Utility-Friendly Interface Options for Variable Speed Drives

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Abstract

Non-linear loads such as diode and thyristor rectifiers contribute to grid supply degradation through generation of harmonic waveforms and low power factor. Harmonic currents drawn by non-linear loads result in distortion of the supply voltage waveform at the point of common coupling. Utilities are increasingly enforcing harmonic standards such as IEEE 519 to alleviate harmonic related problems. Although IEEE 519 is a recommended practice and is really not enforceable, most installations are now required by the utilities to meet this standard. This paper examines relative merits of industrial power quality solutions within the framework of technical and commercial viability. Several topologies presented in the technical literature and released in the market are compared for their performance attributes and economic competence. Operating principles, design aspects and issues such as indirect costs are discussed. Detailed commercial analysis along with critical technical assessment is presented in the paper.

I. Introduction

The most common topology for front end of variable speed drives is a diode bridge rectifier with dc side capacitor [1]. Unfortunately, this is one of the most challenging systems from a power quality perspective. The supply line current is discontinuous and is limited only by the line inductance, thereby resulting in very high peak currents. Numerous techniques have been reported in the literature for harmonic mitigation with such loads and many of them are available now as standard products in the market [2]. This paper is devoted to a critical assessment of these solutions and their comparison against a candidate clean utility interface.

Drives with active front end have traditionally been looked upon as regenerative and hence focussed single-pointedly towards markets which demand regeneration exclusively [3]. The fact that such rectifiers can also draw sinusoidal currents has been treated as a secondary advantage. Moreover, this approach has always been viewed as the most expensive and most complicated solution. This paper shows that, today this picture has changed and one can pose this as a commercially competitive clean utility interface for the adjustable speed drive market.

Operating principles of active rectifiers, practical design aspects and issues of interfacing them with the utility are discussed in the paper. The technical viability of this approach is verified through computer simulations. And most importantly, detailed commercial analysis from the customer point of view of this approach as compared with the traditional approaches is also included in the paper.

II. The Problem

Most power electronic loads used in the industry today convert the incoming utility ac voltage to an intermediate or final dc voltage. This rectifier function is frequently uncontrolled, realized with an input diode bridge, or may be controlled using thyristors. Perhaps the most common topology for front end of Adjustable Speed Drives (ASD) is a diode bridge with dc side capacitor filter as shown in Figure 1 [1]. The "load" block in this figure represents the ASD driving a motor in the plant.

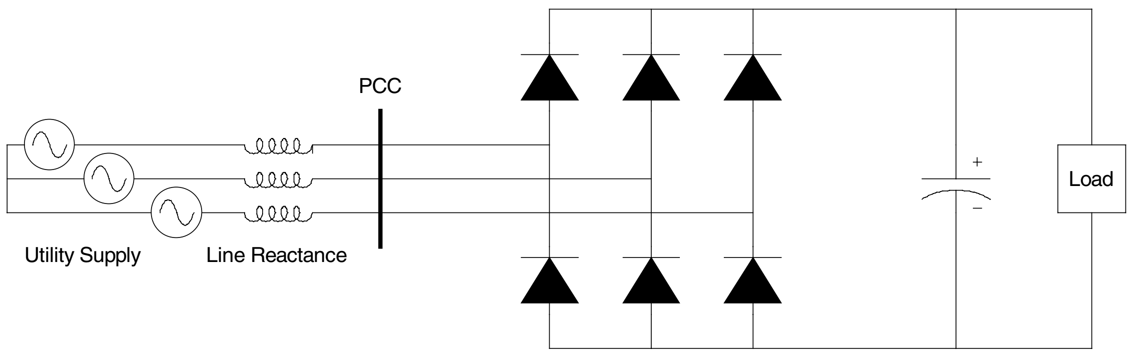


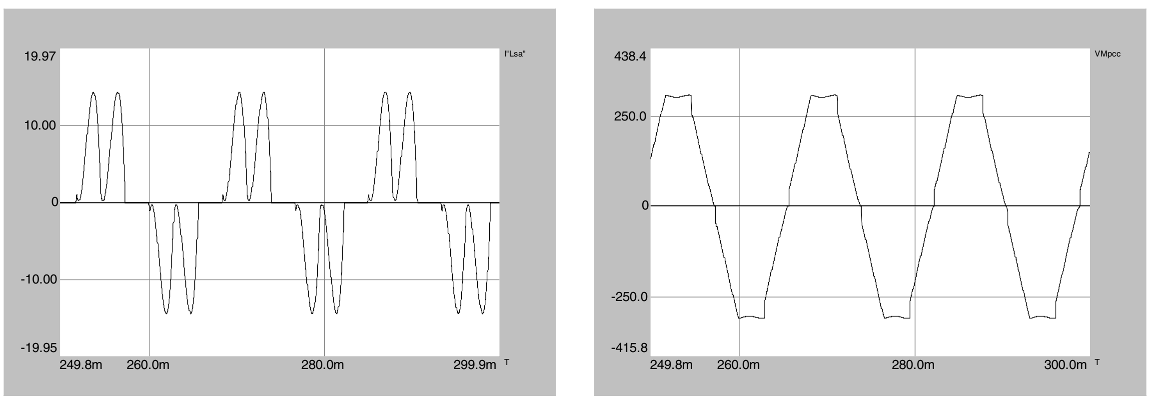
Figure 1. Simplified schematic of a diode bridge rectifier with dc side capacitive filtering.

Unfortunately, this is one of the most challenging systems that can degrade the quality of the utility. The supply line current is discontinuous and is limited only by the line reactance, thereby resulting in very high peak currents. Normally, the line reactance gives a measure of Short Circuit Ratio (SCR) at the Point of Common Coupling (PCC). For weak utility lines the SCR may be as low as 20, but in most cases it is 20-100. This implies that the typical values of ac line reactance are around 1-5%. The Total Harmonic Distortion (THD) in the current is high, typically around 60-130%, and is worse for stiffer utility lines [4]. Although such front ends are typically employed in low power ASDs (< 20 HP), a large number of such units tied at the same PCC can cause significance degradation. This is briefly explained as follows:

Let us consider a utility system capable of supplying a 480V, 2MVA load as a candidate utility system. The value of the line reactance (this may also be transformer leakage reactance) is fixed at 5%, thus assuming the SCR to be 20. Now, as a typical case, let us assume that this system is loaded with one 20HP drive. The value of line reactance is assumed to be 15μH (5% at 2MVA).

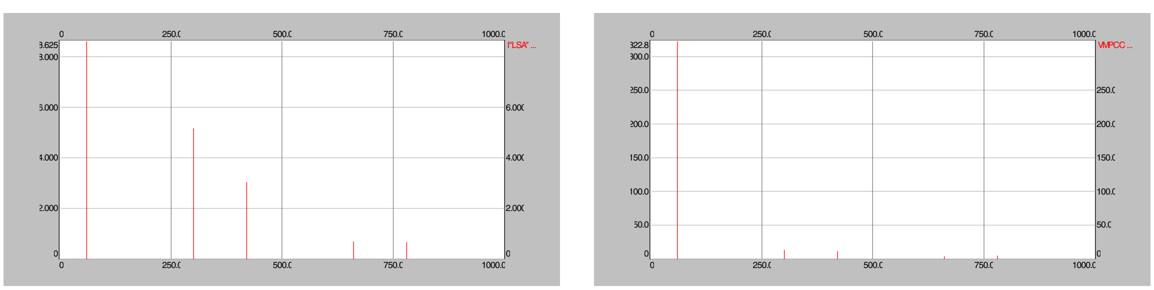
It will be observed that even though the 5th, 7th, 11th, 13th etc. harmonics are dominant harmonics in the line current which makes it pretty distorted, the voltage waveform remains to be reasonably sinusoidal. This is because of the very low equivalent reactance the light (20HP) load sees when it is put on an oversized (2MVA) source. It may be noted that 5% reactance at 2MVA is equivalent to 0.037% at 20HP even though physically it is 15μH reactance. Owing to this loading effect, the drive does not impose heavy penalty in terms of voltage distortion. Hence, if the customer has the rest of the 2MVA power supplying reasonably linear loads, it is more likely to meet standard like IEEE 519 which is based on the measure of distortion against total demand current.

Further, let us consider that a customer has multiple (say, twenty) 20HP drives connected at the same point of common coupling. The value of line reactance is still 15µH (but now, it may be noted that 5% reactance at 2MVA is equivalent to 0.737% reactance at 400HP). It will be observed that in such a scenario, the distorted line current causes visible distortion in the voltage waveform. A common method adopted to alleviate this distortion is to use either ac or dc chokes in the drives. As will be shown later in this paper, this solution makes the current more continuous, thereby decreasing the voltage distortion. In practical sense, it allows increase of load at the same point of common coupling while maintaining compliance with IEEE 519. However, one cannot increase the load indefinitely without running into distortion limits. One soon reaches a point where the voltage and current distortion is prominent even with the introduction of ac / dc chokes typically when the load rating is of the order of power capability of source. This paper documents several options employed to interface such loads with the utility in order to comply with harmonic standards such as IEEE 519.



a) Line Current *b) Line-line Voltage*

Figure 2. Current and voltage waveforms at PCC for the diode bridge rectifier with dc side capacitive filtering.



(a) Line Current *(b) Line-line Voltage*

Figure 3. Current and voltage spectra at PCC for the diode bridge rectifier with dc side capacitive filtering.

As an example case, a system as depicted in Figure 1 and rated for 230V, 3HP load is simulated in Simplorer. The value of line reactance is fixed at 1.25% (0.78mH), thus assuming the SCR to be 80. The dc bus capacitance is 940 μF and the load resistance is 40Ω. Figure 2 shows line current and line-line voltage waveforms at the point of common coupling. The corresponding frequency spectra of these parameters are shown in Figure 3. It may be observed that the 5th and 7th harmonics are the dominant harmonics.

III. Solution 1: AC/DC Chokes

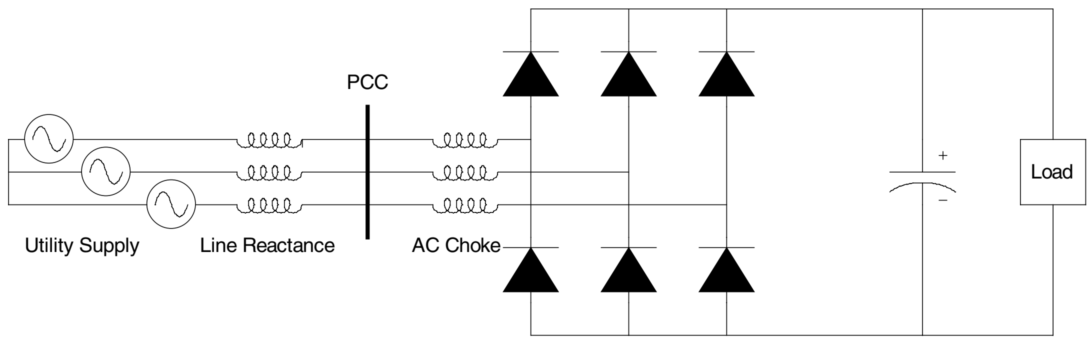


Figure 4. Simplified schematic of a diode bridge rectifier with additional ac side inductive filtering.

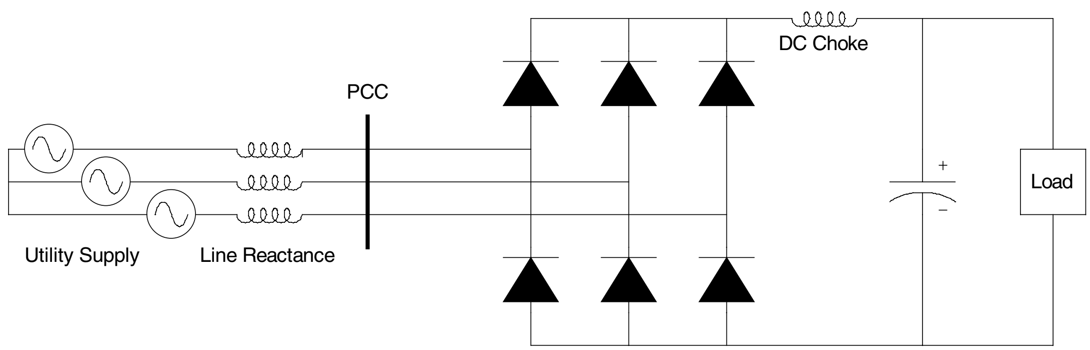
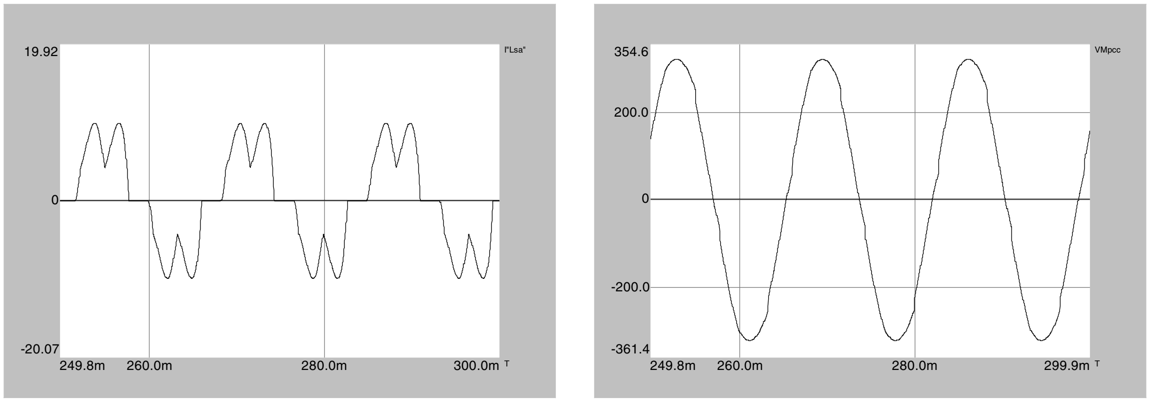


Figure 5. Simplified schematic of a diode bridge rectifier with additional dc side inductive filtering.

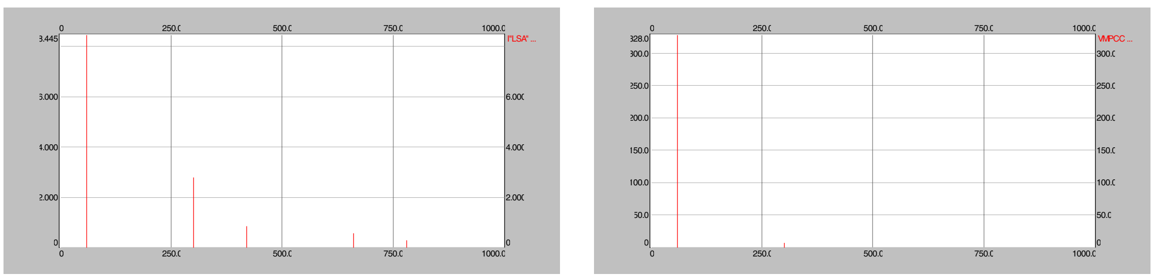
A simple solution to alleviate this problem is addition of chokes, either on ac or on dc side as shown in Figures 4 and 5. Typically, adding a 3-5% choke reduces the current THD to 40% [5]. The same 230V / 3HP system as depicted in Figure 1 with 3% (1.8mH) choke connected on the ac/dc side is simulated in Simplorer. Figure 6 shows line current and line-line voltage waveforms at the point of common coupling for the ac choke case. The corresponding frequency spectra of these parameters are shown in Figure 7. It may be observed that although the 5th and 7th harmonics are still prominent in the line current, it is more continuous which makes the voltage at the PCC less distorted as compared to the earlier case (Figure 2).

Figure 8 shows line current and line-line voltage waveforms at the point of common coupling for the dc choke case. The corresponding frequency spectra of these parameters are shown in Figure 9.



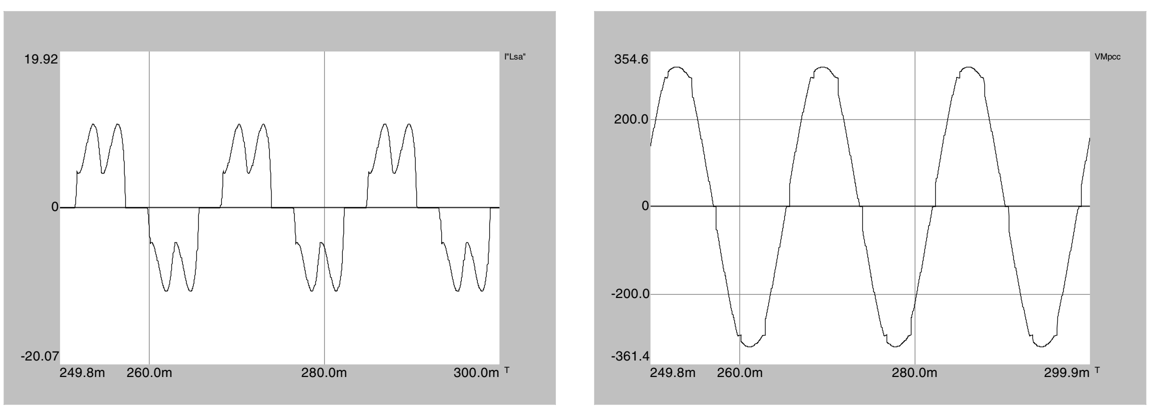
a) Line Current *b) Line-line Voltage*

Figure 6. Current and voltage waveforms at PCC for the diode bridge rectifier with additional ac side inductive filtering.



(a) Line Current *(b) Line-line Voltage*

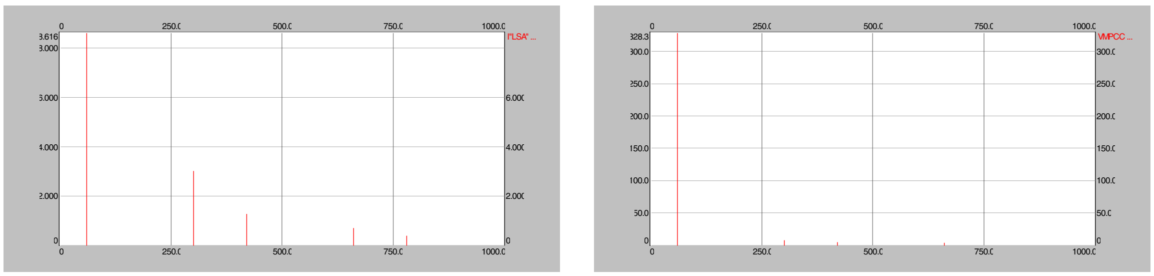
Figure 7. Current and voltage spectra at PCC for the diode bridge rectifier with additional ac side inductive filtering.



a) Line Current *b) Line-line Voltage*

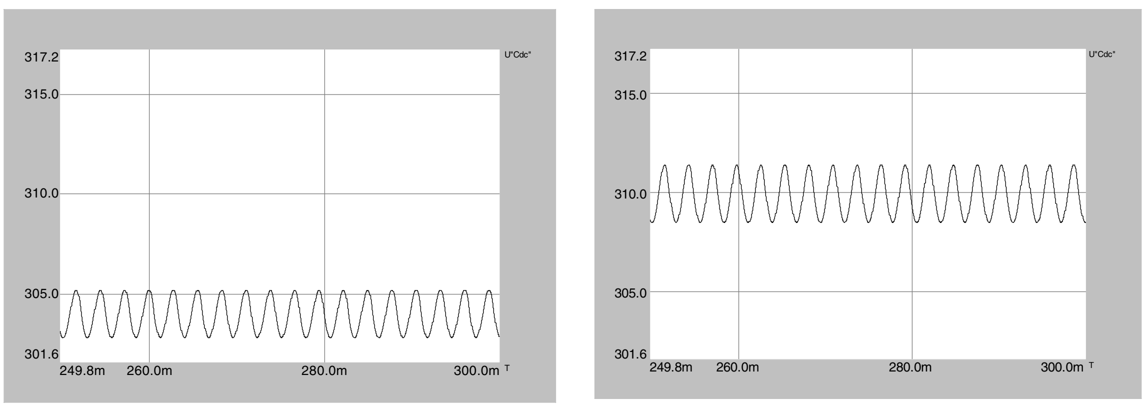
Figure 8. Current and voltage waveforms at PCC for the diode bridge rectifier with additional dc side inductive filtering.

It may be observed that the performance of dc chokes is almost identical to that of ac chokes in terms of attenuating the harmonics in the line current and line-line voltage at the PCC. In addition, the voltage regulation is even better with dc chokes. As shown in Figure 10, under full load conditions, the average dc bus voltage is about 3% lower in the case of ac chokes as compared to the dc choke case. This is because of the 3% voltage drop across the 3% ac reactance at almost 1 per unit current, which reduces the voltage fed into the rectifier. Furthermore, the size of dc choke is small as compared to the ac chokes. However, the dc choke design and fabrication is tricky which might lead to higher premiums. Moreover, the ac chokes have the ability to limit the fault current in case of a line-line fault caused by a shorted diode, wherein dc chokes are ineffective. Thus, there is a trade-off in the choice between ac and dc chokes, and the preference is often dictated by the target application and product volume.



(a) Line Current *(b) Line-line Voltage*

Figure 9. Current and voltage spectra at PCC for the diode bridge rectifier with additional dc side inductive filtering.



a) AC side choke *b) DC side choke*

Figure 10. DC bus voltage waveforms for the diode bridge rectifier with additional inductive filtering.

IV. Solution 2: Multipulse Configurations

Analysis of six-pulse currents drawn by a rectifier with inductive filter (Figures 7 and 9) reveals that the current distortion of 40% is mainly caused by 5^{th} and 7^{th} harmonics. A common practice to reduce this further has been to employ phase shifting transformers that draw multipulse current waveforms from the utility [6]. A simplified schematic of a twelve-pulse rectifier fed from an isolation transformer with multiple secondary windings is shown in Figure 11. It may be observed that the first secondary winding is configured in delta whereas the second is configured in wye. By virtue of this arrangement, the 5^{th} and 7^{th} harmonics in these windings are in antiphase, thereby mutually canceling each other in the primary winding. Introducing interphase reactor in the dc link ensures independent operation of two rectifiers which maintains the semiconductor device conduction at 120^{o}.

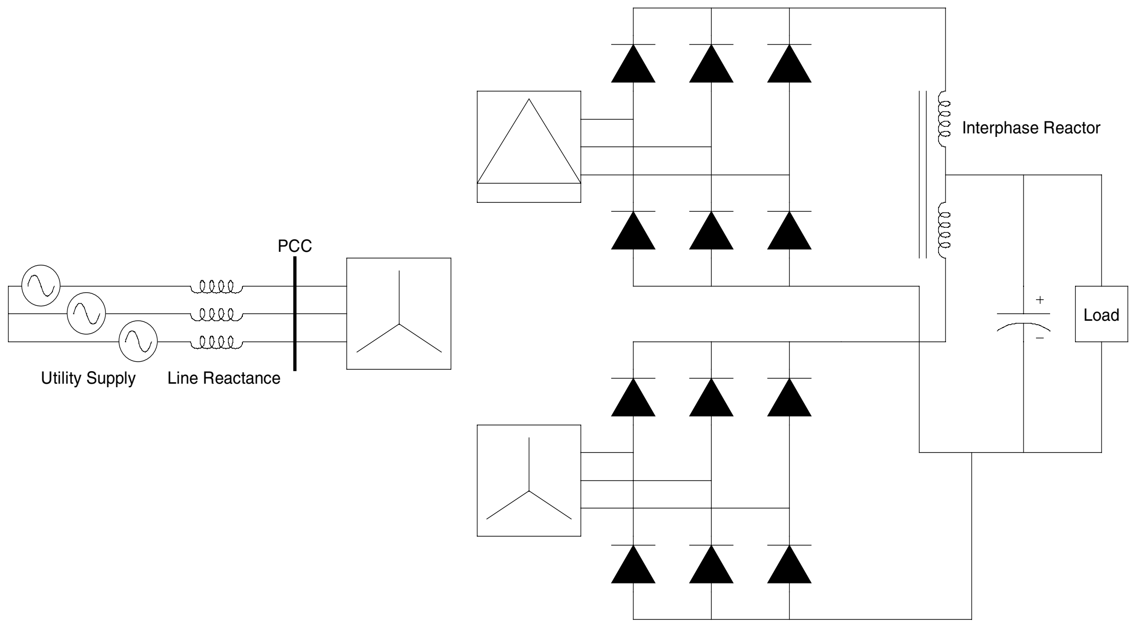


Figure 11. Simplified schematic of a diode bridge rectifier with twelve-pulse isolation transformer.

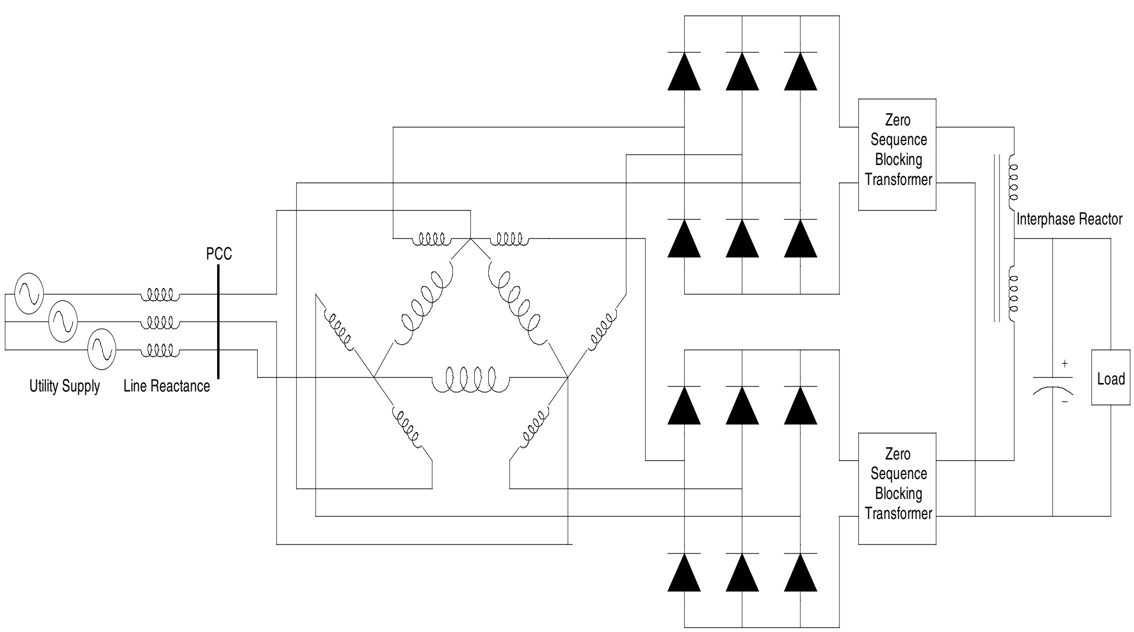


Figure 12. Simplified schematic of a diode bridge rectifier with twelve-pulse autotransformer.

The kVA rating of the transformer used in this scheme is little higher than 1 per unit, i.e. almost equal to the power rating of the drive. One may reduce the kVA rating requirement by employing autotransformer configurations thereby relinquishing isolation between two rectifiers. A simplified schematic of a rectifier fed from a representative autotransformer is shown in Figure 12. Since the rectifiers are no longer isolated, one needs a zero sequence blocking transformer to prevent circulating currents between the two rectifiers in addition to the interphase reactor. It has been reported that the kVA rating of this autotransformer is approximately 0.2 per unit, i.e. about one fifth of the power rating of the drive [7]. It is possible to improve the performance even further by adopting configurations with higher pulse numbers such as eighteen, twenty-four etc. This may be done either by putting three or more rectifiers in parallel [6] or by adding semiconductors to the circuit [8].

These solutions offering multipulse current waveforms are quite attractive in case of high power ASDs (> 100HP) which require multiple six-pulse rectifiers to carry rated currents. Although it is possible to reduce current THD to 6-8% with such configurations, they require large footprint and can become quite expensive [9].

V. Solution 3: Passive Filters

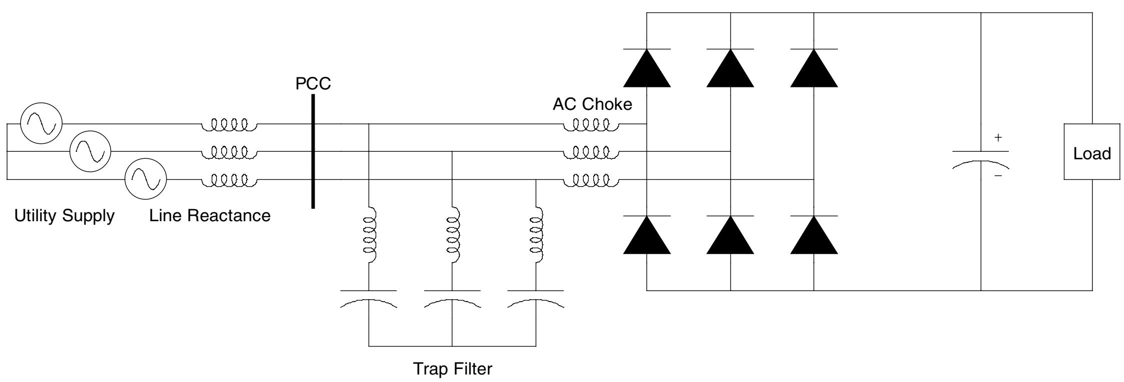
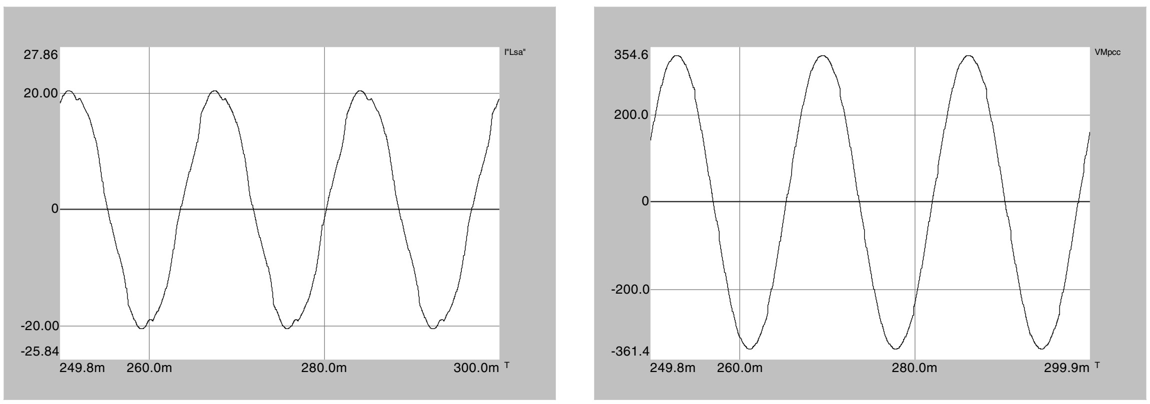


Figure 13. Simplified schematic of a diode bridge rectifier with tuned L-C shunt passive filter.

As stated earlier, introducing ac or dc chokes in the diode rectifier reduces the THD in the line current by several decades of percents. Besides shaping the current and making it more continuous, this approach also restores near sinusoidal voltage at the point of common coupling (Figures 6(b) and 8(b)). However, the performance is not quite sufficient to meet the stringent <u>individual</u> current harmonic limits dictated by standard IEEE 519 [10].

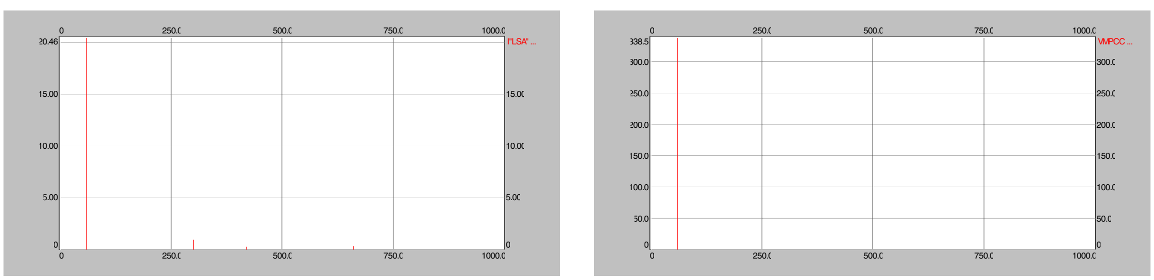
Historically, this has led to view such non-linear loads as harmonic "current" sources which generate harmonic currents that cross the enforced limits. Accordingly, shunt L-C passive filters as shown in Figure 13 have commonly been applied to mitigate harmonic related problems [11]. The principle of shunt passive filtering is that it provides a low impedance shunt branch to the harmonic currents generated by the load, thus diverting the harmonic current from flowing into the line.

This may be observed from the results of the same 230V/3HP system simulated with trap filters for 5th and 7th harmonics. The values of inductance and capacitance in 5th and 7th harmonic filter are 1.8mH/180µF and 1.8mH/88µF respectively. It may be noted that the resonant frequencies of these filters are 280Hz and 400Hz. Ideally, the filter must be tuned exactly to the characteristic harmonic it is supposed to suppress. Practically, however, the filters are tuned to a frequency slightly lower than the nominal resonant frequency in order to avoid the possibility of parallel resonance in case the filter component parameters change due to temperature and aging. Most harmonic filters, including the ones in these simulations, are tuned to about 0.95 times the nominal resonant frequency. Figure 14 shows line current and line-line voltage waveforms at the point of common coupling. The corresponding frequency spectra of these parameters are shown in Figure 15. It may be observed that the 5th and 7th harmonics are attenuated considerably with the shunt passive filters.



a) Line Current *b) Line-line Voltage*

Figure 14. Current and voltage waveforms at PCC for the diode bridge rectifier with tuned L-C shunt passive filter.



(a) Line Current *(b) Line-line Voltage*

Figure 15. Current and voltage spectra at PCC for the diode bridge rectifier with tuned L-C shunt passive filter.

As may be verified from these results, the shunt passive filter is indeed effective in compensating the harmonic currents of non-linear loads that have sufficient ac or dc side inductance. Besides the diode front ends with ac or dc chokes (Figures 4 and 5), such a non-linear load is a phase-controlled thyristor rectifier which has sufficient dc inductance to produce non-pulsating dc current. However, it should be noted that this shunt filtering approach fails when applied to systems without sufficient inductance. A typical example is the system with just a dc side capacitive filter as shown in Figure 1. It has been shown that parallel L-C filters not only cannot cancel the harmonic currents but also cause problems such as enlarging dc voltage ripples and ac peak current of the rectifier in such systems [12]. This is because a diode rectifier with smoothing capacitors behaves like a harmonic "voltage" source rather a harmonic "current" source. It has been reported that series passive filters as shown in Figure 16 are more effective to mitigate harmonics in such cases [12].

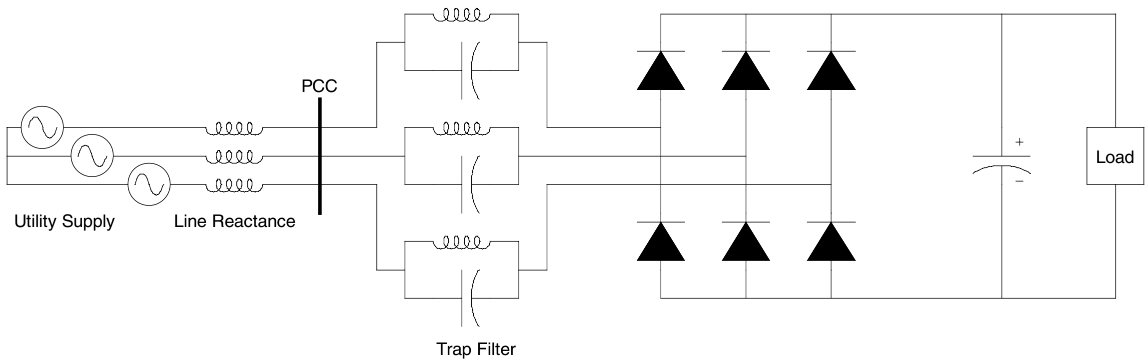


Figure 16. Simplified schematic of a diode bridge rectifier with tuned L-C series passive filter.

Extensions of pure shunt and series passive filters such as broadband filters [13] and universal filters [14] have also been reported by filter manufacturers which claim to satisfy IEEE Std. 519. Passive filters have primarily been used due to their low cost and high efficiency [15]. However, with the growing proliferation of semiconductor technology and the resultant increase in product volume, relative costs of reactive elements as compared to the silicon devices needs to be re-addressed. Contrary to the popular belief, power devices are no longer the most expensive elements in a drive. In fact, in some cases, passive elements such as filter chokes or input contacters could cost more than the active device inverter bridge in the circuit. So also, high efficiency assumes extremely high Q-factor in the filter which is not a realistic solution. With finite Q-factors, the efficiency of the filter is almost equal to the efficiency of the drive. In addition, passive filter solutions are plagued by their interaction with ambient loads and unwanted resonance [16]. The filters are also susceptible to load and line switching transients and their performance is strongly dependent on the supply impedance which mandates extensive system studies and considerable engineering effort.

VI. Solution 4: Active Filters

Active filter solutions were developed to mitigate the problems of passive filters and may be classified into pure active and hybrid active filter solutions. Several active filter topologies are reported in literature, which claim to assist in meeting IEEE 519 [17]. It should however be realized that there is not one optimal active filter solution, since the optimal filter solution is application and utility specific. The most popular topology of active filter is a shunt active filter [18] as shown in Figure 17.

The control philosophy is simple - extraction of load harmonic current to form reference current for the active filter from the measured load current and a feedback loop for the dc bus voltage of the active filter. The documents in support of this technique claim that the power rating of the active filter is a product of harmonic current and the fundamental voltage [18]. For a typical diode front end system with a 3% choke (Figure 4), the current THD levels are around 40%. This would imply that the necessary filter rating is 40%. However this overlooks the fact that the filter has to supply the harmonic current through the interconnecting reactance which is about 3-5%. Since the inductive reactance increases at higher frequencies, this problem is even worse. Consequently, one needs more dc bus voltage to compensate for the higher order harmonics to meet the constraints of IEEE 519 satisfactorily. Usually, the dc bus voltage of the active filter is required to be about 15-20% more than that of the drive, which adversely affects its design, increases the device ratings and incurs more losses. Furthermore, the required bandwidth for the current controller is also an issue of concern. Typically, existing commercial drives rated for 500 HP employ switching frequencies of around 2-4 kHz. The current control bandwidth required by an active filter for satisfactory harmonic mitigation is about 2 kHz, which demands the switching frequency to be about 20 kHz. Not only does this decrease the efficiency, but also it raises issues of heat management and disposal. In a typical case, the required power rating of the filter is found to be than that of the drive.

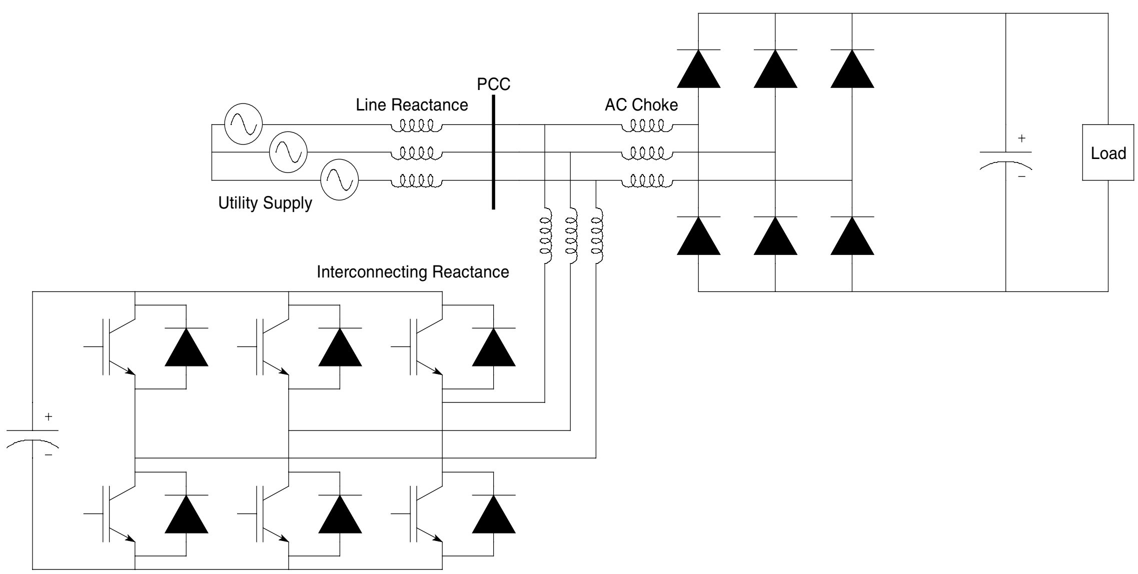


Figure 17. Simplified schematic of a diode bridge rectifier with shunt active filter.

Some of these problems of pure active filters are alleviated by a hybrid approach. In this approach, the required rating of the active filter is made considerably small by adding a passive filter. In turn, the problems associated with passive filter are eliminated with the aid of active filter. There are several forms of hybrid filters. A simplified schematic of a representative topology is shown in Figure 18. This configuration consists of a small series active filter and a shunt passive filter [19]. The rating of active filter is 5% of the load and is controlled to act as a harmonic isolator between the supply and the load by constraining the load harmonic currents to flow into the shunt passive filter. This also prevents supply-load interaction and resonance problems. The harmonic isolation feature reduces the need for precise tuning of passive filters and allows their designs to be insensitive to supply impedance and eliminates the possibility of filter overloading due to ambient loads. In turn, the voltage rating of the active filter is only the harmonic residual voltage. However this solution is not economically viable, because it needs reactive elements along with the active power product. So, although one is successful in keeping the power rating of the filter low, the total cost of a passive filter and a small rating active filter is higher than the cost of drive.

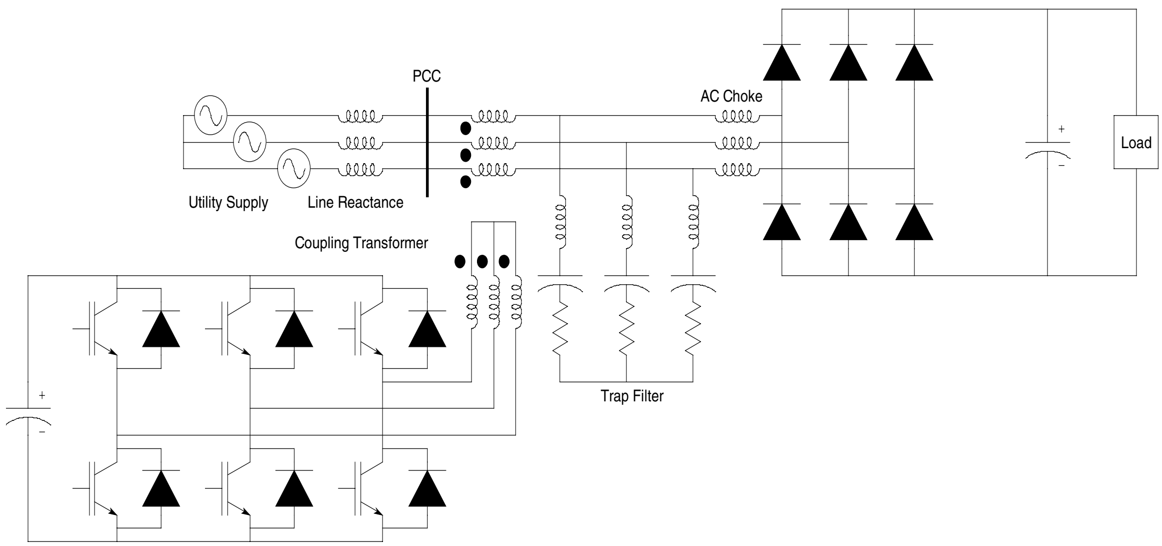


Figure 18. Simplified schematic of a diode bridge rectifier with hybrid active filter.

VII. Solution for the New Millennium: Active Rectifier

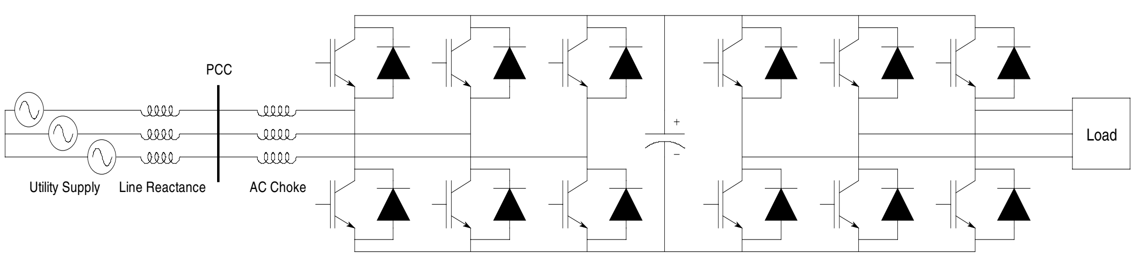


Figure 19. Simplified schematic of an adjustable speed drive with a clean utility interface.

The discussion so far leads to the fact that it is most cost-effective to replicate the inverter in the drive at the utility side and build a back-to-back intertie as shown in Figure 19. Drives with active front end have traditionally been looked upon as regenerative and hence focussed single-pointedly towards markets which demand regeneration exclusively such as elevators and centrifugal pumps. The fact that such drives can also draw unity power factor sinusoidal currents has been treated as a secondary advantage. Moreover, this approach has always been viewed as the most expensive and most complicated solution. Nevertheless, with sufficient control intelligence, one can pose this as a commercially competitive clean utility interface for the adjustable speed drive market.

With growing costs of copper and steel accompanied with ever-decreasing costs of silicon, it is anticipated that it is more attractive to make a semiconductor product than to make reactive elements for a given power range and product volume. Operating principles of active rectifiers, practical design aspects and issues of interfacing them with the utility are discussed in the following section.

VIII. Design and Implementation of the Clean Utility Interface

Figure 20 shows a simplified schematic of the proposed clean utility interface [20]. Seen from the ac supply side, this clean utility interface can be viewed as a synchronous voltage source. At fundamental frequency, the amplitude and phase of the rectifier terminal voltage, for a given dc bus voltage and through modulation index control, controls the power factor to an arbitrary value, including unity. The equivalent circuit and vector diagram is shown in Figure 21. To allow line current control for a given dc bus voltage, the modulation index should usually be set to between 0.8 and 0.9.

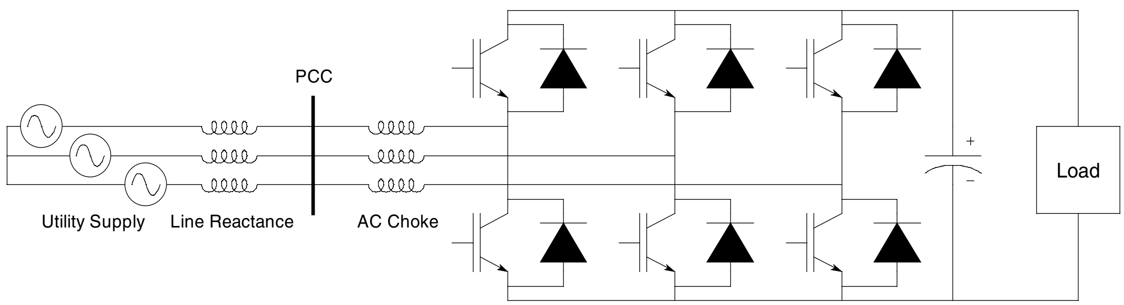


Figure 20. Simplified schematic of the proposed clean utility interface.

In theory, an active front-end rectifier can be used as a reactive power compensator, in addition to serving as a rectifier. This is an additional virtue, since an active rectifier interfaced with the utility can supply reactive currents to other loads connected at the same point of common coupling. This of course, increases the current drawn by the rectifier and hence the amount of reactive power compensation is limited by the absolute power rating of the converter.

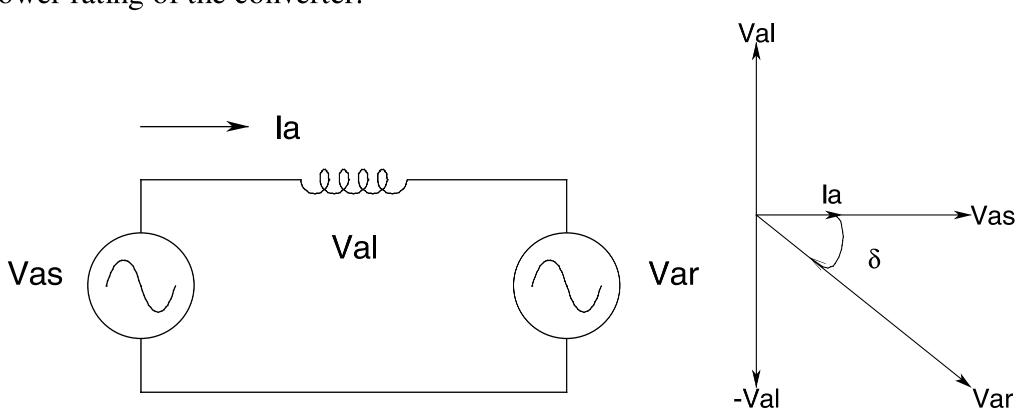
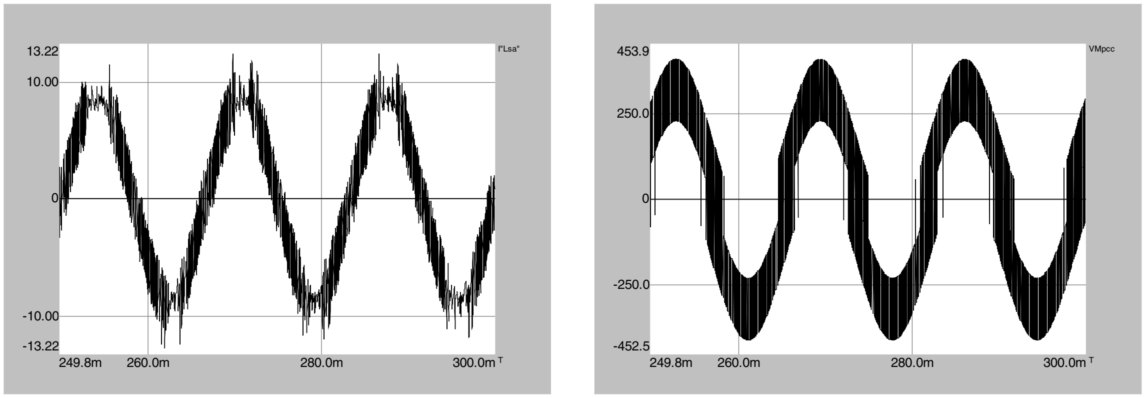


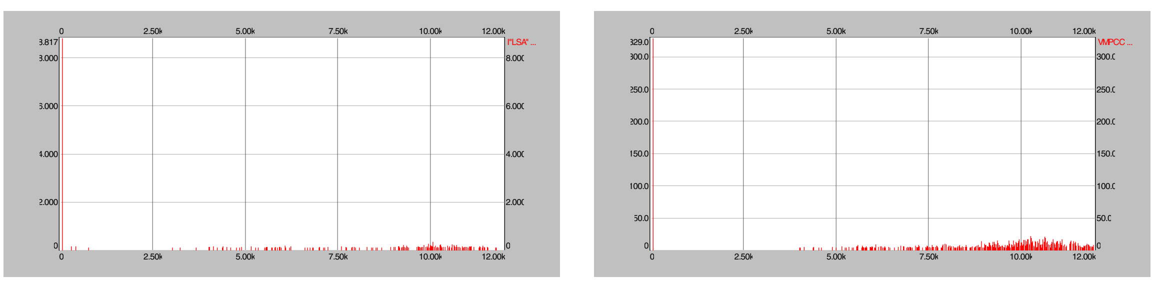
Figure 21. Simplified equivalent circuit and vector diagram for the proposed clean utility interface to obtain unity power factor current.



a) Line Current *b) Line-line Voltage*

Figure 22. Current and voltage waveforms at PCC for the clean utility interface.

A system as depicted in Figure 20 and rated for 230V, 3 HP load is simulated in Simplorer. The value of line reactance is fixed at 1.25% (0.78mH) and the value of ac choke is 3% (1.8mH). The dc bus capacitance is 940 μF and the load resistance is 160Ω. The active rectifier is regulated using hysterisis current control technique in the inner loop and a proportional-integral voltage regulator in the outer loop. The dc bus voltage reference is set at 600V. Figure 22 shows line current and line-line voltage waveforms at the point of common coupling. The corresponding frequency spectra of these parameters are shown in Figure 23. It may be observed that there are no low frequency harmonic components in the current and voltage spectra. However, the voltage at the PCC is quite distorted and composed of non-characteristic frequency components arising due to hysterisis type current control. It is possible to filter these components out using a broadband L-C-L filter in T-configuration connected at the point of common coupling.



(a) Line Current *(b) Line-line Voltage*

Figure 23. Current and voltage spectra at PCC for the clean utility interface.

IX. Conclusions

Operating principles of various front-end options, practical design aspects and issues of interfacing them with the utility are discussed in this document. A brief summary of the reported interface options is tabulated in Table 1.

It is observed that, historically, seeking a harmonic-free interface has been dominated by development in passive solutions such as ac/dc chokes, multipulse configurations and passive filters. Active solutions found their way into this area primarily as compensators for the residual harmonics which could not be cancelled by passive solutions. The approach so far has been a reactive one, where harmonics are generated by the load and a device is developed to cancel the harmonics. The road taken in the clean utility interface is pro-active which when stated simply says, develop a device that does not generate the harmonics in the first place, rather than generating the harmonics and then canceling them. It is important to note that this solution offers a clean utility interface generating near-sinusoidal currents without demanding any ambient network analysis. The technical viability of this approach is verified through computer simulations and extensive prototype testing. A family of products is now commercially available over a wide power range. It is anticipated that this clean utility interface would be more beneficial to the customer even from the commercial perspective when compared with the alternative solutions.

Table 1: Comparison of utility-friendly interface options.

Interface	**Performance**	**Complexity**	**Cost**	**Special Requirements**
AC / DC Chokes	Low	Low	Low	None
Multipulse Configurations	Medium	Medium	Medium	Multiple Rectifiers
Passive Filters	Medium	High	Medium	Network Analysis
Active Filters	High	High	High	Network Analysis
Clean Utility Interface	*High*	*Medium*	*Medium*	*None*

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