A Study of AC/DC Converter with Improved Power Factor and Low Harmonic Distortion

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***Abstract-* AC/DC converters are widely used in industrial applications. Input AC voltage is rectified and filtered using filtering circuit which consists of large electrolytic capacitors. These capacitors draw a large amount of current and the efficiency of the converter system decreases drastically. Low power factor, high harmonic distortion and large ripple factor have made the converter system inefficient. This paper analyses about different converter topologies and proposes a different design by which power factor can be improved and harmonic distortion can be reduced. The results of respective topologies are shown through P-simulation program with integrated circuit emphasis (PSPICE) simulation and their parameters are calculated. Five parameters are considered for the comparison of these topologies.**

Keywords- AC/DC converter, Harmonic distortion., Power factor

I. INTRODUCTION

Most of the research on PFC for non linear loads is actually related to the reduction of the harmonic content of the line current. There are several solutions to achieve PFC [1]-[2]. The shape of the input current can be further improved by using a combination of input and output filters [3]-[6] In the past, designers have used three passive wave shaping methods to improve the input power factor and reduce total harmonic distortion THD of conventional ac-to-dc rectifiers [7]. When the input power factor correction stage is used to regulate the converter dc bus voltage, the converter performance improved substantially in comparison with the conventional ac to dc converters [8].Regarding the quality of the current waveform, pure sinusoidal waveforms are best but that usually cost very high. So there are the so called “single stage converters” that offer many advantages, which composed of a diode bridge and filters. Among various schemes available for PFC, the single stage scheme is best suited for low power application because of its cost effectiveness [9]-[11].

II. AC/DC CONVERTER SYSTEM

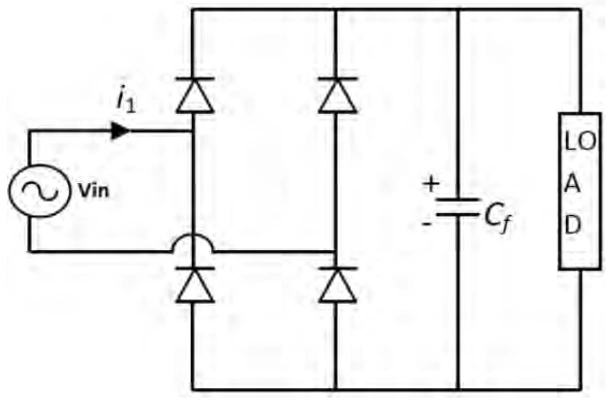

Figure 1: Full wave rectifier with DC side filter

The diode bridge rectifier, shown in Fig.1 has non-sinusoidal line current. This is because most loads require a supply voltage 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.
Two common reasons for including the dc-side filter:

1. Obtain good dc output voltage and acceptable ac line current waveform.
2. Filter conducted EMI (Electromagnetic Interference) generated by dc load.

Power factor is defined as the ratio of active power (P) to the apparent power(S).

$$PF = \frac{P}{S} \qquad (1)$$

When an electric load has a PF lower than 1, the apparent power delivered to the load is greater than the real power that the load consumes. Only the real power is capable of doing work, but the apparent power determines the amount of current that flows into the load, for a given load voltage. The basic idea of PFC is design circuits with certain means to force the line current to follow the waveform of the line voltage. Because of the nature of PFC, there exists an unbalance of instantaneous power between the input power, which is an alternative quantity with two times the line frequency, and its dc output power. Therefore, power factor correction involves processing the input power in certain way that it stores the excessive input energy when the input power is larger than the dc output power, and releases the stored energy when the input power is less than the dc output power. To accomplish the above task, at least one energy storage element must be included in the PFC circuit.[12]

III. Simulation Results

Some assumptions were made to analyze the circuits which are the following:-

1. Load is purely resistive.
2. Ideal filter components.
3. The forward voltage drop and reverse leakage current of diodes are neglected.

Table I shows the specifications of the components used in the topologies.

TABLE I. Specification of the components

Components	Specifications
AC supply	220V/50Hz
Diodes	DIN4936
Resistances	100Ω
Capacitors	60mF/0.1mF/100mF/500µF
Inductor	1mH/50mH/5mH/.005mH

Five different passive power factor improvement topologies for low power output with 220volt/50 Hz ac input have been considered.
The five different topologies are:-

1. Conventional single phase diode rectifier with filter capacitor.
2. Single phase diode rectifier with LC filter.
3. Single phase diode rectifier circuit with parallel input resonant filter.
4. Single phase diode rectifier circuit with series input resonant filter.
5. Single phase diode rectifier circuit with improved parallel input resonant filter.

All methods are compared in terms of THD (Total harmonic distortion), Input current distortion, Input current harmonic factor, Input displacement factor, and Power factor. Figure 2 shows the conventional single phase diode rectifier circuit with load of 100Ω.

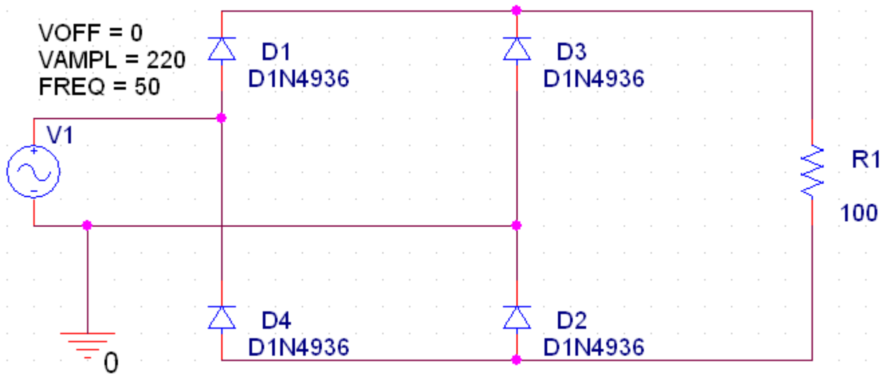

Figure 2: Conventional single phase diode rectifier

From the conventional single phase diode rectifier shown in figure 2, the values of all the five parameters are calculated, which are kept as reference to compare the parameters of other five topologies. Figure 3 shows the waveform of input current and input voltage, and there are no harmonic distortions in input current.

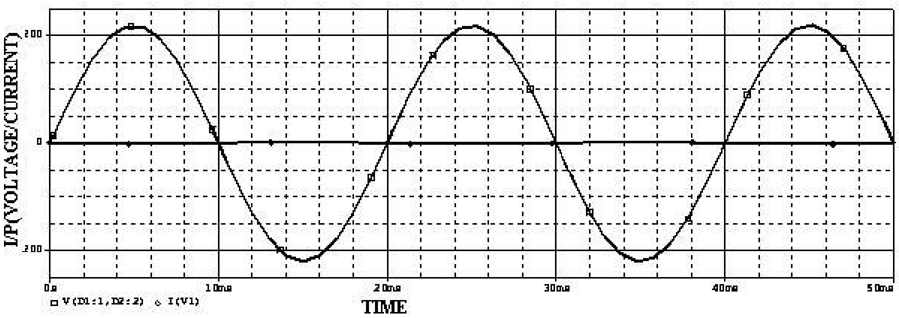

Figure 3: I/P voltage and current waveform for conventional single phase diode rectifier

Table II shows the values of all the calculated parameters with which the parameters of rest of the topologies will be compared.

TABLE II. Values of parameters for conventional single phase diode rectifier

Parameters	Values
PF	0.991
DF	0.999
CDF	0.9925
HF	0.123
THD	0.033%

Figure 4 shows the simulated prototype of a conventional single phase diode rectifier with filter capacitor. The output filter capacitor value (C_1) is calculated using eq. 2.

$$C_1 = \frac{1}{4fR}\left[1 + \frac{1}{\sqrt{2RF}}\right] \quad (2)$$

RF:- ripple factor
R:- output resistance
f:- frequency of ac source
To get minimum ripple factor we have chosen C_1=60 mF (mili farads).

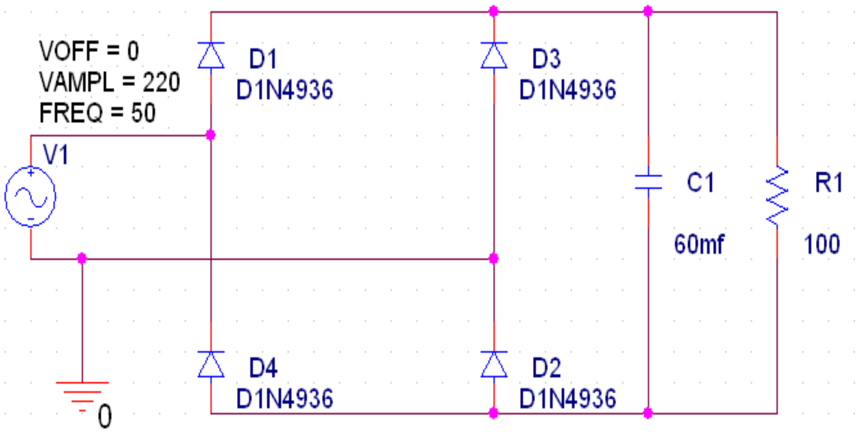

Figure 4: conventional single phase diode rectifier with filter capacitor

Figure 5 shows the waveform of input current and input voltage for filter capacitor circuit, in which the harmonics of input current which are highly undesirable are seen.

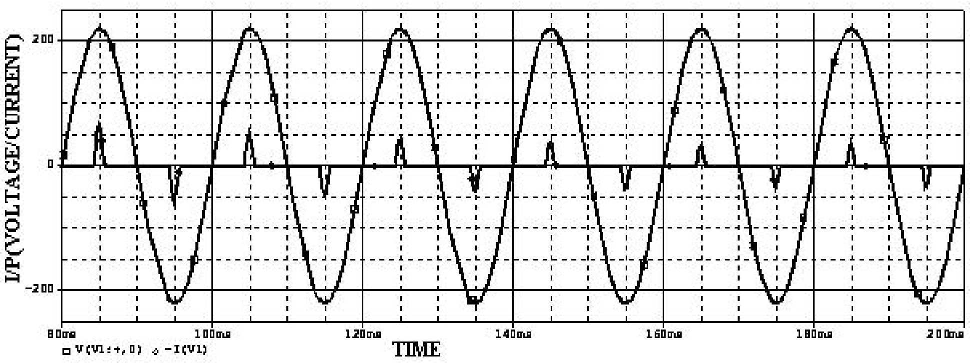

Figure 5: I/P voltage and current waveform for conventional single phase diode rectifier with filter capacitor

Table III shows the values of all the calculated parameters for a conventional single phase diode rectifier with filter capacitor in a tabulated form.

TABLE III. Values of parameters for conventional single phase diode rectifier with filter capacitor

Parameters	**Values**
PF	0.215
DF	0.999
CDF	0.215
HF	4.527
THD	176.9%

From the calculated values, it is clear that the Total Harmonic Distortion is 176.9% which is very high which needs to be reduced which is achieved in the proceeding methods. The power factor is also very low which should be improved.

Figure 6 shows the simulated prototype of a conventional single phase diode rectifier with LC filter. The inclusion of the inductor results in larger conduction angle of the current pulse and reduced peak and r.m.s values.

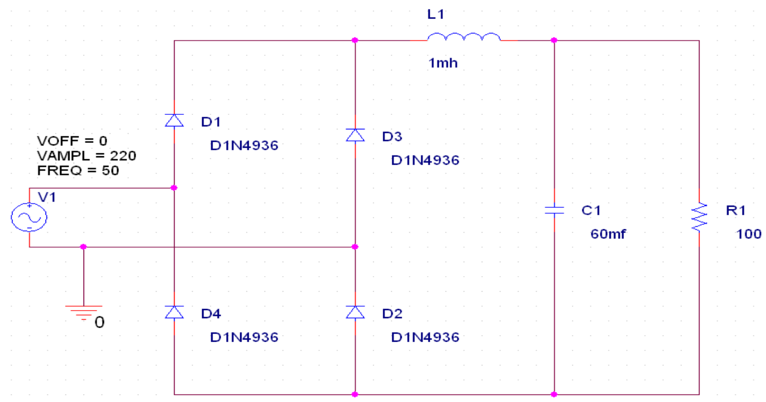

Figure 6: Single phase diode rectifier with LC filter

For low values of inductance the input current is discontinuous and pulsating. However, it is shown [13] that even for infinite value of the inductance; the PF cannot exceed 0.9 for this kind of arrangement.
Figure 7 shows the waveform of input current and input voltage for circuit with LC filter, and the harmonics of input current are reduced as compared to the previous topology.

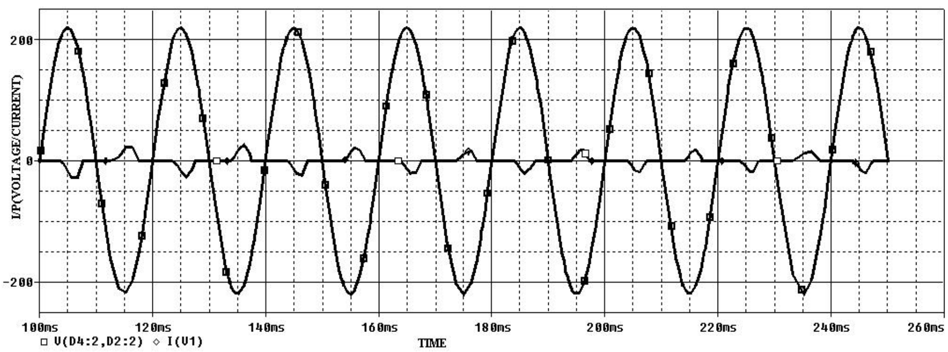

Figure 7: I/P voltage and current waveform for single phase diode rectifier with LC filter

Table IV shows the values of all the calculated parameters for a conventional single phase diode rectifier with LC filter in a tabulated form.

TABLE IV. Values of parameters for conventional single phase diode rectifier with LC filter

Parameters	Values
PF	0.3629
DF	0.967
CDF	0.375
HF	2.471
THD	84.09%

It is clear from the above calculated parameters that LC filter topology gives better results than the previous topology as the value of Total Harmonic Distortion decreased and Power Factor improves but still not up to very satisfactory level, so we will proceed towards other topologies.
Figure 8 shows the simulated prototype of single phase diode rectifier using parallel resonant circuit as a passive wave shaping method. The value of inductor and capacitor are calculated using the analysis discussed below.
The n^{th} harmonic component of the equivalent impedance of the input parallel resonant filter is given by eq. 3.

$$Z_n = \frac{nX_{L_n} * \frac{X_{C_n}}{n}}{jnX_{L_n} - j\frac{X_{C_n}}{n}} \qquad (3)$$

X_{L_2} :-impedance of input resonant inductor L at fundamental frequency.
X_{C_2} :- impedance of input resonant capacitor C at fundamental frequency.
The third harmonic impedance of the input resonant filter will be infinity (theoretically). Therefore,

$$3X_{L_2} = \frac{X_{C_2}}{3}$$

And $$L_2 = \frac{1}{9\omega^2 C_2}$$

Where $\omega = 2\pi f$ and f is in Hz.

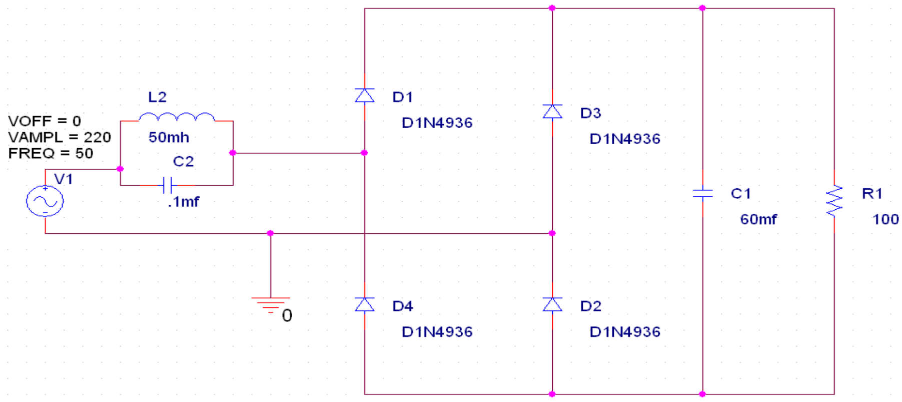

Figure 8: Single phase diode rectifier circuit with parallel input resonant filter

Figure 9 shows the waveform of input current and input voltage for single phase diode rectifier circuit with parallel input resonant filter. It is clear that the input current harmonics are reduced as compared to the previous topology.

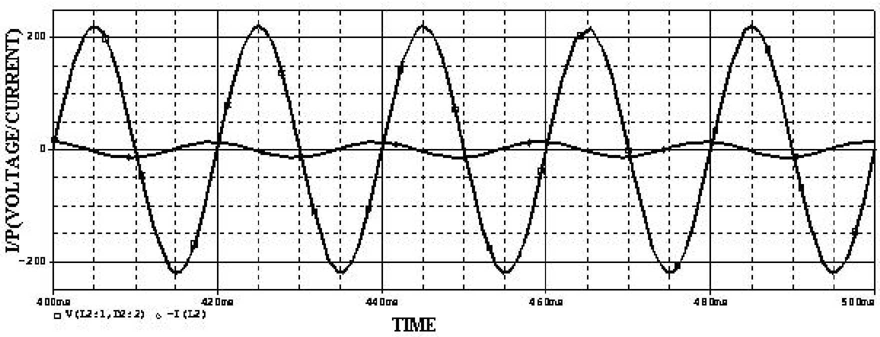

Figure 9: I/P voltage and current waveform for single phase diode rectifier with parallel input resonant filter

Table V shows the values of all the calculated parameters for single phase diode rectifier with parallel input resonant filter in a tabulated form.

TABLE V. Values of parameters for single phase diode rectifier with parallel input resonant filter

Parameters	Values
PF	0.592
DF	0.919
CDF	0.644
HF	1.186
THD	23.39%

The input Total Harmonic Distortion is reduced to 23.39% which was 84% in previous topology, but power factor is still non-unity. Therefore, some more efficient topologies are required.
The simulated prototype of a single phase diode rectifier with series input resonant filter is shown in the figure 10. The values considered in the prototype are calculated using the analysis discussed below.
For a series resonant filter at the input end of a single phase rectifier, the capacitance C_2 and L_2 is chosen such that the resonance condition is satisfied which in shown in eq. 4, and the minimum ripple is achieved.

$$\omega = \frac{1}{\sqrt{L_2 C_2}} \tag{4}$$

Where $\omega = 2\pi f$ and f is in Hz.

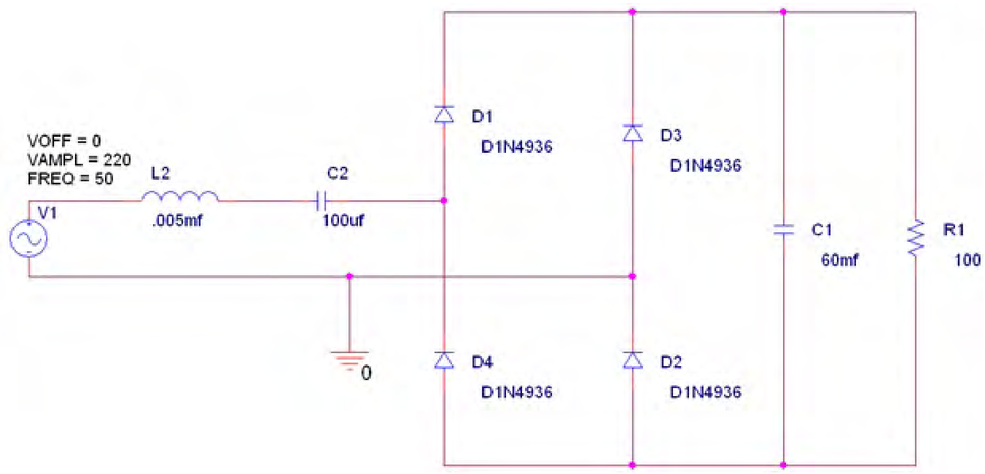

Figure 10: Single phase diode rectifier circuit with series input resonant filter

The waveform of input current and input voltage for single phase diode rectifier circuit with series input resonant filter is shown in figure 11, in which harmonics in input current are very less as compared to the previous topologies.

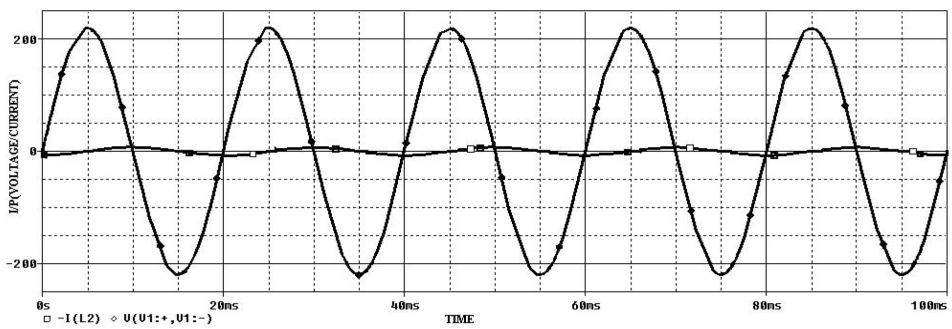

Figure 11: I/P voltage and current waveform for single phase diode rectifier with series input resonant filter

Calculated parameters for single phase diode rectifier with series input resonant filter circuit are shown in table VI in a tabulated form.

TABLE VI. Values of parameters for single phase diode rectifier with series input resonant filter

Parameters	Values
PF	0.64
DF	0.953
CDF	0.679
HF	1.08
THD	10.12%

It is clear from figure 11 that the harmonics in input current is greatly reduced and power factor reached 0.64 with Total Harmonic Distortion 10.12% which is shown in table 6, but still power factor is very less than unity. Figure 12 shows the simulated prototype of a proposed single phase diode rectifier circuit with improved parallel input resonant filter, in which values of C_3 are chosen ranging from 100µf(micro farads) to 1mf(mili farads) and is selected such that the input power factor at rated output power reaches its peak value.

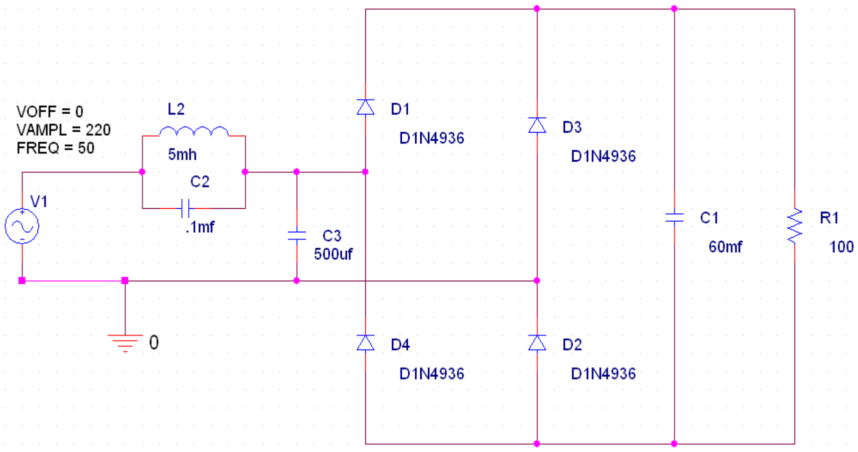

Figure 12: Single phase diode rectifier circuit with improved parallel input resonant filter

The input current and voltage waveform for single phase diode rectifier circuit with improved parallel input resonant filter is shown in figure 13. For different values of C_3, different waveforms are obtained.

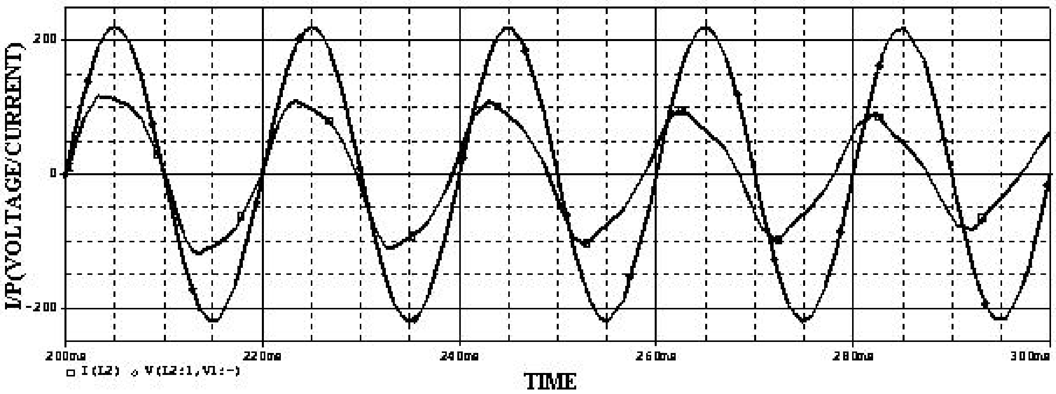

Figure 13: I/P voltage and current waveform for Single phase diode rectifier circuit with improved parallel input resonant filter

Table VII shows the calculated parameters for single phase diode rectifier circuit with improved parallel input resonant filter in tabulated form.

TABLE VII. Values of parameters for single phase diode rectifier with improved parallel input resonant filter

Parameters	Values
PF	0.931
DF	0.99
CDF	0.94
HF	0.36
THD	5.591

The results obtained from single phase diode rectifier with improved parallel input resonant filter are closest to the reference values obtained from conventional single phase rectifier circuit.

IV. RESULTS & DISCUSSIONS

The calculation of all five parameters are done by the below written formulise.
Input current distortion factor (CDF):-

$$CDF = \frac{I_{s_1}}{I_s} \qquad (5)$$

Input current harmonic factor (HF):-

$$HF = \sqrt{\left[\frac{I_s}{I_{s_1}}\right]^2 - 1} \qquad (6)$$

$$HF = \sqrt{\frac{1}{CDF^2} - 1} \qquad (7)$$

Power factor (PF):-

$$PF = \frac{I_{s_1}}{I_s} Cos\varphi_1 \qquad (8)$$

Where: - φ_1 is the phase angle between the 1st harmonic of current and the voltage

Input displacement factor (DF):-

$$DF = Cos\varphi_1 \qquad (9)$$

Total Harmonic Distortion (THD):-

$$THD = \frac{\sqrt{I_{2rms}^2 + I_{3rms}^2 \ldots + I_{nrms}^2}}{I_{1rms}} \qquad (10)$$

Where I_{nr} is the rms value of the n^{th} harmonic of the current. Fourier series expansion is used to get the harmonic components of i/p current.
Figure 15 shows the variation of input current harmonic distortion of various topologies in form of bar plot.

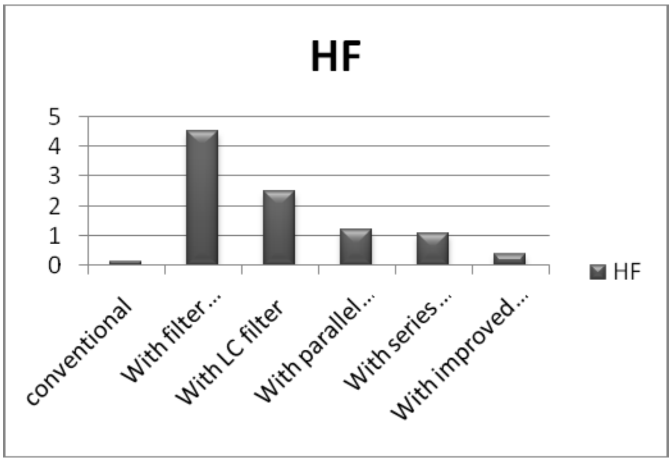

Figure 15: Variation of HF of various passive topologies

The value of HF should be as low as possible; it is minimum for single phase diode rectifier circuit with improved parallel input resonant filter among all topologies.
Figure 16 shows the variation of power factor of various topologies in form of bar plot.

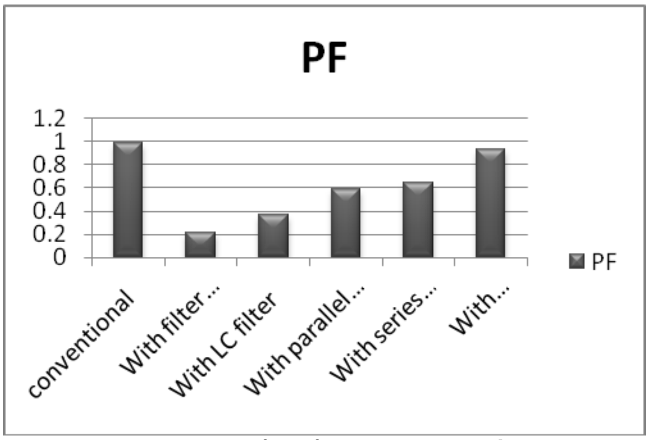

Figure 16: Variation of PF of various passive topologies

Power factor should be unity but it is very diffcult to achive unity PF. So it should be close to one. For single phase diode rectifier circuit with improved parallel input resonant filter, its value is 0.93 which is best among all the topologies.
Figure 17 shows the variation of input displacement factor of various topologies in form of bar plot.

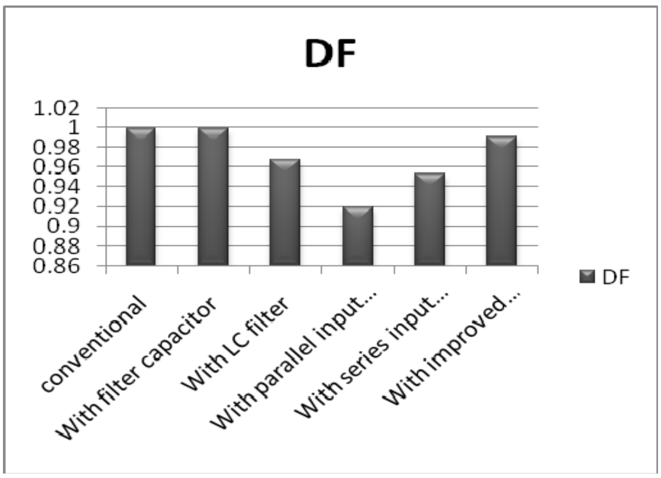

Figure 17: Variation of DF of various passive topologies

Input displacement factor is very important factor to determine power factor, its value should be close to one. Conventional single phase diode rectifier with capacitor filter has its value close to one.

Figure 18 shows the variation of input current distortion factor of various topologies in form of bar plot.

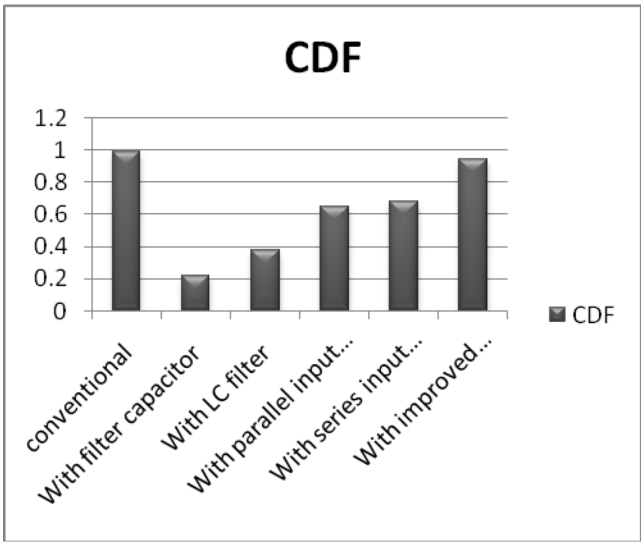

Figure 18: Variation of CDF of various passive topologies

Input current distortion factor should be close to one, or the multiplication of displacement factor and input current distortion factor should be close to one. For single phase diode rectifier circuit with improved parallel input resonant filter, it is close to one.

Figure 19 shows the variation of total harmonic distortion of various topologies in form of bar plot.

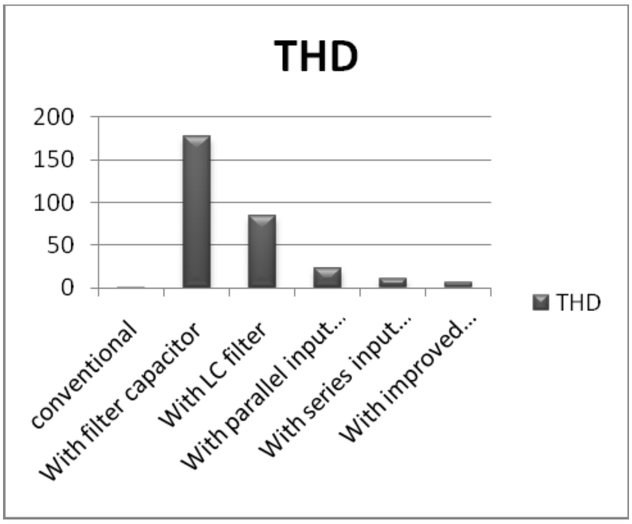

Figure 19: Variation of THD of various passive topologies

The value of total harmonic distortion should be zero. It is not possible to achive zero value so it is tried to achive minimum value of THD. For single phase diode rectifier circuit with improved parallel input resonant filter, THD is minimum. Values of all the parameters for different topologies are shown in tabulated form in table VIII.

TABLE VIII. Values of all the parameters with their respective topologies

Types	PF	DF	CDF	HF	THD
conventional	0.991	0.999	0.992	0.123	0.033
With filter capacitor	0.215	0.999	0.215	4.527	176.9
With LC filter	0.362	0.967	0.375	2.471	84.09
With parallel i/p resonant filter	0.592	0.919	0.644	1.186	23.39
With series i/p resonant filter	0.64	0.953	0.679	1.08	10.12
With improved i/p resonant filter	0.931	0.99	0.94	0.36	5.591

It is seen from above table that the value of PF, CDF, HF and THD for single phase diode rectifier circuit with improved parallel input resonant filter is very close to conventional single phase diode rectifier, but the value of DF for conventional single phase diode rectifier with capacitor is close to conventional single phase diode rectifier. DF is not the only deciding factor, so it can be concluded that single phase diode rectifier circuit with improved parallel input resonant filter is better than the other compared topologies.

V. Conclusion

From the above discussion, it is clear that among above five topologies last topology with improved parallel input resonant filter gives the best result in terms of all compared parameters. Better PF can be achieved by active method of power factor correction in which switching circuit is used and switching frequency is varied to achieve high power factor. All the above discussed topologies are used for low power output. These can be used with three phase circuit for higher power output.

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