Passive Techniques for Compliance of Single-phase Rectifiers with IEC 1000-3-2 Norms

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Abstract - A single-phase rectifier is often a frond-end power stage for many power electronic circuits. The single-phase rectifier with capacitor filter generates high harmonic currents in the ac line that is unacceptable by the IEC 1000-3-2 harmonic-current-limit specifications. Passive circuits can achieve requisite compliance at low cost, with simplicity and reliability. Various techniques of the passive input-current-shaping are reviewed in this paper. Their design for compliance is presented.

I. INTRODUCTION

Applications like computer systems, electronic lighting ballast, consumer electronic products, UPS, portable tools and machine drives use a single phase rectifier. Most conventionally, the rectifier has a dc-smoothening capacitor (figure 1a) and the resultant input current waveform is alternating pulse shaped with peak many times more than the RMS value (figure 1b). The total harmonic distortion (THD) of such current wave-shape is typically more than 100% and power factor (PF) less than 0.6. Such a harmonic-rich current waveform has several undesirable effects on the power systems which are very well known.

For the prevention of harmonic pollution, therefore, several harmonic limit specifications, recommendations, guidelines and standards have been introduced [1]. The IEC 1000 series deals with all types of electromagnetic compliance. Part 3 sets limits and section 2 is to limit harmonic current emissions for equipment input currents less than 16 A per phase. The IEC 1000-3-2 standard [2] (also adopted as EN 61000-3-2) thus enforces limits on the harmonics injected in utility line. The requirement to achieve compliance with these norms has prompted power electronic researchers to intensify study for power factor correction.

The methods for meetings harmonic limit standards with the single-phase diode rectifiers can broadly be classified as active and passive depending based on additional components used. Active solutions use a high frequency switching circuit, typically a boost converter

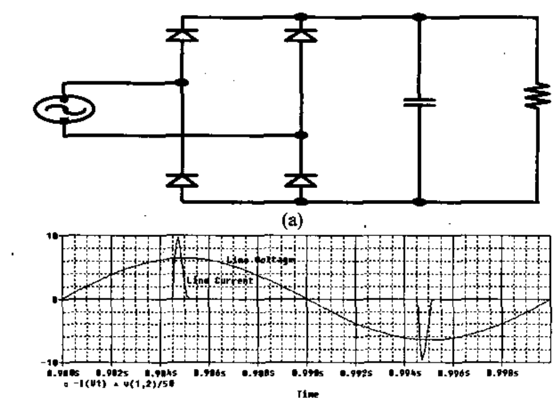

Figure 1: (a) Conventional single phase rectifier with capacitive output filter. (b) Typical line voltage and current waveform.

as shown in figure 2. In these circuits, the input current is programmed to follow the sinusoidal reference. Input current waveform is thus of excellent quality, near unity PF and THD less than 5%. The main advantages are smaller magnetic components, and universal line voltage operation. However, additional circuitry significantly reduces reliability and increases complexity. Active solutions turn out to be costly; they generate EMI and require additional filters to comply with EMI norms. Passive solutions for input current wave shaping are the ones without any controlled switches and have re-gained attention of researchers in the recent past. These circuits are reliable, simple, cost-effective, robust and they do not generate EMI. They provide the compliance with the norms. They are, however, bulky, heavy and in many cases increase the output impedance of the rectifier.

In this paper a review of passive techniques for compliance with IEC 1000-3-2 is presented. Section II summarizes the IEC 1000-3-2 harmonic limit specifications. In section III desirable features of a rectifier circuit are listed. General features of various passive wave shaping techniques are given in section IV. A comparative evaluation of their relative merits and demerits presented in section V.

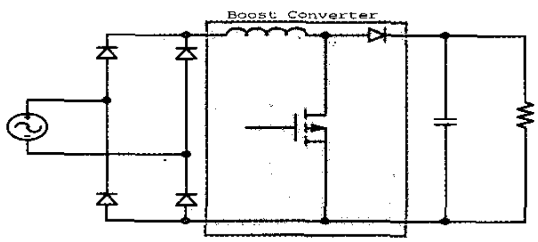

Figure 2: Active input current wave shaping circuit using a boost converter.

II. IEC 1000-3-2 HARMONIC LIMITS

The IEC 1000-3-2 standard limits harmonic currents generated by electrical and electronic equipment having an input current not exceeding 16A per phase and intended to be connected to a public single-phase or three-phase low voltage ac distribution system (with 220V to 240V phase to neutral and 380-415 phase to phase nominal voltage). Note that the IEC 1000-3-2 specifications need to be met only at the rated voltage and at rated (full) output power. In IEC 1000-3-2 four classes of equipment are defined:

a) **Class A:** Balanced three-phase equipment and all other equipment except that stated in Classes B, C and D.
b) **Class B:** Portable tools
c) **Class C:** Lighting equipments with dimming devices
d) **Class D:** Equipment having "special wave shape" as defined in figure 3 and having active input power in the range 50W≤P≤600W.

The limits for each class of equipment defined above are given specifically in [2]. Most of the single-phase rectifier for power electronics applications need to comply either with Class A or Class D norms. In this paper compliance with only these norms is considered for the comparison.

III. PRACTICAL CONSIDERATIONS

A single-phase diode bridge rectifier is used as a front end circuit. In many applications, it is required to exhibit the following desirable features.

Harmonic Content: Advancement in power electronics technology does present many options to achieve a clean, harmonic-free input current waveform at the

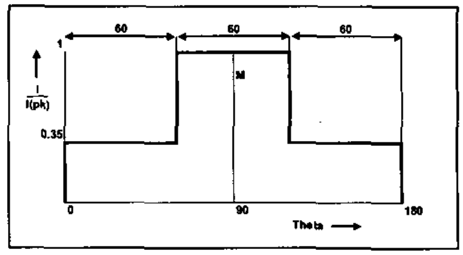

Figure 3: IEC 1000-3-2 Class D template. The equipment belongs to Class D only if each half cycle of the line current is within the envelop for at least 95% of the time when the peak coincides with center lineM.

rectifier input. The question is whether to keep the harmonic content to the "minimum" or "low enough" to achieve compliance. Cost and benefit issues of the harmonic current reduction are studied in [3] with a conclusion that the cost of power factor correction (PFC) can be recovered in about three years time. However to achieve this simplicity, reliability and ruggedness is sacrificed.

Output Voltage Regulation: If a rectifier gives coarsely regulated DC voltage, the optimization of the converter stage to follow is facilitated.

Interaction with Line Parameters: Mainly, line inductance interacts with capacitive components in rectifier resulting in voltage overshoots, high frequency oscillations and excessively large currents drawn from line. Also, if rectifier draws the leading current from the line it acts as the static VAR generator increasing the supply voltage at the point of utility service end.

EMI and EMC: Electromagnetic interference and susceptibility is more relevant to the high frequency switching active wave shaping techniques. The switching at high frequency injects common mode (CM) and differential mode (DM) noise in the line. EMI related problems are less severe in the passive techniques. Passive circuits are also less susceptible to the high frequency noise due to filtering effect of passive components.

Sensitivity: Sensitivity of the line current waveform on the component values is also an important issue as the commercial components come either with some manufacturing tolerance or drift with time.

Efficiency: A high efficiency not only saves energy but also reduces overall volume with smaller heat-dissipating elements.

IV. PASSIVE TECHNIQUES FOR COMPLIANCE

In order to achieve compliance with IEC 1000-3-2 norms, researchers and manufacturers are looking for an effective and economical solution. Different passive techniques that have been observed and tested are summarized below.

A. Series Inductor (SI) Filter [4,5]

Placing an inductor in a rectifier circuit either in series with the ac line or in the dc bus is the most common and traditional way of mitigating the harmonic problem. Figure 4 shows the rectifier with series inductor filter. A detailed analysis of the circuit is available in the literature for various performance characteristics [4] and for the compliance with the norms [5]. It has been shown in [4] that the PF is at local maximum of 0.76 for L_{ON} = 0.016 and at global maximum of 0.90 for near infinite L_{ON}. L_{ON} is the normalized value of filter inductor defined as,

$$L_{ON} = L_o \frac{P_{in}}{V_{in}^2 T_L} \tag{1}$$

Where, L_o is the filter inductance, V_{in} is RMS line voltage, P_{in} is input power and T_L is the line period.

If we design the rectifier filter inductor for compliance with IEC 1000-3-2 Class D norms [5], we get different results. Table 1 shows the range for the L_{ON} for which the rectifier is compliant. The lower limit is determined by the third harmonic limit and the upper limit is governed by the 11th and higher harmonic limits. Also the range becomes more restrictive as the line voltage approaches to the minimum voltage.

If the input power is more than 600 W, the rectifier must comply with Class A limits irrespective of the input current waveform. Since the Class D limits are absolute, the THD allowed at any power level up to 600 W is fixed. However, the Class A limits being absolute, allowable THD reduces progressively as the output power goes up. Therefore, for power output in excess of 600 W, the minimum inductance required also increases progressively with power. The maximum limit on the inductance is still imposed by the higher order harmonics exceeding the limit. This is because, the rectifier enters in DCM-II [4], where the input current has steps in the waveform. We derive the required

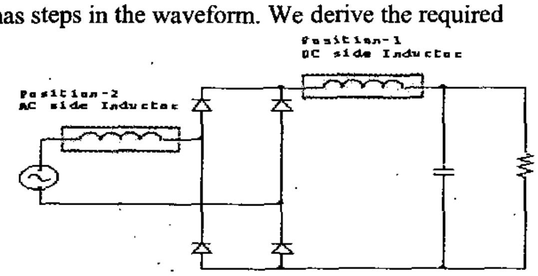

Figure 4: Diode rectifier with SI filter.

TABLE 1

RANGE OF L_{ON} FOR IEC 1000-3-2 CLASS D COMPLIANCE OF RECTIFIER WITH SERIES INDUCTOR.

V_{in} (V)	L_{ON} range
220	0.006-0.03
230	0.004-0.03
240	0.003-0.03

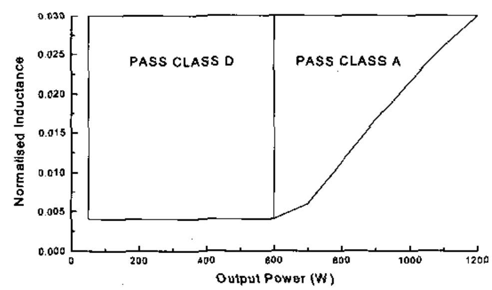

Figure 5: Diode rectifier with series inductor filter. Required inductance for Class-D and Class-A compliance.

inductance range for Class A compliance and output power above 600 W. The results are shown in figure 5 for operation at 230 V, 50 Hz. It is seen that, with the single-phase rectifier, the compliance with IEC 1000-3-2 norms can be achieved for maximum output power up to ≈ 1200 W.

B. Series Connected Series Resonant (SCSR) Filter [2]

The diode rectifier with the SCSR filter is shown in figure 5. When the quality factor and the characteristic impedance of the series resonant circuit are high, only the currents at the notch frequency (tuned to be the line frequency) can get through to the line and the power factor will be near unity. However, this means a large inductor is required along with a series capacitor. The data is not available for the choice of L and C for the compliance with Class D norms. With repeated simulation, therefore, we derive the minimum value of the inductor required. The results are summarized in Table 2. There is no upper limit on the value as the harmonic content decreases monotonically with increasing inductance. A comparison with the series inductor filter shows that there is no advantage with SCSR filter for the compliance. In fact, the peak and RMS current through inductor is nearly the same in both and so is THD and PF when both circuits are operated with minimum required inductance. Further, the SCSR filter needs an additional series capacitor, thereby increasing the cost.

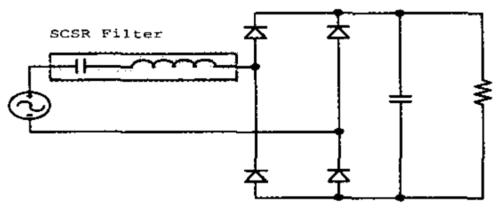

Figure 5: Diode rectifier with SCSR filter.

TABLE 2

RANGE OF L_{ON} FOR IEC 1000-3-2 CLASS D COMPLIANCE OF RECTIFIER WITH SCSR FILTER.

V_{in} (V)	Minimum L_{ON}
220	0.006198
230	0.004725
240	0.003472

C. Parallel Connected Series Resonant (PCRF) Filter [2]

The PCSR filter is shown in figure 6. The parallel resonant branch is tuned to the third harmonic frequency (150 Hz) so as not to allow the component of the current to flow in the input line. However, if the line voltage has the third harmonic component, the resultant current in the resonant branch would be very high, limited only by the parasitic resistance of the inductor and the capacitor. Therefore, the resonant circuit is de-tuned on the line side by adding an extra inductor. This shifts the resonant frequency as seen by the source to some other value but does not completely eliminate the possibility of high circulating currents. The power factor of PCSR filter is leading with respect to fundamental voltage and current. This will tend to increase the supply voltage at the point of utility service end and load the branch with more RMS current. These reasons make this filter less attractive and the benefit in terms of size diminishes with the requirement of two inductors.

D. Series Connected Parallel Resonant (SCPR) Filter [2, 6]

A parallel LC resonant circuit (with a high shunt resistance for damping) tuned to the third harmonic frequency and connected in series with the line (figure 7), presents theoretically infinite impedance to the third harmonic current component. The resulting benefit claimed are: Lower value of input peak current and lower input voltage distortion, Higher input power factor, Higher efficiency because of lower RMS input current, No leading VARs drawn from the line eliminating consequent interaction, The waveform of

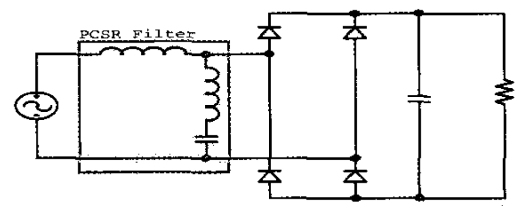

Figure 6: Diode rectifier with PCSR filter.

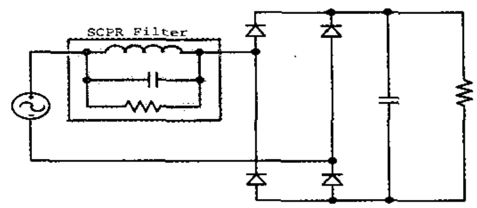

Figure 7: Diode rectifier with SCPR filter.

input current can be made to stay outside the Class D template thereby changing the compliance norm from Class D to Class A. On the negative side, the parallel resonant tank carries large circulating current, typically more than the source current. Thus the size of inductor would grow. Further a large value AC capacitor is required which is larger in size than a unipolar electrolytic capacitor.

E. Other LC Filter Circuits [7]

A passive power factor correction circuit or input current wave shaping circuit optimized for minimum size and cost, demands only one inductor. It has been shown that one or more additional capacitors help to reduce distortion and

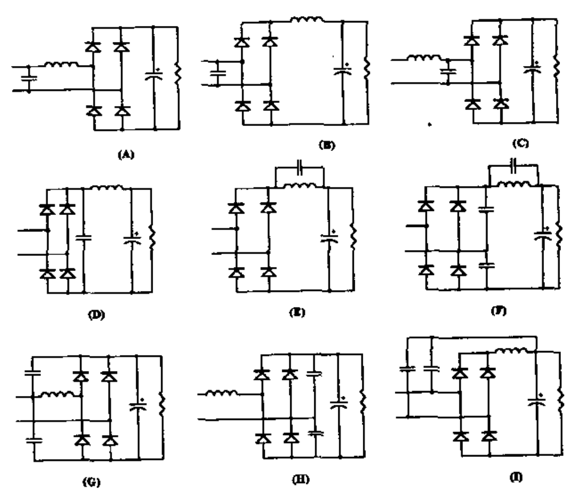

Figure 8: Other LC filter circuits.

TABLE 3

SOME CHARACTERISTIC FEATURES OF THE CIRCUITS OF FIG. 8

Cir	Load regulation %	Leading VARs	Sensitivity to component values	Resonance with line inductance
A	20	YES	LESS	YES
B	20	YES	LESS	YES
C	1	NO	LESS	YES
D	6	NO	LARGE	NO
E	10	NO	LARGE	NO
F	50	NO	LARGE	NO
G	55	NO	LESS	NO
H	82	NO	LESS	NO
I	18	YES	LESS	YES

to increase PF in the rectifier circuits. Nine useful circuits (named A though I) are shown in figure 8. General characteristics of these circuits are summarized as reported in [7]. The features given in the table 3 would help in deciding the suitability of these circuits in practical applications. In the circuits F, G and H the output voltage increases more than 50% at light loads. This is because; these circuits act as the voltage doubler due to low drop across inductor at light load. Circuits A, B and I present a capacitor at the ac input. This capacitor draws reactive VARs and may form a resonant circuit with the line inductance. Circuit C is the rectifier with classical LC input filter. In circuits A, B, C and I additional damping is required to avoid voltage and current overshoots. Passive damping either results in more loss (placing a resistor in series with the inductor) or bulky reactive components (inductive or capacitive damping).

Circuits D and E have all favorable properties except for the large sensitivity of input current wave shape on the component values. This dependence is also a characteristic of circuit F. This sensitivity is due to the resonance between filter inductor and second capacitor which also increases RMS current in inductor.

F. LCD Rectifier Topologies

A LCD rectifier is an improved version of some of the circuits discussed in the last section, the difference being an additional diode in series with the inductor. Three such LCD rectifier circuits are shown in figure 9. The circuits LCD-1 and LCD-2 were suggested in [7] and their detailed study is presented in [8] and [10, 11] respectively. Another circuit, LCD-3, is derived from the circuit F of figure 8. LCD rectifiers aim mainly towards exploiting higher harmonic limits of IEC 1000-3-2 Class A at low powers by changing the input current waveform in such a way that it remains outside Class D template. The said improvement is mainly due to the fact that the additional diode prevents the recharge of capacitor and extends the conduction angle of the bridge diodes. In other words, it prevents the resonance between the capacitors and inductors avoiding all the ill effects mentioned earlier. The presence of an additional capacitor causes a steep edge to appear in the line current waveform and it reduces peak line current. The appearance of steep edge changes the class of waveform from Class D to Class A. However, circuit parasitic components such as ESR of capacitor and line inductance have profound effect on the waveform and play an important role in achieving compliance. The ESR of capacitor tends to reduce the peak of the leading edge and the line inductance tends to increase the peak by forming a damped resonant circuit. Both, in combination, limit the rate of rise of the edge reducing high-frequency harmonics. Thus, the parasitic components can either improve or worsen the situation for compliance. Never-the-less, the plots of figure 10 show the range of values of L and C for which the input current belongs to Class A or Class D. These plots are obtained from the repeated simulations with component values normalized to following base values:

$$L_{base} = \frac{V_{in}^{\ 2} T_L}{P_o} \tag{2}$$

$$C_{base} = \frac{1}{(2\pi f)^2 L} \quad \text{(f is the line frequecy)} \tag{3}$$

The LCD-1 and LCD-2 circuits behave almost identically when output ripple is zero. However, required inductor value and size in LCD-1 increases with output ripple and that in LCD-2 remains nearly independent of ripple [10]. Thus for practical range of

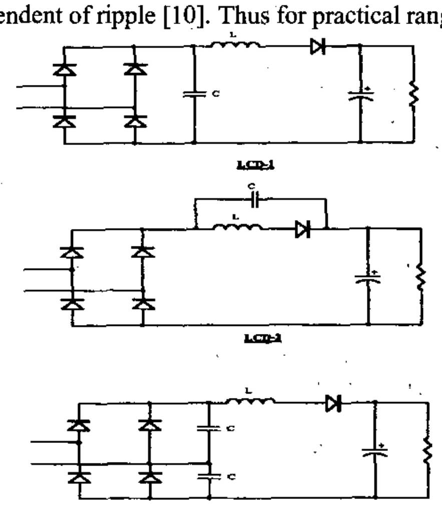

Figure 9: Other LC filter circuits.

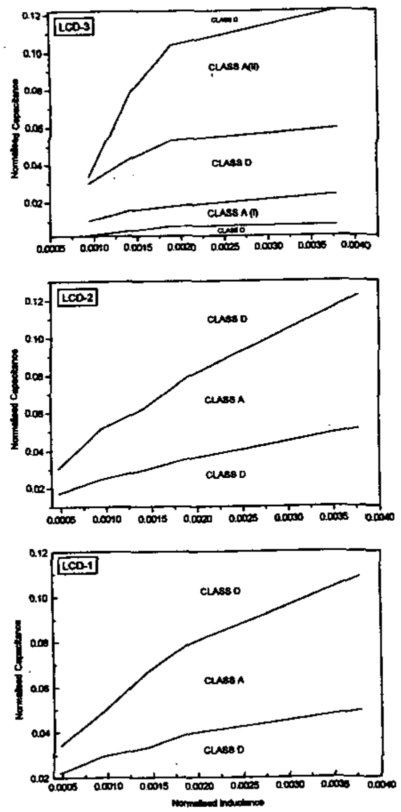

Figure 10: Normalized inductance and capacitance in LCD rectifiers for Class A and Class D operation.

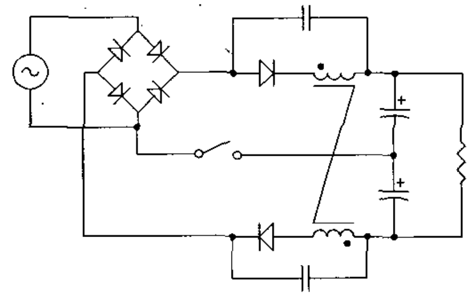

Figure 11: LCD-2 voltage doubler topology.

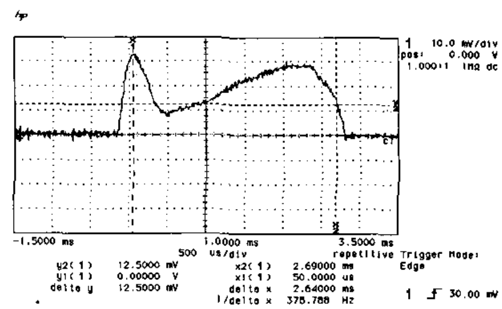

Figure 12: Experimental line current waveform in a 100 W LCD-2 rectifier circuit.

output ripple (up to 20 %), the LCD-2 circuit requires a smaller inductance for compliance than LCD-1. The LCD-3 circuit behaves in more complex manner. There are two regions each for Class D and Class A in the L-C plane. In region A-II, the voltage regulation is poor as the output voltage doubles at light load. In A-I region, the voltage is always near the double value and the load regulation is therefore better. To determine minimum requirements of the passive components for the rectifier to be just compliant with Class A norms, ideal LCD circuits were with zero-parasitic components were simulated for 230V, 50Hz line voltage and different power levels for approximately 10% output ripple. Note that it is advantageous to use minimum required capacitance as THD increases with capacitance. Table 4 gives the minimum inductance and capacitance required for compliance. At low output power, the Class-A limits (being absolute) are many times higher than the actual harmonics in the input current waveform. Now recall that the waveform belongs to Class A only if the input current after the leading edge drops to 35% of the peak value not before 2.17 mS for 50 Hz input frequency. The minimum inductance at low power outputs is

A topological extension of LCD-2 rectifier is shown in figure 11. This is a voltage doubler rectifier circuit with range selector switch and two LCD sections. Figure 12 shows experimental line current waveform obtained with a 100 W LCD-2 rectifier.

V. COMPARISON

Sixteen different passive circuits are identified and their main characteristics are summarized. A meaningful comparison of these circuits should first identify which class of the IEC norms they comply with. The series inductor filter, SCSR filter and PCSR filter circuits have an input current waveform that fits into the Class D template. On the other hand, all the LCD rectifier circuits and the SCPR filter comply with the Class A norms. LCD-3 is explored as a voltage double circuit that complies with Class A norms.

PSCR filter needs an additional inductor to de-tune the filter from third harmonic distortion in line voltage increasing bulk and cost. Also, it can draw leading VARs. The SCPR circuit being a resonant filter has a significant energy circulating in the parallel tank circuit increasing bulk and cost. This makes the PSCR and SCPR circuits less attractive. Other nine LC circuits have either poor load regulation or draw leading VARs from line or have high sensitivity to component values and may resonate with line inductance. Therefore, they are also not considered for comparison.

A. Circuits for Class D Compliance

With reference to tables 1 and 2, it can be observed that for compliance SCSR filter needs an inductor of larger value than series inductor filter. A 1 kW single phase rectifier with SCSR and series inductor filter was simulated. It was found that the peak and RMS current through inductor is nearly the same in both the circuits and so are THD and PF. Owing to larger value, the size of filter inductor in SCSR filter would be larger than that in series inductor filter. Additionally, the SCSR filter needs an additional series capacitor increasing the cost. Thus the SCSR filter has no advantage over the series inductor filter if the design is dictated by compliance norms. Of course, a high Q SCSR filter circuit gives nearly sinusoidal current waveforms but the required inductor is very large. Therefore for Class D compliance, series inductor filter is the most suitable passive technique.

B. Circuits for Class A Compliance

The better solution for the Class A compliance is LCD rectifiers. Of the three LCD circuits described earlier, LCD-3 is a voltage doubler circuit and therefore it is not considered for direct comparison. A detailed comparison of LCD-1 and LCD-2 rectifiers is presented in [10]. The IEC1000-3-2 Class D harmonic current limit is defined for the input power range between 50W and 600W. On the lower end of this range, the Class A limits are many time more than the Class D limits. This difference progressively reduces as the power goes up and above 600W input power, there is no difference between these two limits. Therefore the LCD rectifiers are deemed advantageous at low power levels. Table 5 summarizes the results of simulation of LCD-1 and LCD-2 circuits at different power levels with minimum required component values on 230 V, 50 Hz AC line. Also presented are the results of simulation with series inductor filter for comparison. Apart from the PF, THD, peak and RMS currents, the table also gives the area-product coefficient "K" for the filter inductor which can be used as an index of its physical size. The area product of an inductor is proportional to the inductance value, RMS current and peak current. The coefficient "K" is therefore defined as:

$$K = L \cdot I_{rms} \cdot I_{pk} \tag{4}$$

It can be observed from table 5 that the LCD-2 circuit offers a great reduction in volume of the inductor. At 100W output the size of the inductor is 14% that of series inductor filter and 57% that of LCD-1. At 300W it is 36% and 82% respectively. As expected, the difference is not very significant at 600W output. However, the THD of LCD rectifiers is very low

TABLE 4

MINIMUM L AND C REQUIREMENTS OF LCD RECTIFIER CIRCUITS AT DIFFERENT POWER OUTPUTS

LCD CKT.	100W		200W		300W		400W		500W		600W	
	L (mH)	C (μF)	L (mH)	C (μF)	L (mH)	C (μF)	L (mH)	C (μF)	L (mH)	C (μF)	L (mH)	C (μF)
LCD-1	5.30	50	2.75	90	4.5	80	5.5	80	6.5	80	7.5	80
LCD-2	2.30	55	1.5	100	3.5	75	4.5	85	5.5	80	6.5	80
LCD-3	10	32	5	60	7.5	60	8.5	65	10	65	12	70

TABLE 5

COMPARISON OF THE PROMISING PASSIVE SOLUTIONS FOR COMPLIANCE

Po,W	Ciruit	L (mH)	C (μF)	I_L (A) Pk	I_L (A) RMS	K x 1e-3	I_C, (A) Pk	I_C, (A) RMS	I_{in}, (A) Pk	I_{in} (A) RMS	THD %	DPF	PF
100	SI	46.6	-	1.41	0.61	40.0	-	-	1.41	0.61	84.6	0.94	0.72
	LCD1	5.3	50	2.43	0.76	9.78	1.90	0.53	1.89	0.69	118	0.99	0.63
	LCD2	2.3	55	2.92	0.83	5.57	1.87	0.56	1.87	0.68	116	0.99	0.64
300	SI	15.5	-	4.23	1.82	119.3	-	-	4.23	1.82	84.6	0.94	0.72
	LCD1	4.5	80	5.66	2.06	52.47	4.18	1.40	4.18	1.77	88.0	0.99	0.73
	LCD2	3.5	75	5.87	2.10	43.14	3.91	1.41	3.92	1.72	82.6	0.99	0.74
600	SI	7.8	-	8.45	3.64	239.9	-	-	8.45	3.64	84.6	0.94	0.72
	LCD1	7.5	80	8.53	3.66	234.1	5.82	2.43	5.88	3.07	58.1	0.99	0.85
	LCD2	6.5	80	8.71	3.72	210.6	6.32	2.48	5.94	3.05	56.7	0.99	0.86

and power factor is higher compared to that of series inductor filter at 600W. Since at higher power high frequency harmonics exceed the limits and size advantage diminishes, series inductor filter have an advantage for power output above 500 W.

VI. CONCLUSION

Passive solutions can provide compliance with norms at low cost. Passive rectifier circuits are reliable, simple, cost-effective and robust. They do not generate EMI and contribute to filtering. Many passive techniques emerged to provide compliance, and aimed to reduce the bulk and weight which has been considered as a major limitation.

This paper presented a comprehensive comparison of passive techniques for compliance with IEC 1000-3-2. It has been shown that the classical series inductor filter is the most promising solution for compliance with Class D norms (< 600 W) and with Class A norms (between 600 W and 1200 W). Above 1200 W, this method can not provide compliance. LCD rectfiers, on the other hand are felt very attractive for low powers (< 500 W) since they exploit higher limits specified in Class A. LCD-2 circuit is a better choice among the LCD topologies as it can achieve compliance with smaller inductance.

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