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Optimizing Broadband Harmonic Filter Design for Adjustable Speed Drive Systems

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Keywords

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Abstract

A novel design method of the improved broadband harmonic filter for diode rectifier type adjustable speed drives using genetic algorithm is presented. The design yields high input and output power quality while reducing the filter size, cost and avoiding resonance problems. Results are illustrated using computer simulations and laboratory experiments.

Introduction

AC motors in various industrial variable speed applications are usually driven by adjustable speed drives (ASDs) [1]. However, the 6-pulse diode/thyristor rectifiers converters utilized in the ASDs pollute the AC power line with the dominant harmonics. These harmonics are causing well known problems. Electric power utilities have, consequently, introduced obligatory controlling harmonic standards in an attempt to limit the adverse harmonics effects [2], [3]. Therefore, economical, efficient, and reliable harmonic filters are always indispensable to mitigate harmonics.

Types of rectifier harmonic effective filtering methods are active, passive, and hybrid filtering methods. Active filters are still avoided in many applications due to their high cost and complexity [4]. Passive filtering is the most widely employed method [5], [6]. Among passive filters, only the shunt tuned and broadband filter structures yield high power quality and allow systems to meet recent standards. Since tuned filters carry the risk of forming a lightly damped resonant circuit, their application requires a relatively high degree of expertise. In contrast, the recently developed broadband harmonic filters are free of both the harmonic resonance risk and structural complexity and can comply with standards. In particular, the lately developed improved broadband filter (IBF) has advanced overall performance and its applications have been increasing rapidly. However, with several power quality requirements and filter efficiency, cost and size requirements, the design process for determining the IBF parameters is complex. Currently, only one linear optimization searching method for the filter parameters was introduced in [7], [15]. Instead such traditional optimization methods utilizing a step-by-step searching algorithm that locates the local optima, genetic algorithms (GAs) can give global optima with the ability of parallel searching through the entire solution space. Using GAs, designers can quickly find optimal parameter values that comply with power quality standards. Simultaneously, GAs are able to handle many constraints at once, which is rarely achievable with other algorithms [8], [9].

In this work, a novel design algorithm using GAs is used to find the optimal power quality indices that can be obtained while minimizing the filter size and avoiding resonance. The method is applied to ASDs of different power ratings and based on frequency domain modeling of the system. Finally, the

performance of the ASD using IBF is assessed and its superior performance is proven through detailed computer simulations and laboratory experiments.

Filter operating principles

The basic LC broadband filter has a simple structure utilizing large components and is free of the harmonic resonance problem [10]. Nevertheless, at no-load, the filter output voltage increase dramatically, which may cause system failure [11]. In addition, leading power factor exists at all load conditions. Actually, the LC broadband filter is utilized along with a buck transformer in order to reduce the filter output voltage which increases cost and size. To overcome the LC broadband filter deficiency, the improved broadband filter (IBF), shown in figure 1, has been developed to eliminate the basic LC filter problems [12], [13]. As shown in figure 1, splitting the individual inductor of the simple LC broadband filter into two elements (L_i and L_f) and adding a smoothing reactor (L_o) the filter input to output performance is changed. Damping resistor R_d is connected to damp the over voltages and over currents during line side switching transients.

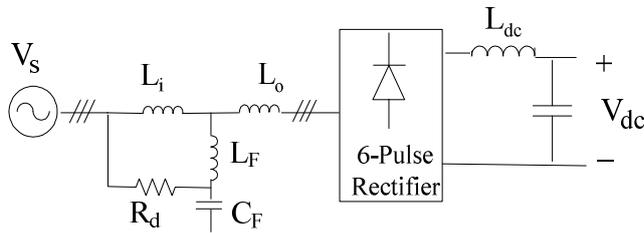


Fig. 1: Improved broadband filter circuit diagram

Through a suitable design, with respect to the shunt filter impedance, high impedance is provided by the large input reactor (L_i) over a broad frequency range and presents a high impedance ratio. As a result, the shunt filter will attract all rectifier current harmonics. L_i also diminishes the effect of the line voltage harmonics on both, the shunt filter and the rectifier. The parallel resonant frequency (f_p) is selected such that harmonic resonance overvoltage stresses are avoided. Therefore, f_p value ranges between the fundamental frequency and the 5th harmonic (the first dominant rectifier current harmonic). The parallel resonant frequency (f_p) is defined as:

$$f_p = \left(\frac{1}{2\pi}\right) * \left(\frac{1}{\sqrt{(L_f + L_i)C_f}}\right) \quad (1)$$

The filter capacitor C_f improves the input power factor while L_f is partitioned with L_i avoiding overvoltage at the rectifier terminals at no load. The very low series impedance provided by filter components L_f and C_f to the dominant rectifier current harmonics short circuit them through its path. The series resonant frequency (f_s) is defined as:

$$f_s = \left(\frac{1}{2\pi}\right) * \left(\frac{1}{\sqrt{L_f C_f}}\right) \quad (2)$$

To reduce harmonic current/voltage stresses exist on the shunt branch components, current smoothing output reactor (L_o) is utilized. This makes the rectifier current waveform less discontinuous, resulting in lower current harmonics and leading to smaller, lower cost filter structure.

Filter design method

The IBF parameters need to be determined in the design process are (L_i , L_o , L_f , C_f , and R_d). Filter efficiency, cost and size along with various power quality requirements limit the design. Therefore, the design procedure is a difficult task. The power quality constraints considered in the design are the

input current Total Harmonic Distortion (THD_I), input power factor (PF), and filter output voltage regulation (ΔV), which are all defined as:

$$THD_I = \sqrt{\left(\sum_{n=2}^N I_n^2\right)} / I_1 \quad (3)$$

where I₁ is the rms line-current fundamental component and I_n terms are the rms line-current harmonic components.

$$PF = (I_1 / I) \times DPF \quad (4)$$

where I₁ is the rms line-current fundamental component, I is the rms line current and DPF is the displacement power factor.

$$\Delta V = (V_{NL} - V_{FL}) / (V_{NL}) \quad (5)$$

where, V_{NL} is the no-load filter output voltage and V_{FL} is its full-load value, both fundamental frequency and rms values.

In the design, the first parameter L_o is selected as 4% reactor.

$$L_o = 4\% \left(\frac{V_{LL}^2}{\omega_e \times P} \right) \quad (6)$$

In the above equation, ω_e is the line radial frequency. V_{LL} and P are the rated line-to-line voltage and power respectively. With this choice, the rectifier full-load current waveform becomes well defined (practically its shape is independent of power ratings). Therefore, the dominant harmonic current components (I₅, I₇, I₁₁ and I₁₃) ratios of the rectifier current fundamental component can be approximated to 34%, 9.5%, 7% and 3.5%, respectively. Closed form formula computation of the remaining filter parameters (L_i, L_f, C_f, and R_d) based on the power quality indices THD_I, PF and ΔV involves very complex mathematics (if possible at all). On the other hand, calculating the filter performance indices using some mathematical models is achievable if initial filter parameters are offered. Then filter parameters solution space can be scanned efficiently to find the optimized performance indices. Due to the nature of the design problem, previously explained, the GA optimizing searching method is utilized.

Genetic algorithm

Genetic Algorithm (GA) utilizes a stochastic global search method and differs substantially from traditional search and optimization methods. The GA is a search mechanism based on the principle of natural selection and population genetics. An increasingly better approximation of the desired solution can be produced by applying the principal of survival of the fittest. In each generation, a new set of approximations of the solution are chosen according to fitness evaluation. The more 'fit' the approximation is, the higher likelihood it has to be selected to reproduce the next generation by using operators borrowed from natural genetics. Thus, the population of solutions is improved from one generation to the next with respect to their fitness evaluation. So, the least fit individuals are replaced with new offspring, which come from a previous generation, and which are better suited to the evolution of the environment.

The Genetic Algorithm used in this work involves several steps. In the first step, a set of possible random solutions is created or initial solutions range can be specified. Every solution in the population

(which can also be called an individual or a chromosome) is represented by a string of numbers that in turn represent the number of variables in the problem. Every variable is encoded in a suitable coding format (binary, integer, etc.). In the second step, every chromosome is applied to the fitness function (also called the objective function) to produce an output of fitness values. In accordance with their fitness values a probabilistic technique, such as the Roulette Wheel [8], is used to select the chromosomes that will contribute to the production of the next generation. The reason for this selection process is to keep the best and most fit chromosomes and increase the number of their offspring in the next generation, eliminating the least fit chromosome. Having selected the parents, the crossover process then takes place by the exchange of genetic information between the selected chromosomes in order to form two new chromosomes (also referred to as children or offspring). This helps to avoid sticking in local optima. In order to ensure that GA will search different zones of the search space, a mutation is applied by randomly selecting and changing the structure of a limited number of chromosomes. This process is repeated until all solutions converge into one optimum solution.

Problem Formulation

The main goal of this optimization problem is to design the improved broadband filter that yields optimal system power quality indices, small filter size and minimal harmonic resonance problems. The power quality indices considered in this optimization problem are THD_i, PF and ΔV. The use of these factors facilitates obtaining a design with acceptable filter parameters. The main filter elements which dominate the design size and performance of the IBF are the inductances L_i, L_f, and the capacitance C_f.

Chromosome Encoding and Selection

As mentioned before, the values of the inductance L_i, L_f, and the capacitance C_f play a very important role in the design of the improved broadband filter and ASD system performance. Therefore, they are considered in the structure of the chromosomes used in this optimization problem.

0 0 1	1 1 0	1 0 0
L _i	L _f	C _f

Fig. 2: Chromosome arrangement utilized in GA.

As seen in figure 2, the number of variables in each chromosome represents the values of the line inductance L_i, and filter inductance L_f, and the filter capacitance C_f, respectively.

Crossover and Mutation

The crossover method used in this study is a single point crossover. Different values of crossover fraction, varied from 10% to 100%, and mutation rates from 1% to 10% have been used in this research project to compare the performance of the proposed GA program. A range of population sizes from 50 to 200 and different numbers of generations varied from 100 to 700 were utilized. A relatively wide range of GA operators was initially used until experience was gained observing their effects. It was found that an appropriate mutation rate will speed up the evolution process and shorten the searching time of GAs. High crossover fractions (80%) and low mutation rates (2%) achieve the best convergence. These GA operators are applied to 200 generations with 100 populations for each generation. In modern computers, this computational requirement is completed in a few seconds.

Fitness Function

The objective of the fitness function illustrated by (7) in the proposed GA program is to find out the minimum line current THD_i, the maximum line PF and minimum output voltage regulation ΔV.

$$Fitness = THD_i + (PF)^{-1} + \Delta V \quad (7)$$

Every chromosome in the current generation will be examined by the above fitness function. To calculate the filter performance indices (THD_i, PF and ΔV) in the fitness function via some mathematical models, an accurate design method is required.

ASD System Modelling Method

The assessment of the filter performance indices, THD_i, PF and ΔV will be through an accurate modeling method for a given set of parameters L_i, L_f, C_f given by the GA solution. This involves utilizing highly accurate filter-ASD system frequency domain equivalent circuits and evaluating the filter performance. Thus, precise model of the drive system is required. For steady state performance analysis, the frequency domain model of the total system is established. At steady state, depending on the frequency considered, the ASD is modeled with equivalent impedance or current source elements. The ASD is reflected to the AC side of the rectifier as an R-L impedance circuit in the 50Hz model of the system at full load, as shown in figure 3(a). The drive is modeled with an equivalent DC resistor as the DC bus capacitor is typically very large and decouples the inverter dynamics from the rectifier side. This DC resistor, DC bus capacitor, and rectifier are all reflected to the filter side as the equivalent load resistor (R_L) and load inductor (L_L). Assumptions such as lossless filter and terminal filter voltage is equal to the nominal voltage are performed to find the equivalent resistor value. Load inductor L_L which has been found empirically presents the rectifier bridge commutation effect and output voltage drop [15]. Figure 3(b) shows the harmonic model of the system at full-load. These R_L and L_L reflected parameters are defined as follows:

$$R_L = \left(\frac{V_{LL}^2}{P} \right) \quad (8)$$

$$L_L \cong (L_i + L_o) \quad (9)$$

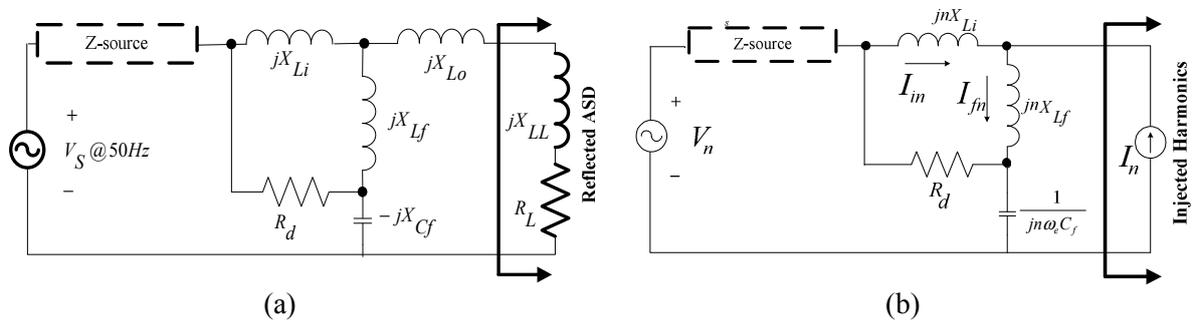


Fig. 3: Full-load model of the ASD system (a) fundamental frequency, (b) harmonic frequency

The full-load equivalent circuit can also be utilized for no-load system modeling by setting R_L larger than the shunt impedance by an order of magnitude. The full-load fundamental-frequency current value is calculated as follows.

$$I_1 = \left(\frac{V_{LL}}{\sqrt{3}R_L} \right) \quad (10)$$

In the harmonic equivalent circuit of figure 3(b), the rectifier side is modeled with a harmonic current source and the grid is represented with a harmonic voltage source. The grid voltage harmonics are selected depending on the utility grid properties. Knowing the rectifier current harmonic ratios, the harmonic currents are found by multiplying the harmonic current ratio with the fundamental component current. For each harmonic frequency, the effect of the line-voltage harmonics and rectifier-current harmonics on the circuit is found by superposing the magnitude (pessimistic approach) of the resulting voltages (or currents). The simplified approach yields satisfactory results.

Substituting the nonlinear behavior of the rectifier bridge by linear circuit elements and sources allows closed form calculations and analysis to be done for the system steady-state equivalent circuit. With all the parameters defined, the circuit can be completely analyzed and its performance can be predicted. Transient conditions investigations of the system for defining damping resistor R_d selection criteria are explained in [7].

Genetic algorithm results

For given power system parameters (supply voltage, frequency, impedance... etc.) and ASD ratings, based on the system equivalent circuits proposed, the filter component values for L_i , L_f , and C_f are initially proposed in a GA MATLAB M-file based computer program [14]. As the GA usually do not quickly achieve the global optima unless suitable initial values are set, the preliminary range of each filter parameter values is estimated by a linear parameter increment approach utilized in [7], [15]. The M-file program implements the closed form derived formulas to calculate the impedances, voltages, and currents at the required harmonics frequencies. Once these fundamental variables are calculated the program can efficiently find the performance indices (THD_I , PF, ΔV) using equations (3), (4) and (5). Based on the performance obtained, every set of solution in the current generation will be checked by the fitness function. The filter parameters are varied and the system performance indices are calculated until the objective of the fitness function is met with appropriate convergence. For a 5.5kW ASD system, figure 4 shows that the optimized solution is obtained in generation number 43 and the whole population ultimately converges toward the optimized solution. Similar figure is obtained for the 55kW ASD system.

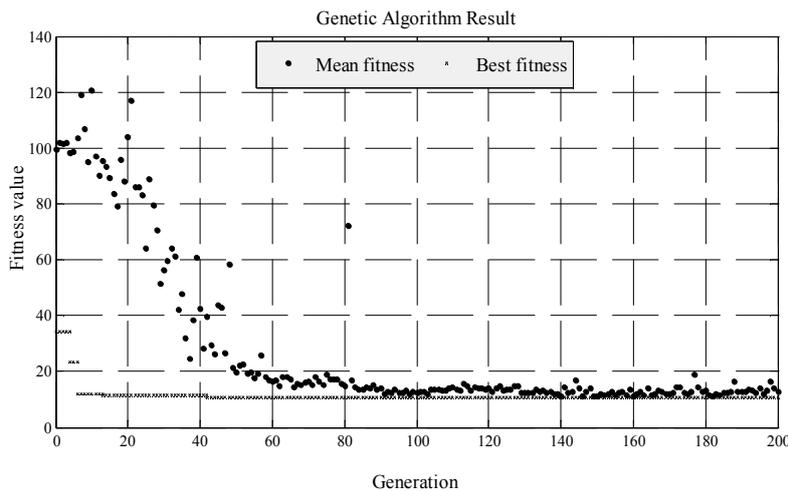


Fig. 4: Best and mean fitness function values in GA for 5.5kW ASD system.

The corresponding 5.5kW and 55 kW ASD power rating filter parameters obtained are shown in tables I and II. The resultant parallel resonance frequency (f_p) value for both cases is 167Hz and 164Hz, respectively. This shows that the harmonic resonance problem risk is negligible for the system.

System performance evaluation

The proposed design method was evaluated for ASDs of various power rating. A practical 3% THD_V utility line voltage value was considered. The source impedance (Z_s) was negligible compared to the input inductance (X_{L_i}). Best fitness value involves system power quality indices of line current $THD_I < 6.5\%$, line PF > 0.98 and filter output voltage regulation $< 3.2\%$ for both 5.5kW and 55kW power ratings. For the same power quality indices criteria applied to the linear searching method [15], filter parameters obtained have higher values. The filter parameters obtained with both methods for 5.5KW and 55kW power rating ASDs are shown in table I and table II, respectively. Reductions of (5-15) % in the input inductance (L_i) and (15-21) % in filter capacitance (C_f) have been achieved. The filter capacitor reduction is very effective in improving the system power factor characteristics, reducing

output voltage regulation from no-load to full-load, and reducing the IBF size and cost. However, the filter inductance (L_f) has increased to keep the series resonance frequency (f_s) within its desired and effective values. Even though, L_f is still less than L_i and is carrying only the harmonic current components while L_i is carrying the full line current. Therefore, a reduction in L_i is crucial and results in smaller filter size and cost. Tables I and II allow a comparison between the performances of the two searching methods. As the tables indicate, the GA algorithm is capable of finding smaller filter components that will achieve better power quality indices.

Table I: IBF Component values and performance comparison for 5.5kW

Searching method	L_i (mH)	L_f (mH)	$C_{f\Delta}$ (μ F)	THD _I (%)	PF	ΔV (%)
Linear	10.6	6.0	21	6.75	0.96	3.75
GA	10.1	8.1	16.6	6.5	0.99	3.0

Table II: IBF Component values and performance comparison for 55kW

Searching method	L_i (mH)	L_f (mH)	$C_{f\Delta}$ (μ F)	THD _I (%)	PF	ΔV (%)
Linear	1.138	0.598	208	6.5	0.95	4.0
GA	0.99	0.75	180	6.0	0.98	3.2

With the filter parameters being determined, the IBF performance characteristics are obtained based on detailed computer simulations utilizing Ansoft-Simplorer [16]. The performance analysis of the IBF based ASD system considered balanced and distorted utility (with 3% THD_V). The parameter values of the improved broadband filter (IBF) for the 5.5 kW and 55 kW, shown in tables I and II, are utilized. The equivalent series internal resistances for the filter reactances are estimated using equation 11, by assuming 99% AC reactors efficiency (their VA rating defines their nominal power that passes through them).

$$R_{intL} = \frac{1\% (V_{LR})}{I_{LR}} \quad (11)$$

where V_{LR} and I_{LR} are the reactor rated voltage and current rms values.

The filter capacitor series internal resistance value is calculated from the product data sheet information. These parameters are implemented in the simulation circuit, shown in figure 5, for all the power ratings considered. Based on the data of the recent industrial products, the ASD system DC link capacitor, precharge resistor, and load parameters are given in Table III.

Table III: ASD parameters for various power ratings

P_R (kW)	L_{dc} (2%) mH	$R_{precharge}$ (Ω)	C_{dc} (mF)	R_{load} (Ω)
5.5	1.5	20	1.0	49
55	0.152	2.0	10	4.9

For the 5.5kW ASD system, the full-load line current and rectifier current simulation waveforms are shown in figure 6, the full-load line current and voltage supply simulation waveforms are shown in figure 7. The line current has a 5.5% THD_I value and the line power-factor is 0.987 leading at full-load conditions. These results are in close correlation with the equivalent circuit based estimation method results shown in table I. They also verify the accuracy of the parameter determination method.

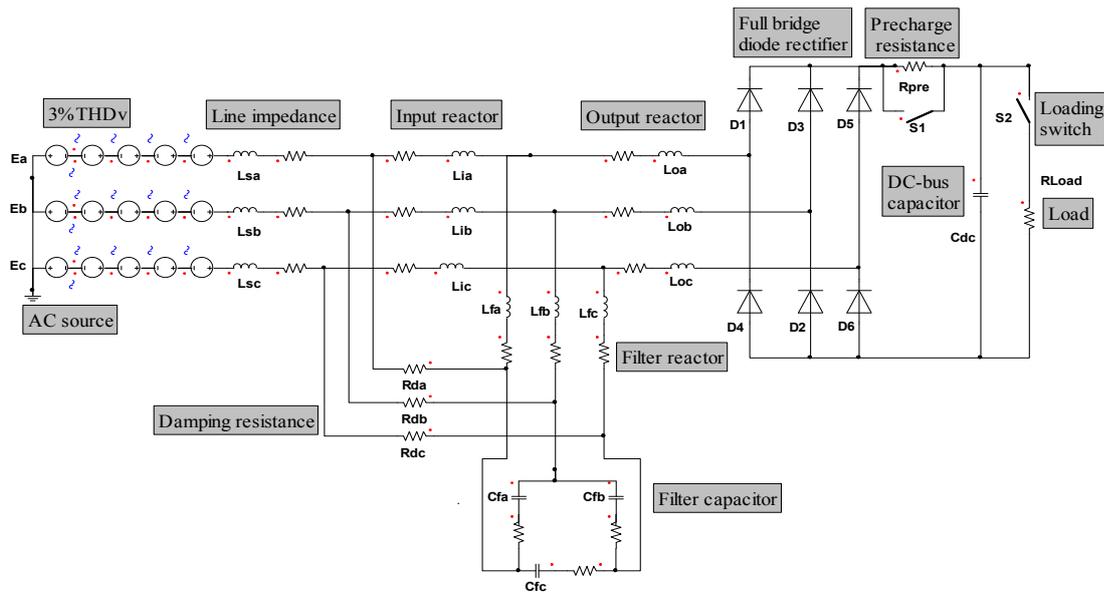


Fig. 5: Simulation circuit for ASD system utilizing IBF.

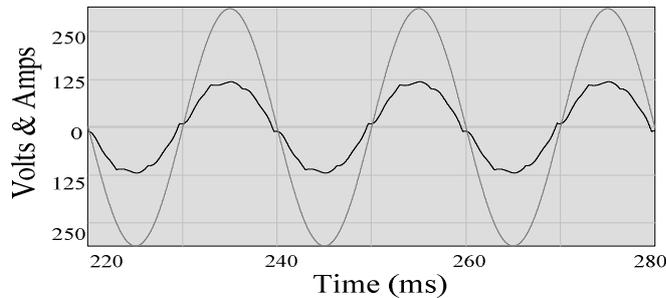


Fig. 6: Full-load line simulation waveforms for 5.5kW ASD system and (a) line current (**bold**) (b) supply voltage (current scale: 10x).

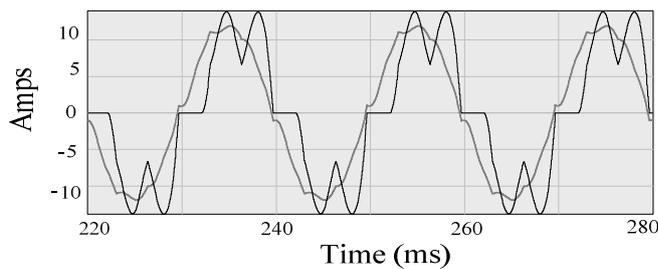


Fig. 7: Full-load line simulation waveforms for 5.5kW ASD system and (a) rectifier current (**bold**) (b) line current.

The IBF line-current THD_1 , line power-factor and efficiency performance characteristics, from no-load to full-load, are shown in figure 8 for the power ratings considered. From nearly 50% load to full load, over a wide range the IBF based system provides high overall power quality performance. The input-current THD_1 is at an acceptable level over the full operating range. The IBF based drive is substantially improved in terms of the harmonic injection to the connected AC network, making the drives impact on the connected power-system and other users in the vicinity of the PCC absolutely minimal. The power factor approaches unity at rated load and thus the IBF filter aids minimizing the reactive power requirement of the drive. In addition, the IBF topology is not sensitive to line voltage unbalances and even under severe line voltage unbalances the line current THD_1 remains low for all phases.

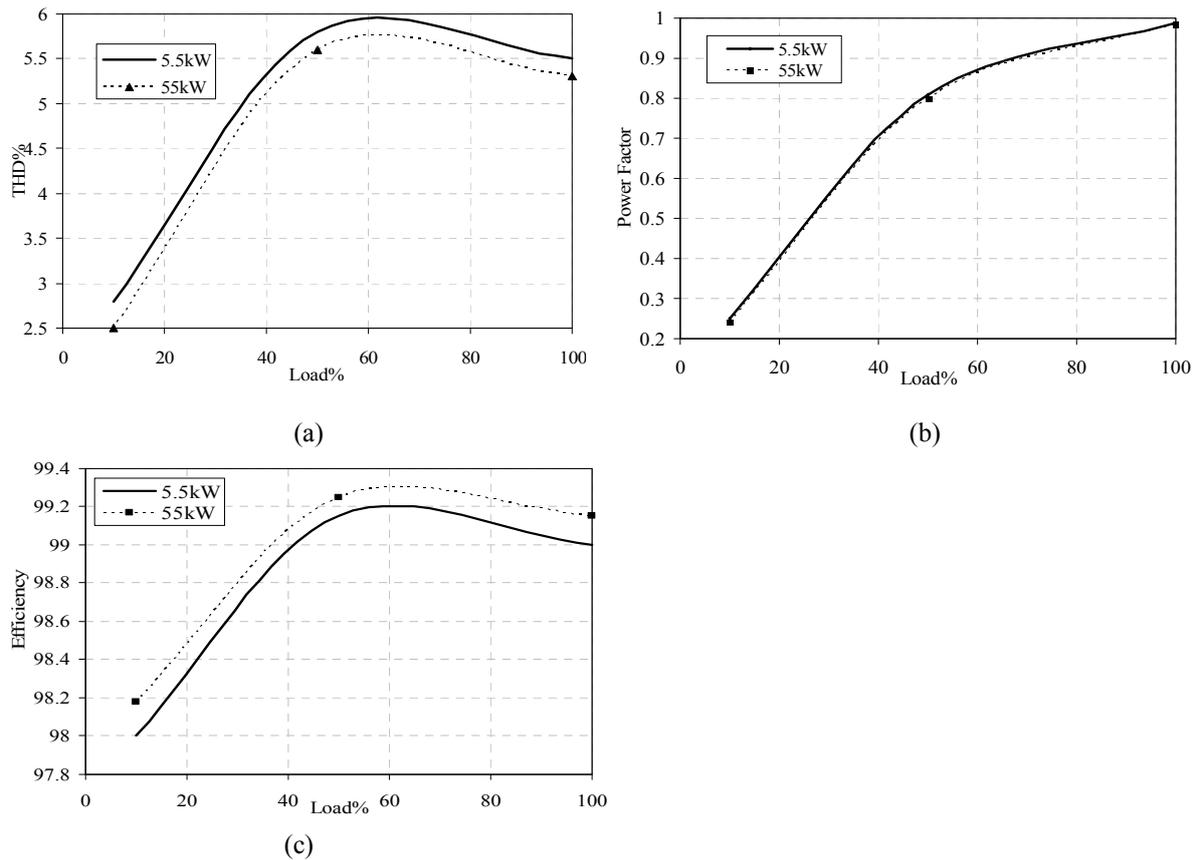


Fig. 8: The load dependency of the IBF (a) line current THD₁ (b) line power factor (c) efficiency.

The experimental full-load input current waveform and related data shown in figure 9 demonstrate the superior performance of IBF. While the line current THD₁ is 33% utilizing a basic in line 4% AC smoothing reactor (L_{ac}), the line current THD₁ is about 4.2% utilizing IBF and practically free of harmonics with a line power factor value near unity (>0.99 leading). In the laboratory tests, over a wide operating region ($\geq 50\%$ loading) the performance of IBF was observed to remain satisfactory.

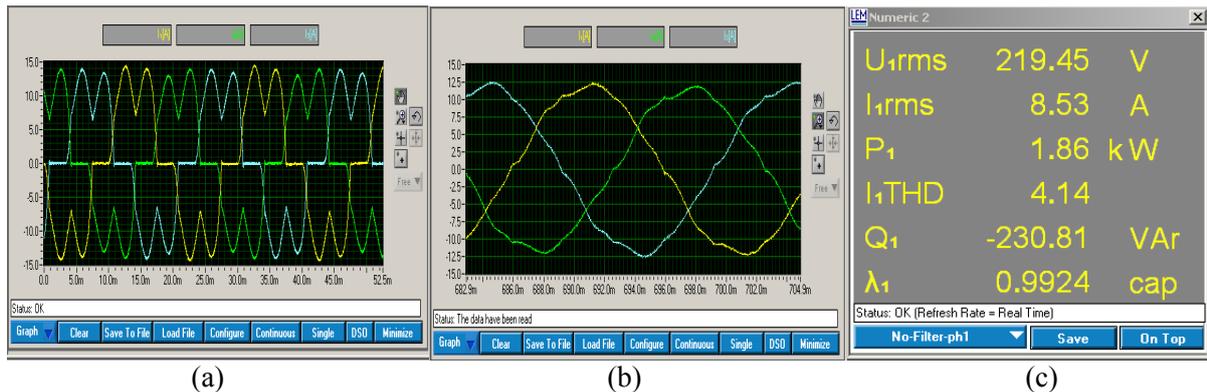


Fig. 9: Experimental 5.5 kW rectifier system (a) Full-load line waveforms utilizing 4% L_{ac} (b) Full-load line waveforms utilizing IBF (c) Phase one voltage, current, power, THD₁ and PF values utilizing IBF.

Conclusion

The genetic algorithm design process, which has been illustrated in this paper, can play an essential role in the optimization of improved broadband filters (IBF) for industrial motor drives. The method permits a high standard of power quality indices (THD, PF and ΔV) to be achieved with a set of filter components. These filter components most probably to have minimal bulk and cost overall. The design case studies presented have shown that the method is robust and has produced advanced designs, with lower filter size and cost, when compared to the results obtained by linear parameter increment searching approach for the same power quality system requirements.

The new and simple frequency domain equivalent circuit based analytical method for the improved broadband filter design is developed by using the GA. The method is efficient, accurate, and results in reduced filter size and cost along with a lesser amount of risk of harmonic excited resonance problems. The optimal filter parameters were validated in detailed computer simulations to obtain the IBF performance. The performance characteristics illustrate that the IBF had very low input current THD₁ from (4 - 5) % and near unity power factor at full load. In addition, the IBF performance under unbalanced voltage supply is satisfactory. The experimental results verify the superior input power quality performance of the IBF based ASD system.

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