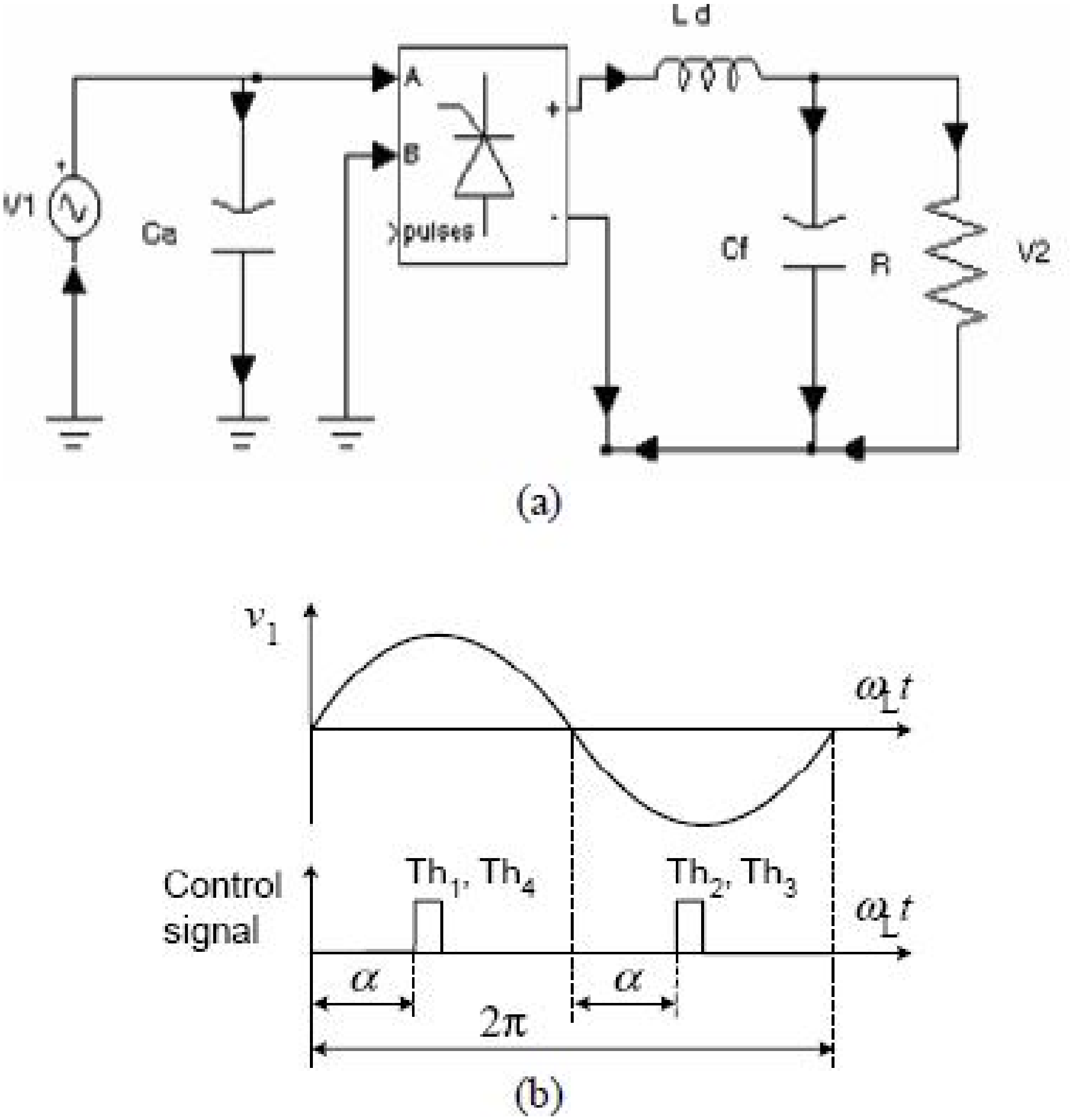


Figure: 3.2(a): SCR full wave rectifier with inductor Ld. (b) Phase control

Depending on the DC side inductor Ld and the firing angle of the Thyristors, a near unity distortion factor Kd or displacement factor cosɸ can be obtained while sacrificing the PF to 0.7. This inductor and firing angle is used for maximizing Kd while lagging displacement factor which is compensated by the input capacitor Ca. This is similar to the passive diode bridge rectifier we used with the DC-side inductor. This solution additionally offers a controllable output while carrying the simplicity, reliability and cheap parts from the passive circuit. But it also has a negative side. The regulation to the output voltage is slow and still a relatively large inductance is required. If we introduce DC to DC converter after the passive filtering techniques, a frequency related harmonic increase appears in the line current which negates the purpose of the passive filter with PFC in the first place.

Chapter : 4

Theoretical Calculations and Comparison:

So far we have calculated all the values from the simulation directly. Now we will attempt to match the values of simulation with the theoretical calculation.

For calculating the I_{rms} we will use the equation below. Since we calculated the harmonics up to the tenth, we will use all of those obtained from the output file of each circuit to find a more accurate value of I_{rms} and thus the Power Factor.

$$I_{rms} = \sqrt{(I_{DC})^2 + \left(\frac{I_1}{\sqrt{2}}\right)^2 + \left(\frac{I_2}{\sqrt{2}}\right)^2 + \left(\frac{I_3}{\sqrt{2}}\right)^2 + \left(\frac{I_4}{\sqrt{2}}\right)^2 + \left(\frac{I_5}{\sqrt{2}}\right)^2 + \left(\frac{I_6}{\sqrt{2}}\right)^2 + \left(\frac{I_7}{\sqrt{2}}\right)^2 + \left(\frac{I_8}{\sqrt{2}}\right)^2 + \left(\frac{I_9}{\sqrt{2}}\right)^2 + \left(\frac{I_{10}}{\sqrt{2}}\right)^2}$$

$$I_{1\,rms} = \frac{I_1}{\sqrt{2}}$$

Power Factor = $\frac{I_{1\,rms}.\cos(\theta_1 - \varphi_1)}{I_{rms}}$

3.1 Rectifier with AC-side inductor:

I_{rms} = 0.43A , $I_{1\,rms}$ = 0.40A

Therefore, Power Factor = 0.769

We obtained the same power factor of the circuit through the simulation using I_{rms} of 0.6A. The result is accurate.

3.2 Rectifier with DC-side inductor:

With the AC capacitor:

I_{rms} = 0.32A , $I_{1\,rms}$ = 0.294A

Therefore, Power Factor = 0.90

The different value obtained from the output file did not contradict with the achieved power factor of the simulation.

Without the AC capacitor:

I_{rms} = 0.40A , $I_{1\ rms}$ = 0.379A

Therefore, Power Factor = 0.776

3.3 Rectifier with series-resonant band-pass filter:

I_{rms} = 0.53A , $I_{1\ rms}$ = 0.531A

Therefore, Power Factor = 0.928

Here we can see a difference in terms of simulation and theoretical results. The simulated power factor was 0.85.

3.4 Rectifier with parallel-resonant band-stop filter:

I_{rms} = 0.45A , $I_{1\ rms}$ = 0.42A

Therefore, Power Factor = 0.89

3.5 Rectifier with harmonic-trap filter:

I_{rms} = 0.82A , $I_{1\ rms}$ = 0.824A

Therefore, Power Factor = 0.96

3.6 Rectifier with an additional inductor, capacitor and diode (LCD):

I_{rms} = 0.67A , $I_{1\,rms}$ = 0.529A

Therefore, Power Factor = 0.78

The theoretical calculations revealed to be almost accurate with the simulation.

Chapter : 5

Data Summary:

SERIAL NO	NAME OF THE CIRCUIT	VALUES FOR THE CIRCUIT		THD	I*rms*	POWER FACTOR (P*f*)	COMMENTS FOR THE VALUES
		Inductor	**Capacitor**				
1	Rectifier with AC-Side Inductor	L1= 250 mH	C1=470 μF	33%	0.6 A	0.77	We use a low inductor at AC side input so the line current slightly becomes sinusoidal with the line voltage. The simulated THD and I*rms* result gives the P*f* value of 0.77.
2	Rectifier with DC-side Inductor (With input capacitor)	L1= 275 mH	C1= 4.8 μF C2= 470 μF	42%	1.7 A	0.90	We add the inductor after the diode bridge which is greater than the inductor value of AC-side inductor and the simulating result gives the I*rms* value greater than that of AC-side inductor which is better for getting the approx. value of P*f*.
3	Rectifier with DC-side Inductor (Without Capacitor)	L1= 275 mH	C1=470 μF	34.16%	1.7 A	0.774	To improve the P*f* we add an input capacitor which compensates the displacement factor $\cos \varphi$ and the line current is distorted for simulated high THD value. So the P*f* of 0.90 is much better than that of AC-side inductor.
4	Rectifier with Series- Resonant Band Pass Filter	L1= 1.5 H	C1= 5.75 μF C2= 470 μF	42.72%	0.65 A	0.85	As we use very large inductance we get very clear variation in the current amplitude for wave shape. After simulation we get the THD and I*rms* values are leading to P*f* of 0.85 which is almost as good as the DC-side inductor with the input capacitor circuit.
5	Rectifier with Parallel-Resonant Band-Stop	L1=500 mH	C1= 4.7 μF C2= 470 μF	34%	0.7 A	0.90	The filter is tuned at 3rd harmonic, so it allows the lower value of reactive elements with comparing to the Series-resonant band-pass filter. Simulated THD result is still high so the wave shape of line current remains distorted and I*rms* value gives the P*f* of 0.90 which is good enough and much stable than Series resonant band-pass filter.
6	Rectifier with Harmonic Trap Filter	L1= 240 mH L2= 200 mH L3= 100 mH	C1= 5.6 μF C2= 4.04 μF C3= 470 μF	4.5%	1.0002 A	0.95	Simulation shows that lowest THD gives radical improved in line current wave shape with continuous, sinusoidal and negligible phase difference which indicates a successful attenuation of 3rd and 5th harmonic contents. And the value of I*rms* gives the approx. unity P*f* of 0.95.
7	Rectifier with an Additional Inductor, Capacitor and Diode	L1= 10 mH	C1= 40 μF C2= 470 μF	78.61%	3.7 A	0.78	Simulating THD result is very high so wave shape of line current is much more distorted than other circuit esp. with Harmonic Trap Filter. And because of high I*rms* value there is significant amount of current flow.

Efficiency Table:

SERIAL NO	NAME OF THE CIRCUIT	COS Φ	INPUT POWER IN Watt	OUTPUT POWER IN Watt	EFFICIENCY
1	Rectifier with AC-Side Inductor	0.58	154.71	50	32 %
2	Rectifier with DC-side Inductor (With input capacitor)	0.67	66.22	47.877	72%
3	Rectifier with DC-side Inductor (Without Capacitor)	0.7604	119.66	45.825	38%
4	Rectifier with Series- Resonant Band Pass Filter	0.67	123.6	43.472	35%
5	Rectifier with Parallel- Resonant Band-Stop	0.91	180.5	61	33%
6	Rectifier with Harmonic Trap Filter	1	300	120	40%
7	Rectifier with an Additional Inductor, Capacitor and Diode	0.97	339.60	89.042	26%

Here we can easily see that the Passive methods of PFC have very low efficiency. The best filter among them is the harmonic trap filter but it has an efficiency of 40% only. If there is an active controller added with the circuit for phase control, the efficiency will increase to almost 100% but the Power Factor will be affected by it. The Passive filters alone are of very little use.

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Benefits of Using PFC:

In Bangladesh, the standard power factor that is to be maintained by the consumers is 0.90. Therefore, if the power factor is lower than the standard, a penalty is issued based on the difference of the power factor. However, if the power factor is higher than the standard level, an incentive is also offered. The rate of penalty is as follows:

Serial No.	Range of Power Factor	Power factor level	Penalty
1	0.895 to 0.900	0.90	0%
2	0.885 to 0.894	0.89	2%
3	0.875 to 0.884	0.88	3%
4	0.865 to 0.874	0.87	4%
5	0.855 to 0.864	0.86	5%
6	0.845 to 0.854	0.85	6%
7	0.835 to 0.844	0.84	7%
8	0.825 to 0.834	0.83	8%
9	0.815 to 0.824	0.82	9%
10	0.805 to 0.814	0.81	10%

In accordance with this table, we can see that only the harmonic trap filter is the desired PFC method than any other circuit we have simulated. In our country, domestic billing system is divided into ceiling system. The rate and the ceilings are given below:

Serial No.	Ceiling in Units	Amount per unit
1	0 to 75	3.33
2	76 to 200	4.73
3	201 to 300	4.83
4	301 to 400	7.93
5	401 to 600	7.98
6	601 and above	9.38

Let us assume a hypothetical situation where we will implement the series resonant band pass filter and the harmonic trap filter and calculate the amount of penalty and the amount of reduction in billing. First we implement the series resonant band pass filter. The power factor of this filter is 0.85. Also let us assume that the total units of electricity consumed in a month is 400 units.

Calculation:

Monthly bill: (Excluding the VAT)

(i) 75 X 3.33 = 249.75BDT

(ii) 200 X 4.73 = 946BDT

(iii) 125 X 4.83 = 603.75BDT

So, the total bill sums up to 1799.5BDT. Due to low power factor, the penalty will be decided with the help of the penalty table above. The penalty is 6% over total bill. The penalty is 107.97BDT. The Grand total will be 1907.47BDT. For the same bill if the harmonic trap filter is introduced, than the penalty becomes 0% therefore a save of 107.97BDT over the entire bill can be seen.

Overall comments:

Since we used the simulated values of the circuits to calculate power factor for each of them, the theoretical values, which are different then the simulated values, provide almost the same power factor for the circuits. Throughout the entire simulation, we also took the Fourier Spectrum of those circuits and analyzed it which led us to the conclusion. Even though the parallel-resonant band-stop filter achieved a higher power factor, the presence of the latter harmonics caused the current wave shape to be highly distorted. In terms of penalty, we have compared the series resonant band pass filter and the harmonic trap filter. We calculated for only 400 units of electricity. If a higher rate is consumed, supposedly over 600 units, the penalty of having the lower power factor is going to be monumental. Which leads to the logical conclusion of choosing the harmonic trap filter with the power factor of 0.95 and a stable input current waveform.

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Conclusion:

Passive methods of power factor correction have certain advantages. The methods are simple, reliable, insensitive to noise and surges, no generation of high frequency EMI and no high frequency switching losses. These solutions, however, are based on passive methods which have poor dynamic response, lack of voltage regulation *[1]*. Most importantly the shape of the input current depends on the load itself. We, in our simulations, used a constant resistive load. It was shown in the simulations that the resonant networks give better results, yet they are sensitive to the line-frequency. In the case of harmonic trap filters, series resonance is used to attenuate specific harmonics and getting a better power factor which is very near to unity. We have also seen the THD of this circuit to be 4.5%. In the Fourier spectrum we saw that the latter harmonics (7th, 9th and so on) has very little values compared to the fundamental harmonic on this circuit. So we can conclude that the Harmonic-Trap filter is the best among the passive filters so far when the load is resistive and constant.

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