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Comparison of Different Common Passive Filter Topologies for Harmonic Mitigation

H. M. Zubi
IET and IEEE member
hz224@bath.ac.uk

R. W. Dunn
IEEE member E-mail
r.w.dunn@bath.ac.uk

F. V. P. Robinson
IET and IEEE member
f.v.p.robinson@bath.ac.uk

Abstract- **This paper will present a performance comparison of different common passive harmonic filters for three-phase diode-rectifier front-ends found in adjustable speed drives. The comparison analyzes and discusses the input power factor, input current total harmonic distortion, rectifier voltage regulation, line voltage unbalance sensitivity, size, energy efficiency and cost The issues related to harmonic-excited parallel or series resonance are addressed, and unbalanced operation performance is investigated. The study is based on detailed analysis and computer simulations.**

Index Terms-- **ASD, broadband, drive, filter, harmonic, power factor, rectifier, THD.**

I. INTRODUCTION

Adjustable speed drives (ASDs) are extensively used for driving induction and permanent magnet motors in variable-speed applications due to the flexible control and high static and dynamic performance possible with such systems. The advantages of modern drives include, low maintenance, high energy efficiency, precise torque and speed control, inherent soft-starting, and the ability to reconnect to a spinning machine. A remaining problem, however, is that the six-pulse diode and thyristor rectifiers that are generally used to provide the DC-bus voltage of ASD inverters injects significant levels of low-order current harmonics (i.e. 5th, 7th, 11th, etc.) into the AC power line. Fig.1 shows the structure of the diode-rectifier front-end commonly used in PWM-VSI AC drive systems [1]. Line-commutated diode rectifiers constitute nonlinear loads and draw non-sinusoidal current from a sinusoidal supply. The typical form of the input line-current waveform and its harmonic spectrum are shown in Fig.2 (a,b). The harmonics have order $2p \pm 1$, where p is the number of ripple pulses in the rectifier output DC voltage. The first four harmonics are dominant (5th, 7th, 11th and 13th). in the spectrum.

Harmonic excited resonances, harmonic-current losses, interference with electronic equipment, line voltage distortion at the Point of Common Coupling (PCC) are typical problems arising from these harmonics; and electric power authorities have already introduced strict regulations to arrest the consequences of these [2], [3]. To comply with the harmonic current limits in regulations, it is now essential to attenuate the harmonics naturally circulated by a rectifier by introducing substantial AC-side filtering.

Rectifier-harmonic filtering techniques are classified as active, passive, and hybrid (passive and active) filtering methods. Among these, the passive filtering methods are the most widely utilized [4], while active filters [5] are still less practicable in many applications due to their higher cost and complexity. A number of of passive harmonic filter configurations exist; and, selecting and sizing a suitable filter for a specific application involves a relatively intricate design comparison, and performance versus cost trade-off [6], [7]. In this work, the extensively used AC-line-reactor filter, single tuned shunt filter, and the recently developed improved broadband filter [8] are investigated and compared in terms of operating performance, size and cost. The operating principle and design rules of the selected filters are reviewed and the performance is evaluated via computer simulations that involve detailed system modeling.

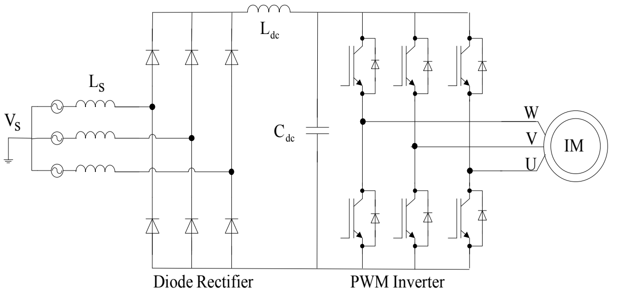


Fig. 1. Diode-rectifier connection within a PWM-VSI AC drive.

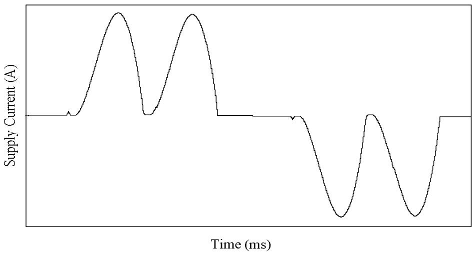


Fig. 2 (a). Typical form of input line-current of a 3-phase diode rectifier.

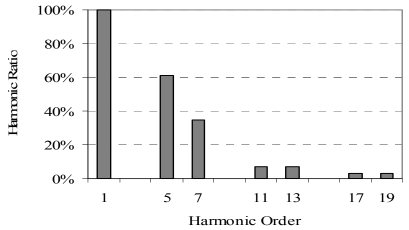


Fig. 2(b). Harmonic spectrum of line-current of a 3-phase diode rectifier.

II. COMMON PASSIVE FILTERS TYPES

Of all the passive harmonic filter options, the AC-side line reactor filter (L_{ac}) is widely used. In this technique, (shown in Fig.3), substantial inductance L_{ac} giving up to 6% voltage drop of the nominal line voltage is inserted in series between the AC line and the rectifier. In this basic filtering method, in addition to reducing the line current Total Harmonic Distortion (THD_I) and improving the current waveform, the filter also provides some protection of the drive from transient overvoltage since line-voltage surges are attenuated. However, the current THD_I performance of the filter is quite limited ($THD_I > 25\%$). In some ASDs, as shown Fig.3, a DC link inductance L_{dc} is inserted between the DC-bus capacitor and the rectifier in order to smooth the rectifier current. As a result, the stress on the DC-bus capacitor is reduced, the in-rush current is reduced, and input current THD_I is decreased. The per-unit inductance used is typically of the order 1-3% which is usually not enough to bring the line current THD_I within an acceptable range of 3-6% L_{ac}.

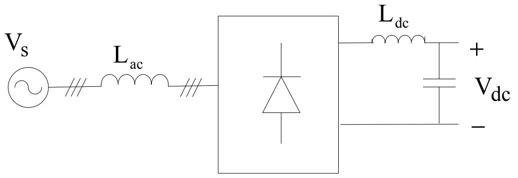


Fig. 3. AC line reactor filter (L_{ac}) and DC link inductance filter (L_{dc}).

In Single Tuned Shunt Filters (STSF), as shown in Fig.4, a series resonant $L_f\,C_f$ circuit is connected in parallel with the rectifier AC line terminals in order to provide a local path to circulate the dominant rectifier harmonic which corresponds to the filter's resonant frequency. Therefore, most of the harmonic current passes through the filter and the line current THD_I decreases. For each dominant rectifier harmonic an individually tuned shunt filter is necessary. The filter resonant frequency is selected with a detuning factor (1 - 5) % of the harmonic frequency in order to avoid filter overcurrents imported from nonlinear loads connected at the same PCC, and to preserve filtering capability when the capacitor value decreases due to aging. For an accurate STSF filter design, a complete study of the power system involved is required.

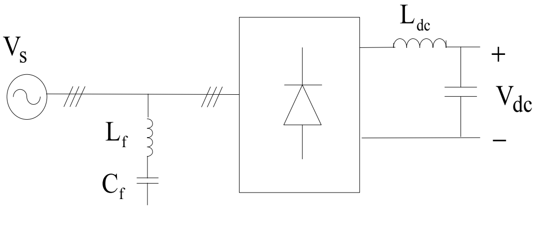


Fig. 4. Single Tuned Shunt filter type

Single Tuned Shunt Filters may draw harmonic currents from other nonlinear neighbor loads connected to the PCC or from the AC grid. To prevent such large harmonic currents from coming to the filter, in most applications 3-6% AC line reactor (L_i) is inserted between the tuned filter terminals and the AC line. Additionally, in order to reduce the size of the tuned filter the dominant rectifier harmonic currents must be reduced. Consquently, 3-6% AC line reactance (L_o) is inserted between the rectifier terminals and the tuned filter. Therefore, the practical single tuned shunt filters configuration shown in Fig.5 is obtained. Seen from the rectifier terminals, the parallel resonant circuit (L_f, $C_f \,\|\, L_i$) will not have a resonant frequency near the dominant rectifier harmonics. To avoid over voltages and over currents due to parallel resonance, filtering must begin from the lowest dominant harmonic and include as many tuned filters as needed for the application. Typically 5th and 7th harmonic tuned filters are utilized together at medium power level below megawatts, and the higher frequency harmonics are either suppressed by a high-pass filter or left without filtering. As a result, the tuned shunt filtering method is more expensive and more complex than the previous type, but also relatively limited in performance.

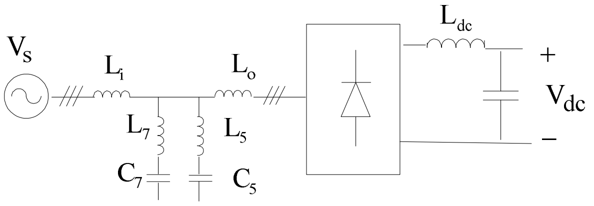


Fig. 5. Single tuned shunt filters for suppressing the 5th and 7th harmonics.

The recently developed Improved Broadband Filter (IBF), although it has similar structure to the Single Tuned Shunt Filters, has a different operating principle and design technique. Unlike STSF that employs a single tuned LC filter for each dominant harmonic to be mitigated, IBF employs only one LC shunt filter per phase and the filter absorbs a broad range of dominant harmonics. The structure of IBF [8], [9] is shown in Fig.6. The inductance L_i that is inserted in series between the rectifier and the AC line is relatively large. Its purpose is to practically provide harmonic isolation between the AC grid and the rectifier. Due to the large L_i value, voltage harmonics of the AC line or current harmonics of other loads connected at the PCC can not have an effect on the ASD. Neither do the current harmonics of the rectifier flow to the AC line or other neighboring loads. The smoothing filter L_o aids in reducing the rectifier current harmonics. The tuning frequency of the shunt filter ($L_f\,C_f$) is between the 5th and 7th harmonic and the performance is not significantly dependent on it. The filter should be designed such that at the dominant harmonic frequencies the L_i path has higher impedance than the $L_f\,C_f$ path. Thus, the dominant harmonics are absorbed by the shunt filter and the filter functions on a broad range of harmonics. The filter acts as low-pass filter to the fundamental component and the active power transfer takes place between the rectifier and the AC line. The filter capacitor provides reactive power compensation at the fundamental frequency (50Hz) so that the Power Factor (PF) at the AC line terminals is near unity at all load operating conditions. The design of IBF involves meeting several criteria. The line current THD, line PF, and the output voltage regulation are the key input parameters in design. Detailed design methodology and performance study of IBF is provided in [10].

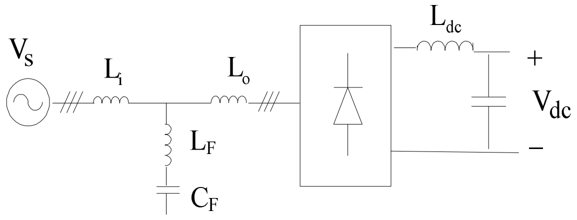


Fig. 6. Improved broadband filter.

III. FILTER SIZING

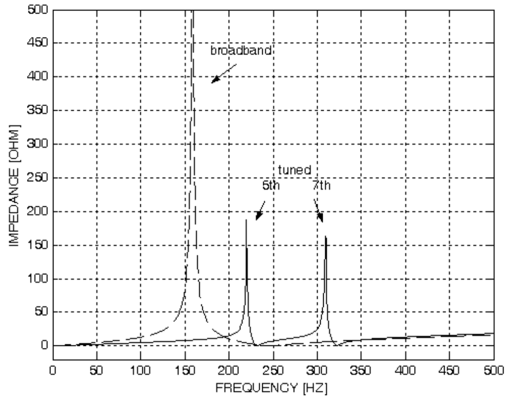
The filter performance requirements are specified once the ASD application requirements are known,. Generally, in the filter design, the input PF, input current THD_I, filter energy efficiency, and output voltage, all at full-load, are the key performance variables. The input PF, input current, and output voltage at no-load may be additional variables depending on the filter type. Along with these performance criteria comes the cost and size criteria which significantly affects the decision regarding the filter type selection. Given the filter performance criteria, filter parameters that meet the performance criteria should be selected and the filter built and tested. Depending on the filter type involved or the designer's background, the design may be carried out using an analytical formula approach, by means of detailed computer simulations of the whole system, looked-up from knowledge-based parameter tables, or more heuristically by trial and error.

In this work the filter parameters of L_{ac} are taken as standard 3% AC-line reactors. When applying L_{ac}, an additional 2% DC-link inductance is employed in order to increase the effectiveness of filtering. The DC link inductance is usually included inside commercial drives in particular at higher power ratings. The filter parameters of STSF are selected as follows: L_i is selected as 6% and L_o as 3%. The shunt filters are tuned to the 5th and 7th harmonics with a detuning factor of 4% and the capacitors are sized, such that at full-load, unity PF is obtained at the line side. IBF parameters are analytically determined and the design meets the highest possible power quality performance [10]. The filter parameters for a 5.5 kW example are shown in Table I. The given filter parameters can be used to compare STSF and IBF filtering techniques. The frequency domain analysis of the filters performance reveals some important results regarding the performance of the improved broadband filter and single tuned shunt filters.

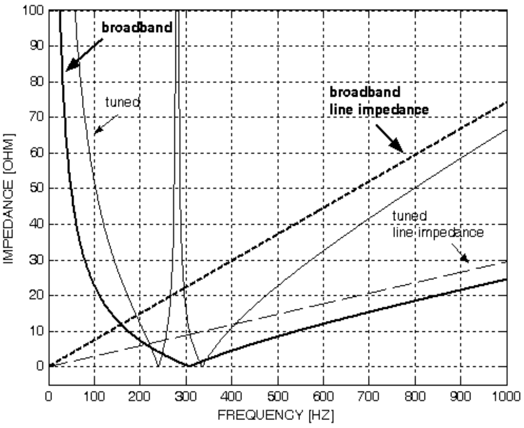
TABLE I
FILTER PARAMETERS FOR DIFFERENT ASD FILTERS
(P =5.5kW, Units: L: mH, C: µF (Δ))

L L_{ac}		**STSF**		**IBF**	
L_{ac}	2.30	L_i	4.60	L_i	10.1
L_{dc}	1.50	L_o	2.30	L_o	3.10
		L_5	29.6	L_f	8.10
		C_5	4.94	C_f	16.6
		L_7	18.5	L_{dc}	1.50
		C_7	4.04		
		L_{dc}	1.50		

Fig.7(a) shows the filter impedance characterisitcs seen from the rectifier side. The parallel resonance frequency of the broadband filter is slightly above 150 Hz; and, in the dominant harmonic frequency, range both filters have similar low impedance values. However, looking at the shunt filter path of the improved broadband and the tuned filters shown in Fig.7(b), reveals the fact that the broadband filter has a higher impedance ratio compared to the tuned filter.



(a)



(b)

Fig. 7.(a): Tuned and IBF output impedance characteristics, (b): tuned and IBF shunt impedance versus line impedance characteristics.

In the single tuned shunt filter, although the impedance at the tuning frequencies is lower than the broadband filter, the relatively small line-side reactance provides a low impedance path and a significant amount of harmonic current leaks to the AC line. If the tuning frequency increases and drifts from the characteristic harmonic frequency, the performance of the tuned filter degrades further. However, in the improved broadband filter, the line-impedance ratio is higher and most of the characteristic harmonics are trapped in the broadband filter *LC* parallel filter path (L_f, C_f) and a little amount of harmonics leak to the AC line. With the input inductance (L_i) filter behaving as band-stop filter to the rectifier harmonics, the line current THD_I is significantly lower than the comparably sized tuned filter. Also important is the possibility, albeit low, of parallel resonance with other loads connected to the point of common coupling. While the broadband filter exhibits only one resonance point slightly above the third harmonic (which is highly unlikely to be excited), the tuned filters may fall into resonance with 5th, 7th harmonic sources in the power network, hence a greater harmonic-excited resonance hazard exists.

IV. COMPUTER SIMULATIONS

With the filter parameter values selected as in Table I, the performance of the considered filters is evaluated in detail via computer simulations utilizing Ansoft-Simplorer [11]. The filter line-current THD_I, line-side PF, filter output voltage regulation (variation from no load to full load), DC-bus voltage, the filter efficiency, sensitivity to line voltage harmonic distortion and line-voltage unbalance are all investigated.

The line impedance is assumed to be negligible compared to the filter inductances. A line-voltage harmonic distortion of 3% is modeled. In the simulations all the filter inductors are designed to have 99% efficiency and the capacitor filters are assumed to have 99.5% efficiency. Thus, their models include an equivalent series resistor of appropriate size. The simulation involves a six-pulse diode rectifier with large DC-link capacitor, and a resistive load that emulates the steady-state behavior of a system consisting of an inverter and motor load. The capacitor size is selected the same as that of a general purpose commercial drive.

The filters are evaluated for 5.5kW ASD power rating and the performance results are summarized in Table II. The steady-state line current THD_I, line PF, efficiency, DC-bus voltage at full-load are all listed in the table. In addition, the no-load to full-load filter output voltage variation in percentage (filter output voltage regulation) are also listed in the table. As the table indicates, the line current THD performance of IBF is superior to all. While the L_{ac} solution is unsatisfactory in terms of IEEE-519 compliance, STSF exhibits ordinary performance. In terms of PF, both IBF and STSF are superior to L_{ac}. The DC-bus voltage of IBF is slightly (4%) higher than the alternatives and this is not considered as a drawback. Although they involve more components than the L_{ac} both STSF and IBF provide acceptable efficiency. In particular IBF has sinusoidal current (at the fundamental frequency) on L_i and the rectifier current harmonics are suppressed via L_o and L_f–C_f such that the harmonic losses are reduced.

TABLE II
STEADY-STATE PERFORMANCE OF FILTERS FOR 5.5KW ASD UNDER CONDITIONS OF 3% LINE-VOLTAGE THD

Filter Type	THD_I (%)	Power Factor	V_{dc}	η(%)	ΔV_o(%)
L_{ac}	36	0.92 lagging	501	>99.5	0.6
STSF	11.6	0.99 lagging	496	>99.0	2.5
IBF	6.0	0.98 leading	515	>99.0	3.1

Simulation waveforms for the considered power rating and the selected filtering techniques give a clear performance comparison. Fig. 8 shows the full-load line-side distorted current and supply voltage waveforms for the 3% L_{ac} filter. The STSF full-load line and rectifier current waveforms are shown in Fig. 9 with better reduction in THD_I value, while the full load line current and supply voltage waveforms are shown in Fig. 10.

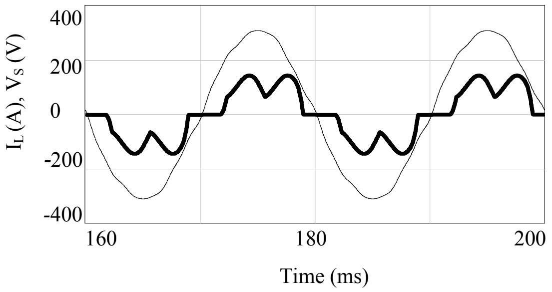


Fig. 8. Full-load line-current (I_L) **(bold)** and supply voltage (V_S) simulation waveforms for 5.5kW ASD system utilizing 3% L_{ac} filter (current scale: 10x).

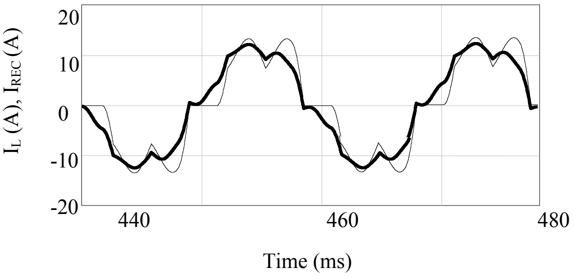


Fig. 9. Full-load line current (I_L) **(bold)** and rectifier current (I_{REC}) simulation waveforms for 5.5kW ASD system, utilizing 5th and 7th tuned filters.

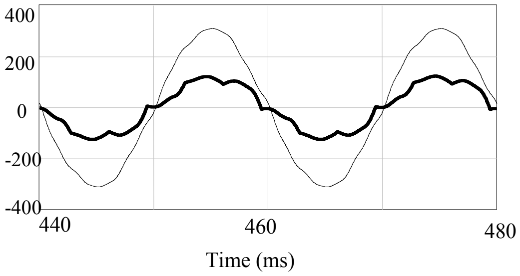


Fig. 10. Full-load line-current (I_L) **(bold)** and supply voltage (V_S) simulation waveforms for 5.5kW ASD system utilizing 5th and 7th tuned filter (current scale: 10x).

The improved broadband filter simulation waveforms show the superior performance of the filter compared to the previous waveforms for the other filters. Fig.11 shows the full-load line and rectifier current waveforms presenting a significant improvement in the line-current shape compared to the distorted rectifier current waveform. The full-load line-current and supply voltage waveforms, representing nearly unity power factor, are shown in Fig. 12.

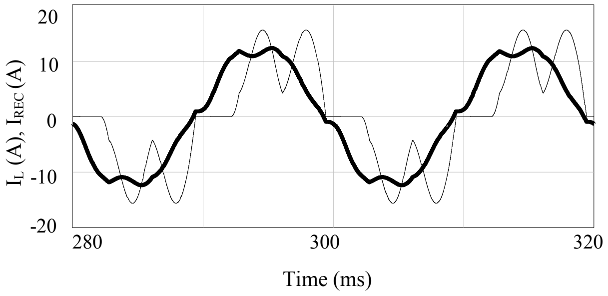


Fig. 11. Full-load line-current **(I_L) (bold)** and rectifier current (I_{REC}) simulation waveforms for 5.5kW ASD system utilizing IBF filter.

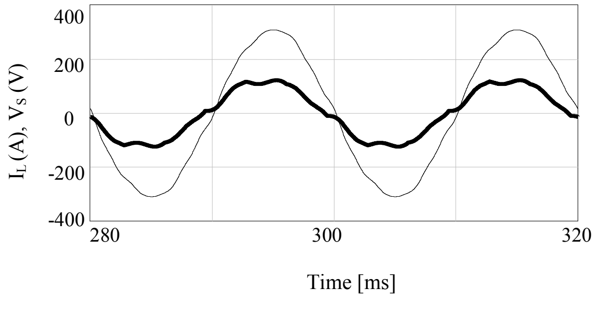


Fig. 12. Full-load line current I_L (**bold**) and supply voltage V_S simulation waveforms for 5.5kW ASD system utilizing IBF filter (current scale: 10x).

AC line-voltage unbalance results in filter-performance degradation and both the DC-bus voltage and AC line-current contain uncharacteristic harmonics. The line current may include a third-harmonic current while the DC-bus voltage contains even harmonics. However, the degree of degradation is strongly dependent on the filter type. The full-load operating performance of the 5.5kW rated ASD under 2.5% line-voltage unbalance (phase "1" voltage magnitude is reduced by 5%) is summarized in Table III. As the table indicates, the line-current THD increases from 36% nominal value to 46.6% with the 3% L_{ac}, The shunt tuned single filter also experiences nearly the same amount of distortion increase. On the other hand, IBF has the best performance of all. Both the line-current THD and DC-bus voltage ripple increase minimally. Additionally, the line-voltage harmonic distortion has minimal effect on the IBF based system, while in STSF the small L_i results in importing line-current harmonics to the shunt branch of the filter and increasing the distortion, the losses and stresses on the shunt filter elements. Therefore, it can be concluded that due to large L_i, IBF is insensitive to line voltage unbalance and harmonic distortion, while others are highly sensitive to both.

TABLE III
FULL-LOAD PERFORMANCE OF 5.5 KW ASD FILTERS UNDER CONDITIONS OF 2.5% LINE-VOLTAGE UNBALANCE

Filter Type	**THD_I (%) Balanced**	**THD_I (%) Unbalanced**			**ΔV_{dc} (%)**
		Phase 1	Phase 2	Phase 3	
L_{ac}	36	45.16	46.59	31.39	3.2
STSF	11.6	13.13	14.78	11.72	1.3
IBF	6.0	6.57	6.71	6.40	1.0

V. PERFORMANCE COMPARISONS

The overall performance of the candidate filters are qualitatively evaluated and the results are summarized in Table IV. The table illustrates that the L_{ac} approach is ineffective in terms of meeting the modern power quality requirements (less than 10% line current THD and near unity PF). Thus, applications requiring high input power quality via passive filtering must involve STSF or IBF. Detailed comparison between the two, clearly favours the IBF approach for a number of reasons. As the size, complexity and cost are comparable in both methods, the determining factor becomes the performance of the filter. From this point of view, the IBF approach is clearly superior to the STSF approach due to the fact that the line-voltage disturbances and unbalances do not degrade the filter performance and the harmonic-resonance risk is non-existent in IBF. Furthermore, implementing the IBF design is an easier task and the line-current THD is significantly better than for the STSF.

However, the no-load line current of IBF is nearly 50% of the full-load line current with zero PF, and at no-load the filter gives a considerable amount of reactive power to the AC line. This may create performance problems and result in large reactive-power-bills in some installations. However, from 50% load to nominal load the IBF PF is high and THD is very low. In ASD applications involving low duty-cycle operation or frequent light-load range operation, the passive filtering approach (including IBF) is not viable and a different filtering technique become obligatory.

TABLE IV
QUALITATIVE COMPARISON OF COMMON PASSIVE FILTERS

Filter Type	**3% L_{ac}**	**STSF**	**IBF**
Total Harmonic Distortion	High	Low	*Lowest*
Voltage Regulation	Low	Low	Low
Voltage Unbalance Sensitivity	Yes	Yes	*No*
Power Factor @ full-load	Low	High	High
Power Factor @ no-load	Not an Issue	Low	Low
Cost	Low	High	*Medium*
Size	Small	Large	Large
Structure Complexity	Low	High	*Medium*
Efficiency	High	Medium	Medium
Harmonic Resonance Risk	No	Yes	*No*

VI. CONCLUSIONS

In this work, the performance of different passive harmonic filters for off-line three-phase ASDs, using diode-rectifier front-ends, have been studied and compared. The study discusses filter design and presents performance evaluation by means of analysis and computer simulations. In the study, the line-current THD_I and PF characteristics along with rectifier output voltage regulation, filter energy efficiency, DC-bus voltage regulation have been evaluated. The influence of the line-voltage harmonics and the line-voltage unbalance on the filter and ASD performance have been studied. Finally overall filter performances are compared and the superior overall power quality performance of IBF is illustrated and its application fields determined. The results of the study will aid the selection of the best harmonic filter for a specific ASD system application.

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