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Multi-Objective Optimization Based Approaches for Active Power Filter Design- A Comparison

Abstract. This paper introduces an optimal active power filter design method to compensate simultaneously current harmonics and reactive power of a nonlinear load. The power filter consists of a passive RL low-pass filter placed in series with the load and a pure active filter which has RL elements connected in series with insulated gate bipolar transistors (IGBT) based voltage source converter. The filter is supposed to inject a current into the connection node of the load and grid in order to eliminate current harmonics and its imaginary current. The voltage source converter is placed in a hysteresis feedback control loop to generate the reference current. The band width and output amplitude of the hysteresis controller are optimized with inductance of RL filters. In solving the optimization problem, three objective functions are considered which include minimizing current total harmonic distortion (THD), maximizing power factor and minimizing the IGBT bridge current. The four optimization methods applied are the goal attainment, max ordering, non-dominated sorting genetic algorithm-II and strength Pareto evolutionary algorithm 2 (SPEA2) methods. The results of the four optimization methods are compared and it is shown that the SPEA2 method gives the best performance in terms of minimizing current THD and maximizing the power factor.

Streszczenie. *Przedstawiono metody optymalizacji projektowania aktywnych filtrów mocy umożliwiające kompensację prądów harmonicznych i mocy biernej przy obciążeniu nieliniowym. Analizowany filtr składa się z pasywnego filtru dolnoprzepustowego RL połączonego szeregowo z obciążeniem i filtrem aktywnym. Filtr aktywny mam elementy R:L dołączane z wykorzystaniem tranzystora IGBT.* (***Wieloparametryczna optymalizacja projektowania aktywnych filtrów mocy – porównanie metod***)

Keywords: Active Power Filter, Multi-Objective Optimization, Goal Attainment, Max Ordering, NSGA-II, Power Factor Correction.
Słowa kluczowe: filtry aktywne , optymalizacja, poprawa współczynnika mocy

Introduction

Power quality issue related to harmonic pollution is presently becoming of utmost concern to power utilities due to increasing usage of power electronics [1-2]. Therefore, minimization of harmonic distortion is very imperative and several types of harmonic elimination devices have been developed using passive power filter (PPF), active power filter (APF) and hybrid power filters (HPF). These devices have to be optimally designed before it can be used to eliminate harmonics in a power system.

From the literature, works related to optimal design of power filters were introduced in the 90's and later [3], [4], [5]. Many multi-objective optimization methods using evolutionary and genetic algorithms have been developed in [6-14], but for optimal design of power filters, single objective optimization has been considered in [14-18]. Always a unique optimal solution is provided by the traditional single objective optimization algorithms. However, for solving real world optimization problems, a set of objectives usually exist and therefore a multi-objective optimization problem has to be considered. Applications of multi-objective optimization in power systems can be found in various fields such as reactive power optimization [19], hybrid active power filter design [20-21], optimal configuration of filters [22], active filter design [23-27], power filter planning [28], FACTS design [29], simultaneous harmonic suppression and reactive power compensation [30]. Hysteresis controller has been applied in the filter design but its parameters are not regarded as optimization variables.

This paper presents a hysteresis inverter based APF for eliminating harmonics and compensating reactive power simultaneously in a power system. The aim of this paper is to evaluate the effectiveness of tuning hysteresis controller parameters using various multi-objective optimization methods, namely, goal attainment, max ordering, non-dominated sorting genetic algorithm-II (NSGA-II) and strength Pareto evolutionary algorithm 2 (SPEA2).

Power Filter

The power filter consists of two main parts, the passive part which is an RL branch in series with a harmonic load, and the other is the active part which is in parallel with the grid. The passive part is supposed to smooth the load current, and the active part injects a current into the grid in a way that cancels the total harmonic and imaginary part of the load current so that the grid only supplies the real part of the load current at the fundamental frequency. Fig.1 shows the system configuration consisting of three phase source voltage, a six-pulse rectifier that feeds an RL DC load and the power filter. The load generates harmonics and the filter is supposed to reduce both harmonic and imaginary current.

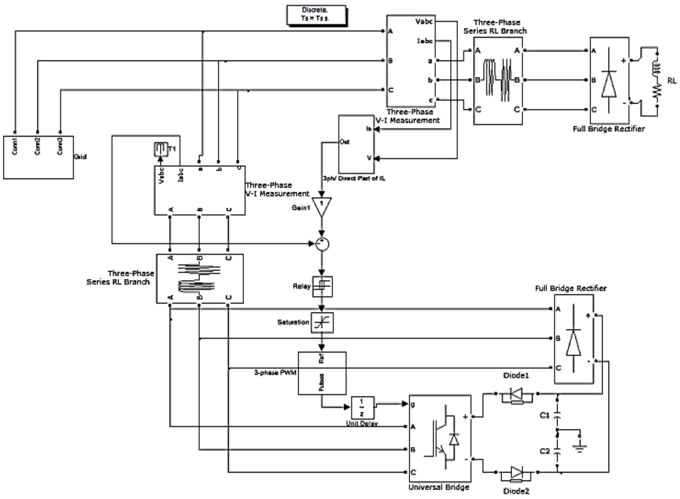

Fig.1.The system configuration with APF

The current control of the IGBT bridge is done by measuring the load current (I_L) and eliminating the real part of the load current (I_D) at the fundamental frequency. After elimination, we get the reference current, $I_R = I_L - I_D$ which is then used as a reference for the hysteresis current controller. The controller controls the parallel branch current which flows towards the node connected to the grid. Therefore, the grid supplies the current, I_D and the IGBT bridge generates the rest of the current. To derive the formulations for the currents, I_D, the Cosine Fourier transform is first considered as follows:

(1)
$$A=\int_0^T I_L(t).\cos(\omega t)dt,\quad B=\int_0^T I_L(t).\sin(\omega t)dt,$$
$$C=\int_0^T V_L(t).\cos(\omega t)dt,\quad D=\int_0^T V_L(t).\sin(\omega t)dt,$$

where, V_L is the grid voltage.

Considering the following definitions:

(2)
$$K=\sqrt{A^2+B^2},\quad \alpha=\arctan\left(\frac{A}{B}\right),\quad \beta=\arctan\left(\frac{C}{D}\right),\quad \varphi=\alpha-\beta$$

The I_D current can be reconstructed as follows:

(3)
$$I_D=K\cos(\varphi)\sin(\omega t+\beta)$$

Clearly, in a three-phase system, the above relation can be rewritten as follows:

(4)
$$I_{D1}=K_1\cos(\phi_1)\sin(\omega t+\beta_1)$$
$$I_{D2}=K_2\cos(\phi_2)\sin(\omega t+\beta_2+\frac{2\pi}{3})$$
$$I_{D3}=K_3\cos(\phi_3)\sin(\omega t+\beta_3-\frac{2\pi}{3})$$

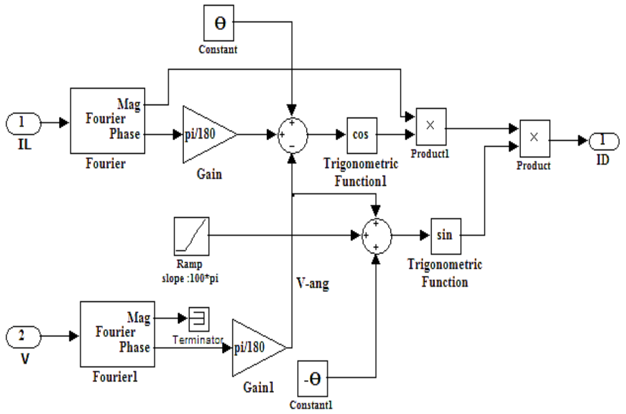

Fig. 2. Block Diagram for Generating I_D

As it is obvious K, φ and β should be calculated for each phase separately. Figure 2 shows the block diagram for generating I_D of each phase, in which $\theta=[0,\frac{2\pi}{3},-\frac{2\pi}{3}]$ for phases a, b and c respectively, and $V_{\_ang}$ is the voltage angle.

The reference currents of the filter for the three phases are given by,

(5)
$$I_{R1}=I_{L1}-K_1\cos(\varphi_1)\sin(\omega t+\beta_1)$$
$$I_{R2}=I_{L2}-K_2\cos(\varphi_2)\sin(\omega t+\beta_2+\frac{2\pi}{3})$$
$$I_{R3}=I_{L3}-K_3\cos(\varphi_3)\sin(\omega t+\beta_3-\frac{2\pi}{3})$$

in which, I_{Ri} and I_{Li} are the reference and load currents for each phase, respectively.

Multi-objective Optimization

The multi-objective optimization problem generally is to find an optimum value of a vector cost function. The multi-objective optimization problem consider three objective functions, namely, minimization of current THD, maximization of power factor and minimization of the IGBT bridge current, I_{Max}. Four variables are to be optimized in the optimization problem and the variables are the series inductance, parallel inductance, the hysteresis output amplitude, and the bandwidth of the hysteresis current controller.

Four different multi-objective optimization methods are applied to the filter design problem, and the methods are named as the goal attainment [31], max ordering [32], non-dominated sorting genetic algorithm-II (NSGA-II) [7-8] and the strength Pareto evolutionary algorithm (SPEA2) [10]. In all the four methods, the variables vector is given by X = [x_1 x_2 x_3 x_4] where x_1 is the half of hysteresis current controller bandwidth, x_2 is the hysteresis current controller's output amplitude, and x_3 and x_4 are the inductance of the series and parallel inductors in mH, respectively. All the variables are in the range of 0-5, except for x_1 with value in the range of 0.01-5. This is due to the fact that a very small value of hysteresis bandwidth causes a very high switching frequency which is not preferable.

The cost function vector is defined by J = [j_1 j_2 j_3] where j_1 is the THD of the current supplied by the grid and j_3 is the IGBT bridge current amplitude. But j_2 is a transformation of power factor in such a way that larger values of power factor give smaller values of j_2. The j_2 definition is $j_2=10^{20(1.15-PF)}$. This definition is somehow empirical and novel in order to make enough sensitivity for values of power factor near 1.0. No separate cost function weights are used except for the goal attainment method, which is discussed later.

Goal Attainment Method [29]

This method uses a set of design goals, $F^*=\{F_1^*,F_2^*,\cdots,F_m^*\}$, associated with a set of objectives, $F(x)=\{F_1(x),F_2(x),\ldots,F_m(x)\}$. The problem formulation allows the objectives to be under/or over-achieved, enabling the designer to be relatively imprecise about the initial design goals. The relative degree of under- or over-achievement of the goals is controlled by a vector of weighting coefficients, $w=\{w_1, w2,\ldots,w_m\}$, and is expressed as a standard optimization problem using the formulation:

(6)
$$\min_{\gamma\in\Re,\,x\in\Omega}\gamma$$

such that

$$F_i(x)-w_i\gamma\le F_i^*,i=1,\cdots,m$$

where Ω is the problem space. The term $w_i\gamma$ introduces an element of *slackness* into the problem, which otherwise imposes that the goals be rigidly met. The weighting vector, w, enables a designer to express a measure of the relative tradeoffs between the objectives. For instance, setting the weighting vector w equal to the initial goals indicates that the same percentage under- or over-achievement of the goals, F^*, is achieved. It can incorporate hard constraints into the design by setting a particular weighting factor to zero (i.e., $w_i=0$). The goal attainment method provides a convenient intuitive interpretation of the design problem, which is solvable using various standard optimization procedures. The goal attainment method is represented geometrically in Figure 3 in two dimensions.

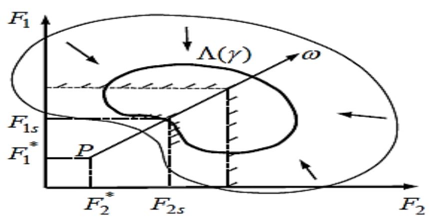

Fig. 3. The goal attainment method

Minimize γ subject to

(7)
$$\gamma,x\in\Omega\quad \begin{matrix}F_1(x)-\omega_1\gamma\le F_1^*\\ F_2(x)-\omega_2\gamma\le F_2^*\end{matrix}$$

Specification of the goals, $F^*=\{F_1^*,F_2^*\}$, defines the goal point, P. The weighting vector defines the direction of search from P to the feasible function space, $\Lambda(\gamma)$. During the optimization, γ is varied so as to change the size of the feasible region. The constraint boundaries converge to a unique solution point, F_{1s}, F_{2s}.

Max Ordering Method [30]

The max-ordering or min-max problem is defined according to the max-order relation between two vectors defined as:

$$f(x) \leq_{MO} f(y) :\Leftrightarrow \max\{f^1(x),\ldots f^Q(x)\} \leq \max\{f^1(y),\ldots f^Q(y)\} \quad (8)$$

The problem $min_{MO}\ F(x)$ which minimizes the worst of the objective values is defined as follows:

$$\min_x \max_i F_i(x)$$

In which F_is are components of the vector objective function, $F(x) = \{F_1(x), F2(x),..., F_m(x)\}$
This optimization method is generally used in conservative planning and robust optimization [33]. However, it has not been applied in power filter design.

Non-dominated Sorting Genetic Algorithm-II (NSGA-II) [7,8]

The NSGA-II is able to find a much better spread of solutions and better convergence near the true Pareto-optimal front and a faster convergence for NSGA- II are expected. The step-by-step procedure in the NSGA-II algorithm are described as follows:

i. Generate a random parent population, P.
ii. Sort parent population based on non-domination.
iii. Assign fitness and create an offspring population Q using binary tournament, recombination and mutation.
iv. Combine parent and offspring populations and form combined population R with size of 2N (except first period).
v. Sort R based on non-domination: R= {F1, F2, …}.
vi. Form the new parent population according no domination and crowding distance.
vii. If the maximum number of generations is reached, then stop, else go to step 2.

The NSGA-II procedure is shown in the Fig. 4. More details of the algorithm like non-dominated sorting and crowding distance sorting are given in [7].

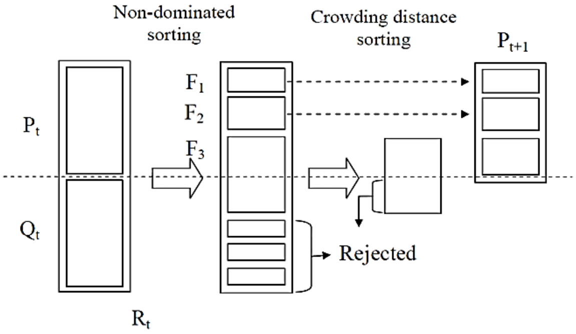

Fig. 4. The NSGA-II method

Strength Pareto Evolutionary Algorithm 2 (SPEA2) [10]

The SPEA is a relatively recent technique for finding or approximating the Pareto-optimal set for solving multi-objective optimization problems. In different studies [12, 13] SPEA has shown very good performance in comparison to other multi-objective evolutionary algorithms, and therefore it has been a point of reference in various recent investigations [11]. Furthermore, it has been used in different applications [9]. In this paper, an improved version, namely SPEA2, is used [10]. The overall algorithm of SPEA2 is described as follows:

Consider input: N (population size), $\boldsymbol{N}$ (archive size) and T (maximum number of generations)
Consider output: ***A** (nondominated set)*
Step 1: ***Initialization**: Generate an initial population $\mathbf{P}_0$and create the empty archive (external set) $\mathbb{P}_0 = \Phi$; Set $t = 0$.*
Step 2: ***Fitness assignment**: Calculate fitness values of individuals in $\mathbf{P}_t$ and $\mathbb{P}_t$
(cf. Section 3.1).*
Step 3: ***Environmental selection**: Copy all non-dominated individuals in $\mathbf{P}_t$ and $\mathbb{P}_t$ to $\mathbb{P}_{t+1}$. If size of $\mathbb{P}_{t+1}$exceeds $\boldsymbol{N}$ then reduce $\mathbb{P}_{t+1}$by means of the truncation operator, otherwise if size of $\mathbb{P}_{t+1}$is less than $\boldsymbol{N}$ then fill $\mathbb{P}_{t+1}$with dominated individuals in $\mathbf{P}_t$ and $\mathbb{P}_t$.*
Step 4: ***Termination**: If $t \geq T$ or another stopping criterion is satisfied then set **A** to the set of decision vectors represented by the non-dominated individuals in $\mathbb{P}_{t+1}$. Stop.*
Step 5: ***Mating selection**: Perform binary tournament selection with replacement on $\mathbb{P}_{t+1}$in order to fill the mating pool.*
Step 6: ***Variation**: Apply recombination and mutation operators to the mating pool and set $\mathbf{P}_{t+1}$to the resulting population. Increment generation counter ($t = t + 1$) and go to Step 2.*

In contrast to SPEA, SPEA2 uses a fine-grained fitness assignment strategy which incorporates density information. Furthermore, the archive size is fixed, i.e., whenever the number of non-dominated individuals is less than the predefined archive size, the archive is filled up by dominated individuals; while with SPEA, the archive size may vary over time. In addition, the clustering technique, which is invoked when the non-dominated front exceeds the archive limit, has been replaced by an alternative truncation method which has similar features but does not loose boundary points. Finally, another difference to SPEA is that only members of the archive participate in the mating selection process.

Results

The optimization problem was solved by the four optimization methods by considering that all the methods were run for 20 iterations and the termination tolerance on x and J is 0.000001. For all the methods, the finite differences are used to estimate gradients of forward type and variable changes are limited from 0.00000001 to 0.1. For all the four methods except NSGA-II, the Initial point is set at [0.01 1 1 2]. For the Goal attainment method, the weights are regarded as [10 1 1]. For the NSGA-II, after the algorithm is completed, the member of the final population which has the least THD is selected and the crossover function is of the scattered type on 80% of the population. Here, the migration is done in the forward direction on 20% of the population according to the Gaussian function. In addition, the selection type is of the uniform stochastic function and the mutation pdf type is Gaussian.

For the SPEA2, the selection type is tournament using 2 individuals. The recombination and mutation probability (both for variables and individuals) is 1% and the variable swap probability is 0.5%. For the NSGA-II and SPEA2, at the end of the optimization process and from the Pareto optimal set (the resultant set of solutions that are shown in Figures 5 and 6), with considering preferences in the objectives, a single solution is selected. There were 21 and 50 solutions in the Pareto optimal set for NSGA-II and SPEA2 methods, respectively.

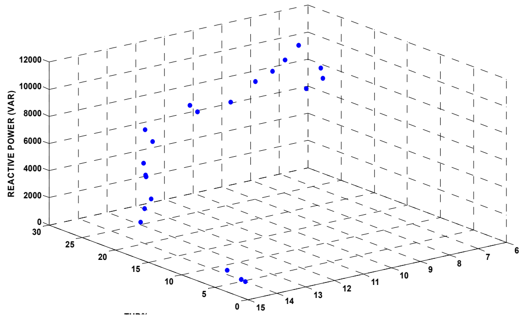

Fig. 5. Pareto optimal set for NSGA-II method

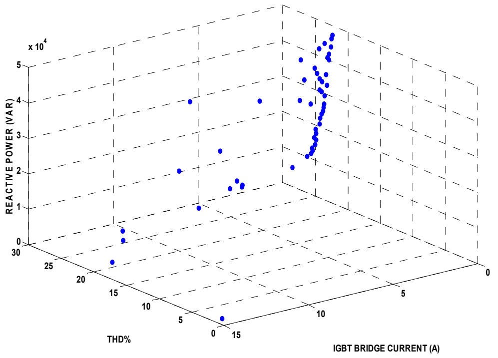

Fig. 6. Pareto optimal set for SPEA2 method

Simulations in MATLAB environment were carried out on the proposed system, as shown in Figure 1. The system parameters are given in Table 1. Figures 7 to 10 show the three phase mains currents, load voltages, load currents and filter currents obtained from the four different optimization methods.

Table 1: Circuit parameters

Parameter Name	*Numerical Value*
AC grid Voltage	*312 V (peak) , 50 Hz*
Load Resistance and Inductance, R, L	*20 Ω, 0.1 mH*
DC Capacitor, C_1 , C_2	*4700 µF*
Sample time Ts	*1 µs*

Figure 11 shows harmonic spectrum of grid current phase ‘a’ obtained from each of the methods. By comparing the results of the four optimization methods shown the figures and Table 2, it is noted that all the methods except for the max ordering method give THD less than 2%, power factor greater than 0.998 and the IGBT bridge currents less than 15 A.

The best results in reducing current THD and reactive power is obtained from the SPEA2 method while the goal attainment method shows better performance in reducing the IGBT bridge current.

Table 2: Results Comparison

Optimization Method	*x_1 (Hys. BW)*	*x_2 (Hys. Amp.)*	*x_3 (Ser. mH)*	*x_4 (Par. mH)*	*j_1 (THD %)*	*j_2 $(10^{20(1.15-PF)})$*	*j_3 (I_{Max} A)*
Goal Attainment	*0.0100*	*0.9999*	*5.0000*	*1.5502*	*1.639*	*1006.22 (PF=0.999)*	*14.61*
Max Ordering	*0.0101*	*1.2307*	*3.2298*	*0.5016*	*5.412*	*1097.01 (PF=0.998)*	*16.13*
NSGA-II	*0.0790*	*1.0168*	*0.8132*	*2.1251*	*1.289*	*1003.84 (PF=0.999)*	*14.80*
SPEA2	*0.0235*	*2.8930*	*2.1517*	*2.3986*	*0.963*	*1002.12 (PF=0.999)*	*14.73*

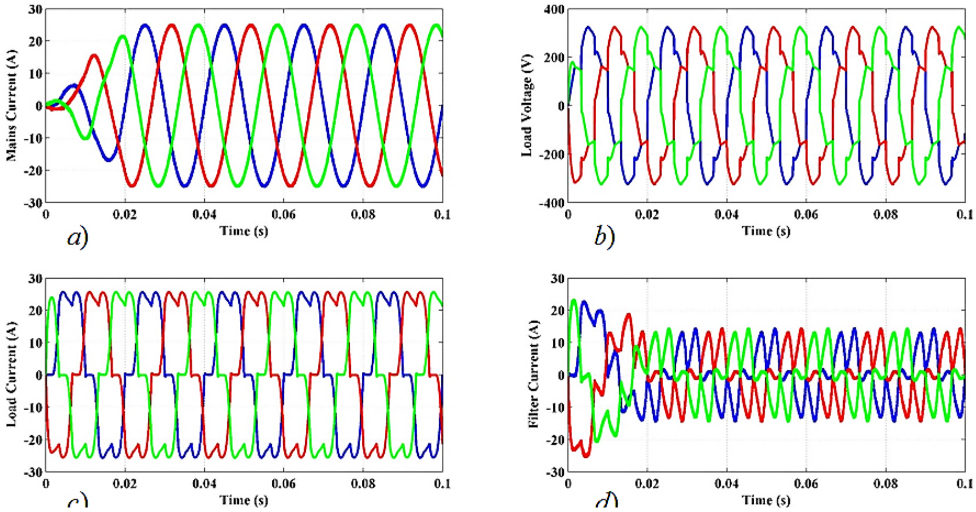

Fig. 7: Results of the Goal Attainment Method

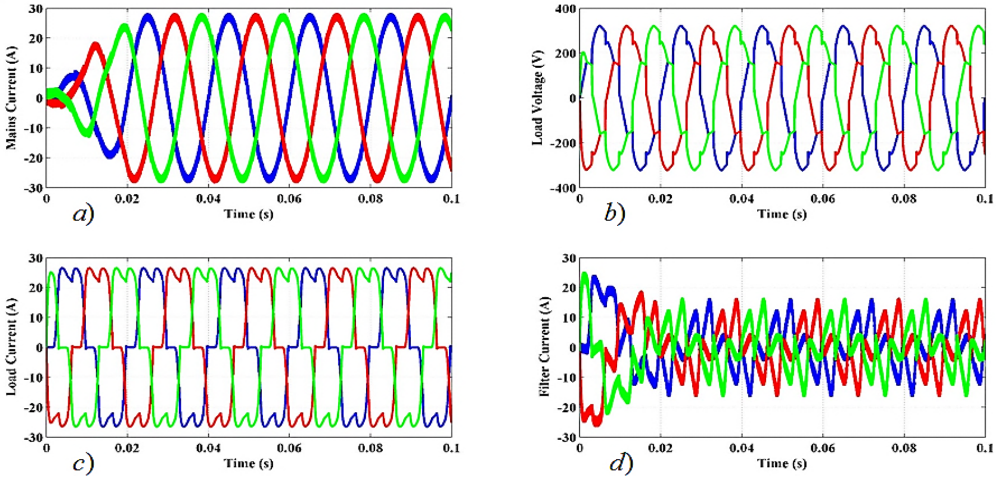

Figure 8: Results of the Max Ordering Method

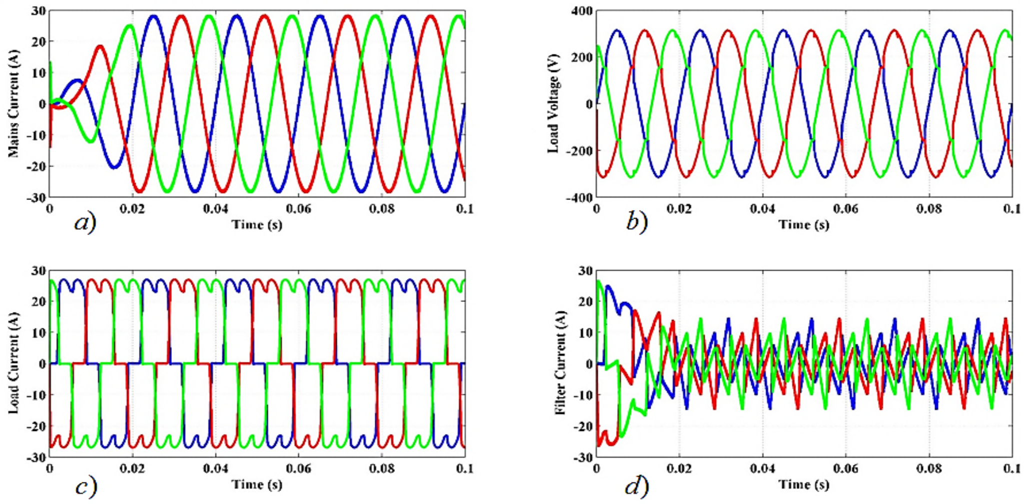

Figure 9: Results of the NSGA-II Method

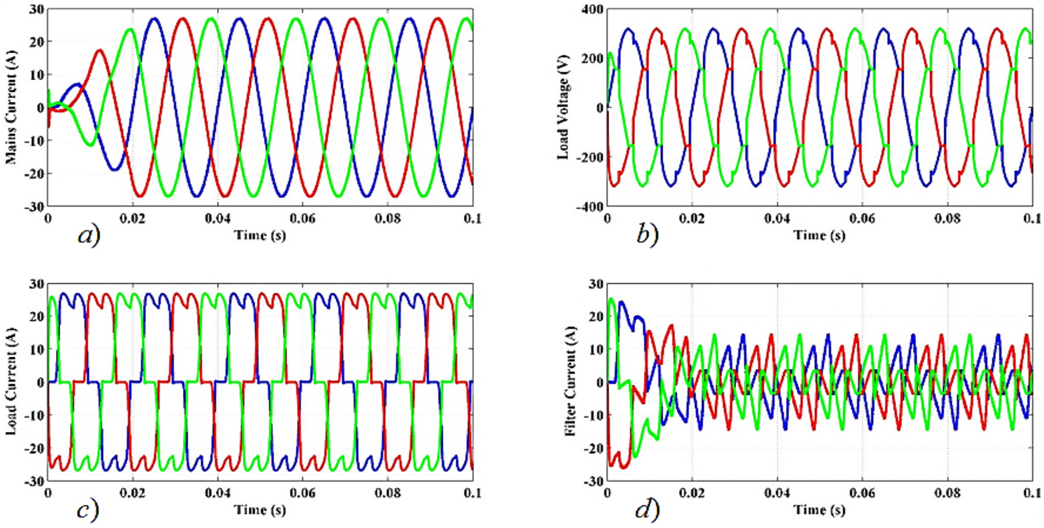

Figure 10: Results of the SPEA2 Method

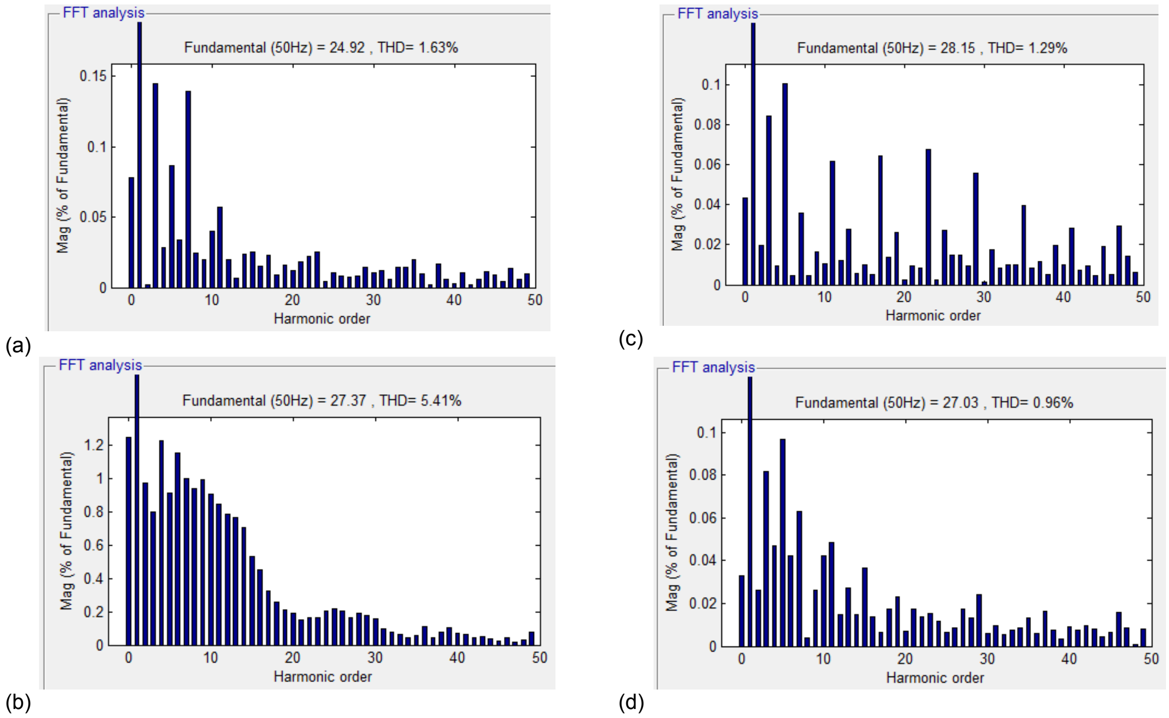

Fig 11- Harmonic spectrum of grid current Phase ‘a’ for (a) Goal Attainment Method (b) Max Ordering Method (c) NSGA-II Method (d) SPEA2 Method

Conclusion

An active power filter design method to compensate simultaneously current harmonics and reactive power of a nonlinear load is presented. Four multi-objective optimization methods have been applied in the active filter design problem by considering hysteresis controller parameters as optimization variables. This designed problem considers finding the optimizing values of the hysteresis controller parameters used in the current generator. The simulation results obtained in MATLAB/SIMULINK environment show that the multi-objective optimization methods are useful in designing active power filters. The optimization results showed that the SPEA2 method gives the best results in reducing current THD and reactive power, while the goal attainment method provides better result in reducing the IGBT bridge current.

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