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Four-Switch Inverter-Based Hybrid Power Filter Optimized By Meta-Heuristic Algorithm of SPEA-II

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ABSTRACT

Power electronics converters application has increased in modern distribution systems due to their advantages to control and process the power flow. Unfortunately, these converters generate harmful harmonics and inject them into the grid. The modern standards of the systems accept that the grid includes harmonics but they have to be less than the specified value. To satisfy standards, power filters must be added to nonlinear loads. This paper proposes a new hybrid power filter to achieve them. Furthermore, the conventional six-switch inverter of active power filters is substituted to decrease the overall cost and complexity of the system. To design the parameters of the passive part of the filter, the SPEA-II meta-heuristic optimization algorithm is used which minimized the overall cost as well as harmonics suppression. Consequently, the four-switch inverter along with the optimized design of the passive part makes the proposed hybrid active filter attractive for practical applications. The THD of the injected current to the grid as a critical index in different nonlinear and dynamic loads is less than 2%. Simulation results in different scenarios show the effectiveness of the proposed hybrid filter.

NOMENCLATURE

V_a	Source Voltage Phase a
V_b	Source Voltage Phase b
V_c	Source Voltage Phase c
I_a	Source current Phase a
I_b	Source current Phase b
I_c	Source current Phase c
V_α	instantaneous voltages in the α axis
V_β	instantaneous voltages in the β axis
I_α	instantaneous Line Current in the α axis
I_β	instantaneous Line Current in the β axis
P	Active Power
q	Reactive Power
$\bar{P}$	Average Active Power
$\tilde{P}$	Oscillating Active Power
$\bar{q}$	Average Reactive Power
$\tilde{q}$	Oscillating Reactive Power
I_{sn}	Source current in the n-th harmonic
I_1	Main current component

I. Introduction

Due to the destructive effects of harmonics in the power systems, it is necessary to decrease their amplitudes. Power electronics converters are used in modern power systems diversely which caused the loads to behave nonlinear [1]. These nonlinear loads could inject harmonics into the grid and deteriorate the power quality. To reject tripled harmonics, a common solution is using the delta winding of transformers. To decrease more harmonics power filters must be added.

Three types of filters are proposed in power systems: Passive power filter (PPF), Active power filter (APF), and Hybrid power filter (HPF) [2-4]. The design of APFs and HPFs is a complex nonlinear optimization problem. PPFs consist of RLC circuits and are tuned to reject a special frequency. Variations of system impedance, during faults, and so on, could decrease the performance of these filters. Therefore, APFs are proposed to overcome the drawbacks of PPFs. The APFs require high-power inverters to handle harmonics and reactive power. It is proposed to utilize HPFs to decrease the overall cost of the system [5-7].

A hybrid passive filter consisting of two passive filters, a series filter and another parallel filter based on TCR, is proposed in [8,9] to suppress the harmonics and compensate for reactive power. The proposed filter has a fast dynamic response and is non-sensitive to source impedance variation, but the series part of the system that the full load current must be handled is the main drawback of this structure. In [10], a new modulation scheme, named variable modulation index, is applied to a parallel active filter to reduce current harmonics in a wind turbine system based on PMSG and a rectifier.

A four-leg eight-switch voltage source inverter is utilized in [11] to reduce the harmonics of the current and unbalanced single-phase nonlinear current. The model predictive control scheme is implemented on the eight-switch inverter in this structure. An APF with Transformer multilevel inverter in a three-phase three-wire system is used in [12] that brings dc-link voltage regulation in addition to current harmonics compensation. In [13], a Transformer HPF based on a two-leg six-switch inverter is proposed to accomplish the injected harmonics standard of IEEE-59.

Due to the nonlinearity nature of designing parameters of the filters, some authors are proposed to use meta-heuristic algorithms to solve the optimization problem. PSO algorithm is used in [14] to optimize the filter parameters to minimize the harmonics content and the cost of the filter. The authors of [15] have proposed to utilize ant colony optimization to optimally design the parameters of a single-tuned filter operating in a non-sinusoidal power system. The objective functions in this study are maximization of efficiency and power factor in addition to harmonics reduction.

The main goal of the authors in [16] is to minimize the overall cost of the filter, including initial cost and maintenance costs. To achieve this goal, the crow search algorithm is used. Genetic algorithm and Monte Carlo simulation are proposed in [17] to optimize the passive filter parameters in a single-tuned filter installed on a distribution system with photovoltaic generation.

H-infinity optimal control design is used in [18] to find the optimal controller parameters of the hybrid active filter via a convex optimization algorithm. An Adaptive Sine-Cosine Moth-Flame Optimization Algorithm for Parameter Identification of Hybrid Active Power Filters is proposed in [19]. The authors claimed a new population-based algorithm named ASC-MFO to optimally design the parameters of the hybrid active power filter. In [20] a hybrid shunt active power filter is optimized by hybrid Particle Swarm Optimization-Grey Wolf Optimization (PSO-GWO) and fractional order proportional-integral-derivative controller. Utilizing space vector modulation instead of sinusoidal pulse width modulation is investigated in [21]. The grasshopper optimization algorithm for optimizing hybrid active power filters' parameters is proposed in [22]. The authors in [23] proposed finite-set model predictive control for a hybrid active power filter. Moreover, a hybrid filter that is equipped with a three-level converter reduces current THD to 3.11 % [24]. In addition, a parallel hybrid filter decreases both current and voltage THD to 16.49% and 5.3%, respectively [25].

It is clear from investigating the previously published works on this topic that the active filters are very effective in case of harmonics cancelation in some steps [26] and complicated methods [27] but the cost of the filter would be high if we just utilize the active filter. Therefore, hybrid power filters could be used in high-power applications to bring the benefits of both active and passive filters. Designing the inductive and capacitive elements of the passive part of a hybrid power filter is a challenging issue that researchers work on the better methods.

Therefore, in this paper, the conventional six-switch inverter is replaced with a four-switch inverter to reduce the cost of HPF [28]. Consequently, the number of switches and drivers in this structure is lessened which could increase the overall reliability of the system. To design the THD and overall cost of the HPF, in this paper, the parameters of the HPF are optimized based on a meta-heuristic algorithm of Strengthen Pareto Evolutionary Algorithm-II (SPEA-II).

This paper is organized as follows. In section II, the structure of the proposed hybrid power filter is discussed. Optimization of the parameters of the passive filter based on the SPEA-II method is presented in section III. In section tor to investigate the performance of the proposed HPF, in nonlinear case study system is presented. The simulation results in different scenarios are discussed in this section. Finally, section 5 concludes the paper.

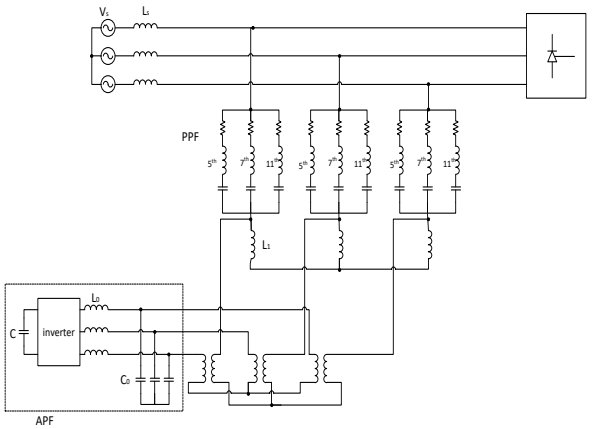


Fig. 1. The structure of the proposed HPF.

II. Methodology

A. THE STRUCTURE OF THE PROPOSED HPF

To reduce the harmonics content and overall cost of the filter, in this paper it is proposed to utilize a HPF. The passive filter of the proposed structure is selected to remove the harmonics orders of fifth, seventh, and eleventh. Furthermore, the parameters of the passive part of the filter are optimized based on the two-objective SPEA-II algorithm. The structure of the proposed HPF is depicted in Figure 1.

B. Reference current generation

Methods of reference current production could be classified into two categories time-based and frequency based. Time-based methods, such as instantaneous active-reactive power theory, relied on measurements and three-phase transformation. FFT is utilized for frequency-based methods such as bandstop filters. In this paper, the instantaneous active-reactive power theory is utilized. Three-phase voltages and currents measured in abc-frame are transformed to αβ-frame as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (2)$$

Therefore, the powers are calculated as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (3)$$

In the presence of harmonics, an oscillatory term is added to the average power that could be formulated as:

In the presence of harmonics, an oscillatory term is added to the average power that could be formulated as:

$$p = \bar{p} + \tilde{p} \quad (4)$$

$$q = \bar{q} + \tilde{q} \quad (5)$$

Where the average terms are denoted with the bar and oscillatory terms with tilde signs. To suppress harmonics components of line currents, the oscillatory terms of powers must be compensated by HPF. Hence, the reference currents of HPF could be derived as:

$$\begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha{}^2 + V_\beta{}^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -\tilde{q} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{c\alpha} \\ I_{c\beta} \end{bmatrix} \quad (7)$$

C. Four-switch inverter

It is beneficial to decrease the cost of inverters in active filters. Therefore, the four-switch structure is proposed in this paper to substitute the conventional six-switch structure. Consequently, the number of active power switches and required drivers was reduced to four instead of six which is attractive in HPFs due to cost reduction and improved reliability of the system.

III. OPTIMIZATION OF PASSIVE FILTER

The parameters of the passive filter are optimized based on meta-heuristic algorithms in this paper. The optimization process is briefly discussed as follows. The main factor to assess the performance of a filter is harmonics reduction. Hence, the first objective is considered as:

$$f_1: \min \left\{ \sqrt{\sum_{n=3,5,7,\dots} \left(\frac{I_{sn}}{I_1}\right)^2} \right\} \quad (8)$$

Where I_{sn} is the source current in the nth harmonic and I_1 is the main current component. The second objective is the overall cost of the filter which is formulated as:

$$f_2: \min\{\text{Cost}(R.L.C) = K_R R_n + K_L L_n + K_C C_n\} \quad (9)$$

Where the cost coefficients of the filter are given by, K_R=100($/KW), K_L=250($/Kvar), and K_C=0.05($/Kvar).

A. SPEA-II ALGORITHM

In this study, SPEA-II is selected as the optimizing algorithm to solve the multi-objective problem of designing the passive filter. SPEA-II is a multi-objective optimization method that the evolution of the population carried on a probabilistic method. In contrast to the other evolutionary algorithms, in SPEA-II the direction and the distance of the current population from other members of the population are selected to teach the search process to a desirable direction. Therefore, the high quality of the produced responses is guaranteed in this method.

For the i^{th} member, a strength value S(i) is assigned, which expresses the number of solutions which it defeats. They are calculated by equation (10).

$$S(i) = |\{j | j \in P_t + \bar{P}_t \cap i \succ j\}| \quad (10)$$

Where, $P_t \; and \; \bar{P}_t$ are populations and archives, respectively. The initial fitness is calculated based on (11), which is computed for all members of the population and archive.

$$R(i) = \sum_{j \in P_t + \bar{P}_t, i \succ j} S(j) \quad (11)$$

When all its members are non-dominant, to compare two Pareto fronts, the Pareto fronts which has the same variety of answers and can spread the answers with more variety in the space of objectives is preferred. For this reason, only using the raw fitness function is not enough, and a secondary criterion is needed to be able to provide the answers in the space of the objective functions, with a suitable variety. Zeitler et al. [15] used the density estimation technique in SPEA-II, which uses the concept of the k^{th} nearest neighbor, where the density at each point is up to the k^{th} nearest neighbor. It is according to relation (12)

$$D(i) = \frac{1}{\sigma_i^k + 2} \quad (12)$$

where σ_i^k is the distance of the i^{th} member from its k^{th} nearest neighbor. k is equal to the square root of the sample size [15] as a result we will estimate the density of responses:

$$k = \sqrt{N + \bar{N}} \quad (13)$$

Finally, the final fitness value is calculated as the sum of the raw fitness and compression as equation (13).

$$F(i) = R(i) + D(i) \quad (14)$$

The lower F(i) is more popular.

In the following, the process of this algorithm is briefly discussed [29]:

Step 1: Create an initial population P_0 and a null external file $(\bar{P}_0 = \emptyset)$, determine generation size as N and generation count as t=0.

Step 2: Calculate the fitness of the population in each of P_t and $\bar{P}_t$ members.

Step 3: Move non-dominated solutions of P_t and $\bar{P}_t$ to. If the archived Pareto solutions size of $\bar{P}_{t+1}$ is greater than the maximum limit cut the size to $\bar{N}$, but if the size of $\bar{P}_{t+1}$ is less than $\bar{N}$, the dominated solutions in the end to the $\bar{P}_{t+1}$ until the size of $\bar{P}_{t+1}$ is equal to $\bar{N}$.

Step 4: If the stop condition is reached, select the non-dominated solutions as the final solution.

Step 5: select parents from $\bar{P}_{t+1}$ based on the championship rule.

Step 6: Implement crossover and mutation operators on parents on $\bar{P}_{t+1}$. Set t=t+1 and go to step 2.

IV. SIMULATION RESULTS

At first, the system under study, schematic in Figure 2, is simulated without any compensation method. The currents injected into the grid are depicted in Figure 3. a. Also, the harmonics content of the current is shown in Figure 3. b. To generate the current's harmonics, in this paper, a nonlinear load with a three-phase diode bridge is used. The parameters of the studied system are presented in Table 1. In the following, the performance of the system is studied in different scenarios. As it is shown in Figure 3. b, the harmonics content of the injected current is very high and it is necessary to compensate these harmonics to comply with the required standards such as IEEE-519.

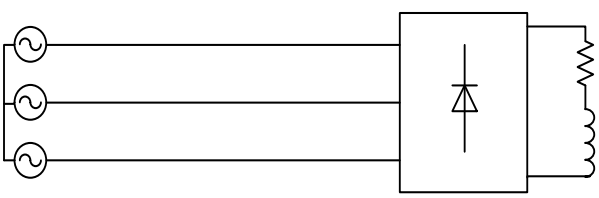
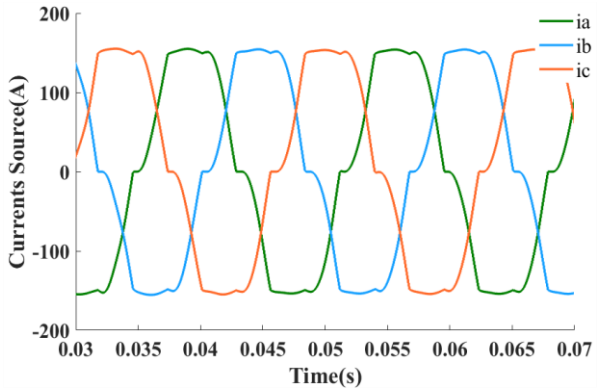


Fig. 2. Schematic of the studied system.

TABLE 1
PARAMETERS OF THE STUDIED SYSTEM

Item	Parameter	Value
1	Source Voltage	380 V
2	Frequency	60 Hz
3	Active power of the load	50 KW
4	Reactive power of the load	62.5 Kvar
5	Line resistance	0.0989 Ω
6	Line inductance	1.58mH



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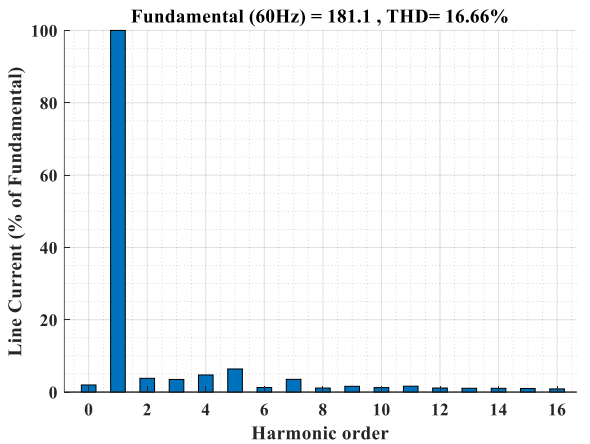
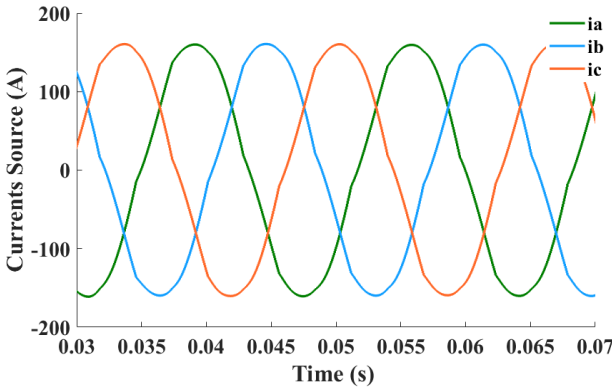


(b)

Fig. 3. The injected currents in the case of the active filter: a) real-time b) harmonics content.



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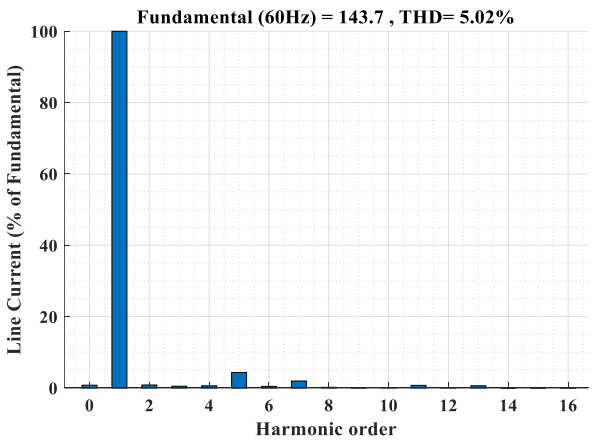


(b)

Fig. 4. The injected currents in the case of the active filter: a) real-time b) harmonics content.

A. Active Filter

If the active filter is utilized to compress the harmonics, the currents injected to the grid are depictedreal-timetime and frequency domain in Figures 4. a and b respectively. In the case of active filter compensation, the harmonics content is reduced but still more than the required standard of IEEE-519. Moreover, the required inverter in this scheme is high power which could limit the selection of this type of compensation in point of the overall system cost.

B. Passive Filter

The conventional method is to use passive filters for harmonics reduction. Even triple harmonics amplitude is very low. Therefore, the passive filter is designed to compress the 5th, 7th, and 11th harmonics. According to eq.15, the values of resistors, inductors, s, and capacitors are effective on the overall cost of the filter and must be designed to minimize the cost in addition to harmonics reduction. Hence, the problem is a two-objective optimization given by:

$$\begin{aligned} &\min F(x) = [f_1(x), f_2(x)] \\ &subject\ to \quad C_i^l \le C_i \le C_i^u \ , \ i = 5,7,11 \\ &\qquad\qquad L_i^l \le L_i \le L_i^u \ , \ i = 5,7,11 \\ &\qquad\qquad R_i^l \le R_i \le R_i^u \ , \ i = 5,7,11 \end{aligned} \tag{15}$$

To solve the above multi-objective problem, the meta-heuristic algorithm of SPEA-II is utilized. The obtained Pareto front is presented in Figure 5 for this problem (one point from it is selected based on the fuzzy min. max method). The designed parameters in this study are presented in Table.2. The compensated system based on the passive filter designed as described above is simulated. The real-time currents and harmonics content of the injected currents to the grid are depicted in Figures 6. a and b, respectively. As it is clear from Figure 6. b, the total harmonics distortion of the system is decreased to 4.96% which is less than the required standard, but the passive filter could not adapt to the changes of the grid and load. Therefore, it is proposed to use the hybrid filter in this paper.

A. The Proposed Hybrid Filter

It is proposed to use the hybrid filter to overcome the deficiencies of the active and passive filters. The power of the inverter of the hybrid filter is less than the active filter resulting in a cost reduction compared with the active filter. Also, including an active filter in the structure of the hybrid filter adds to the system adaptation due to changes in load and the grid.

TABLE 2
OPTIMIZED PARAMETERS OF THE PASSIVE FILTER

Item	Parameter	Value
1	C5	26.5807 μF
2	C7	33.248 μF
3	C11	24.725 μF
4	L5	10.6 mH
5	L7	4.3 mH
6	L11	2.4 mH
7	R5	0.33 Ω
8	R7	0.189 Ω
9	R11	0.166 Ω

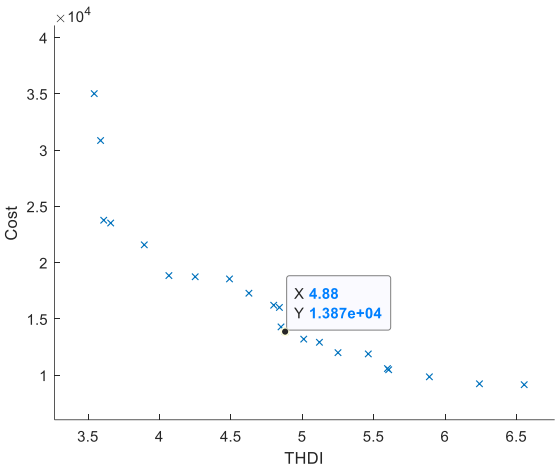
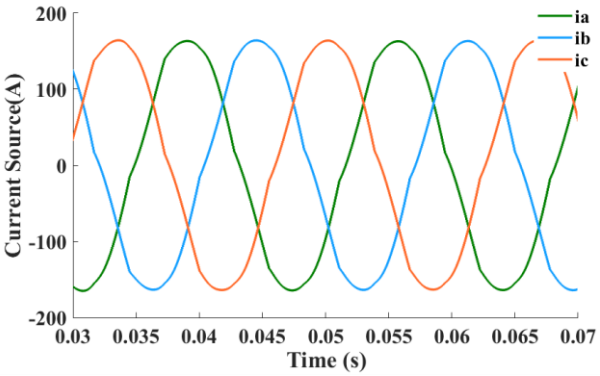


Fig. 5. Pareto front to optimize the passive filter.

TABLE 3
OPTIMIZED PARAMETERS OF THE PASSIVE FILTER

Item	Parameter	Value
1	C5	25.0496μF
2	C7	20.3711μF
3	C11	17.6754μF
4	L5	11.2mH
5	L7	7mH
6	L11	3.3mH
7	R5	0.35Ω
8	R7	0.31 Ω
9	R11	0.23 Ω

Moreover, two-stage filtering brings more effectiveness to the overall quality of the system.



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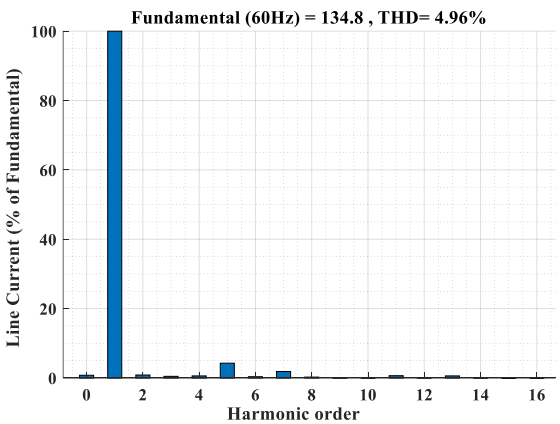

(b)

Fig. 6. The injected currents in the case of the Passive filter: a) real-time b) harmonics content.

To optimize the passive filter parameters in the hybrid filter, the meta-heuristic algorithm of SPEA-II is used. The obtained Pareto front is presented in Figure 7 for this case. The designed parameters, in this case, are presented in Table.3. Comparing results presented in Figures 3 and 8, it is clear that both objectives are improved in the case of the proposed hybrid filter.

The real-time currents and harmonics content of the injected currents to the grid in this case are depicted in Figures 8. a and b, respectively. The proposed hybrid filter not only overcome the deficiencies of high power inverter and adaptation due to changes in system parameters but also reduced the THD of the injected current to 1.75% which is very less than the threshold required standard of 5%.

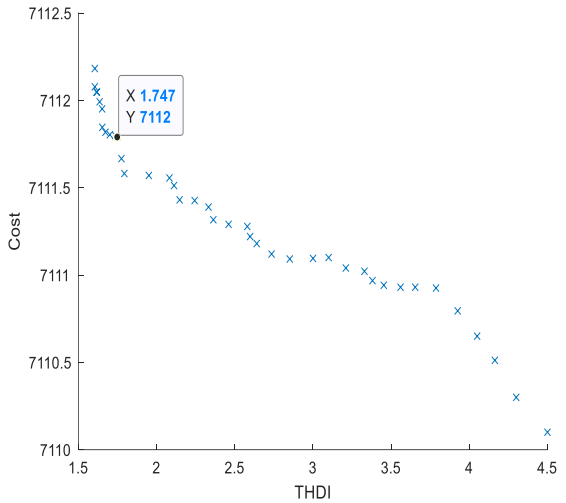

Fig. 7. Pareto front to optimize the proposed hybrid filter.

currents of the induction motor, a well-designed filter must be able to ensure high-quality currents are injected into the grid in all types of loads.

In this case, the hybrid load consists of an induction motor and a nonlinear load. The effective currents of the induction motor and the nonlinear load are 53 A and 120 A, respectively. Figure 9 shows the injected currents to the grid in real time and the frequency domain in this case. As it is measured from harmonics spectrum analysis, the THD of the injected current is 15.84% which could not satisfy the utility standards.

The above simulation is repeated adding the proposed filter in Figures 10. a and b, respectively. The proposed hybrid filter reduced the THD of the injected current to 1.22% which is very less than the threshold required standard of 5%.

The previous methods decrease THD to 3.11% [24], 2.15% [26] and 1.86% [27]. Therefore, the proposed hybrid filter profit more superiority.

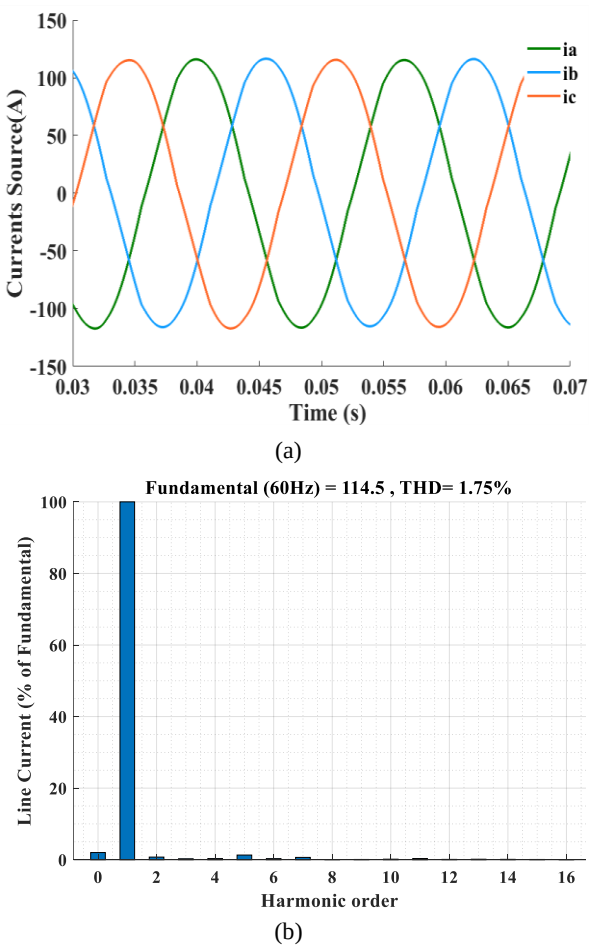

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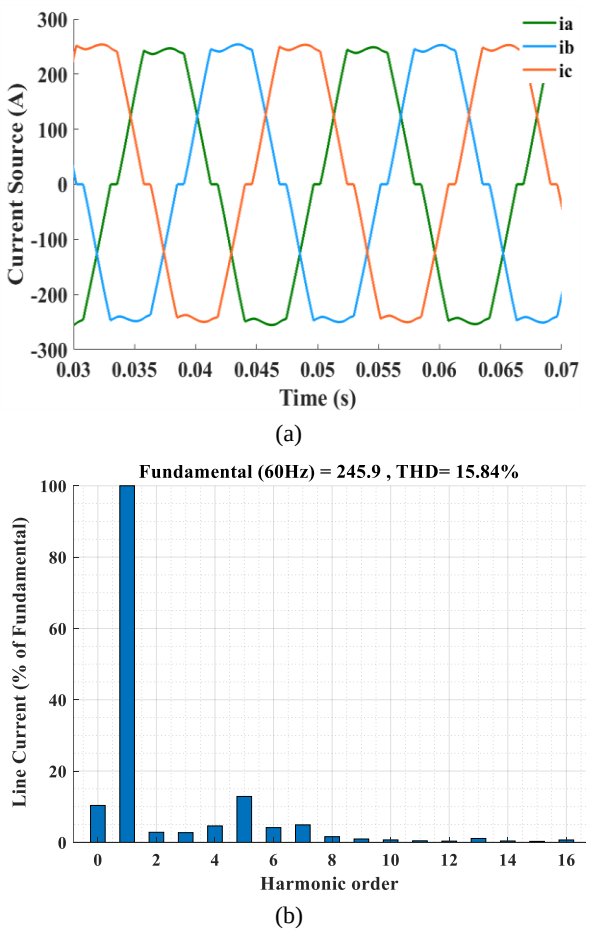
Fig. 8. The injected currents in the case of the Proposed Hybrid filter: a) real-time b) harmonics content.



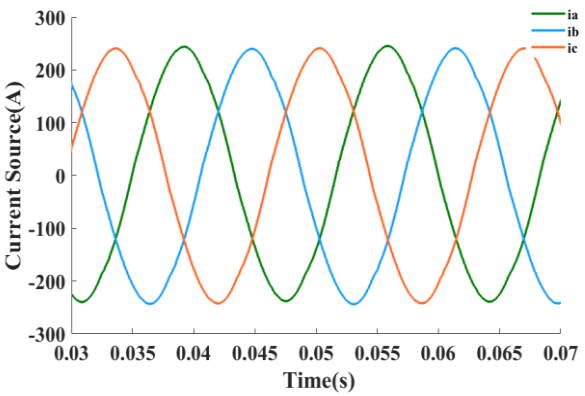
(a)

(b)

Fig. 9. The injected currents in case of the Dynamic load: a) real-time b) harmonics content.

D. Dynamic Load

To investigate the proposed filter's performance in different environments, an induction motor is added to the previous load as a dynamic load. Due to the non-sinusoidal and variable



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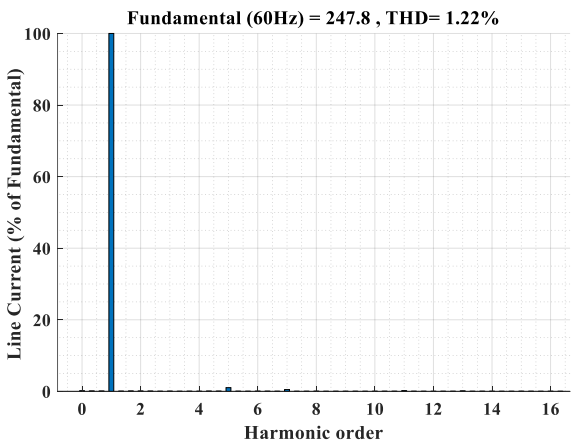

(b)

Fig. 10. The injected currents in the case of the proposed hybrid filter and dynamic load: a) real-time b) harmonics content.

V. Conclusions

In this paper, a hybrid filter is proposed based on a four-switch inverter that is decreased the power of the inverter compared with the conventional active filters. Moreover, compared with passive filters the proposed system is capable of adaptation with variations in load and grid parameters. To improve the performance of the hybrid filter, two objective functions related to current harmonics and the overall cost of the system are considered. Therefore, utilizing a four-switch inverter with two switches than the conventional structures and optimized design of the passive filter makes the proposed hybrid filter an attractive choice for selection.

The parameters of the system are optimized based on a meta-heuristic algorithm of SPEA-II. Simulation results show that the THD of the injected currents to the grid is reduced from 16.66% in the original system to 5.02%, 4.96%, and 1.75% with active, passive, and the proposed hybrid filters respectively. Therefore, the proposed filter is effective based on performance and overall cost of the system.

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