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Active Power Filter Design by a Novel Approach of Multi-Objective Optimization

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ABSTRACT
This paper presents an innovative active power filter design method to simultaneously compensate the current harmonics and reactive power of a nonlinear load. The power filter integrates a passive power filter which is a RL low-pass filter placed in series with the load, and an active power filter which comprises an RL in series with an IGBT based voltage source converter. The filter is assumed to inject a current into the connection node of the load and grid to eliminate current harmonics and its reactive part. The voltage source converter is placed in a hysteresis feedback control loop to generate a harmonic current. The bandwidth and output amplitude of the hysteresis controller are optimized with the inductance of RL filters. Three objective functions are considered in the optimization problem, which include minimizing of current total harmonic distortion, maximizing of power factor, and minimizing of the IGBT bridge current. For solving the optimization problem, two well-known multi-objective evolutionary algorithms are applied, namely, non-dominated sorting genetic algorithm-II (NSGA-II) and Strength Pareto Evolutionary Algorithm 2 (SPEA2). Test results showed that the SPEA2 technique exhibited a better performance in comparison to NSGA-II relative to the objectives.

KEYWORDS: Power Filter, Multi-objective Optimization, NSGA-II, SPEA2, Harmonic Filtering, Power Factor Correction.

1. INTRODUCTION

Power quality issues, particularly harmonic pollution, have become more common and serious and are thus subjects of increasing concern. Therefore, harmonic minimization has become imperative and have yield to the development of several types of compensators, such as passive power filters, active power filters (APFs), and hybrid APFs (HAPFs). These power filters can eliminate harmonics, however should first be designed optimally before use. Designing a power filter is a common issue in power engineering. A review of past works shows that the use of power electronics to enhance electric power quality has been studied since the 1980s [1-2].

However, optimal designs have only been introduced in the 1990s [3-5]. A number of previous methods for solving multi-objective optimization problems were proposed in [6-14]. However, most recent power filter optimization problems were single-objective [15-18]. Traditional single-objective optimization algorithms provide a unique optimal solution. However, many real world optimization problems are not intended for identifying a solution that minimizes (maximizes) a single objective. Instead, a set of objectives, which are often in conflict with each other, must be considered. Thus, a sole solution may not exist. The applications of multi-objective optimization methods in power systems were introduced and employed in various fields, such as reactive power [19], HAPFs [20], optimal

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configuration of filters [21], active filter design [22-25], power filter planning [26], FACTS design [27], simultaneous harmonic suppression and reactive power compensation [28]. A number of these systems use the hysteresis current controller. However, the parameters of such controller are not regarded as optimization variables. This paper aims to demonstrate the effectiveness of tuning hysteresis controller parameters by using multi-objective optimization methods for designing a hysteresis inverter-based active filter, which simultaneously eliminates harmonics and compensates reactive power. A comparison is made by applying two multi-objective optimization methods; non-dominated sorting genetic algorithm-II (NSGA-II) and strength Pareto evolutionary algorithm 2 (SPEA2). The objectives for solving the optimization problem are to reduce current total harmonic distortion (THD), reduce reactive power and minimize the insulated gate bipolar transistor (IGBT) bridge current.

2. ACTIVE POWER FILTER DESIGN AND OPTIMIZATION

2.1. Estimation of reference current

Figure 1 shows shunt active power filter (SAPF) [29] that is controlled to supply a compensating current at the point of common coupling (PCC) and to cancel current harmonics on the supply side. The SAPF is controlled to draw/supply a compensated current from/to the utility to eliminate harmonic and reactive currents of the non-linear load.

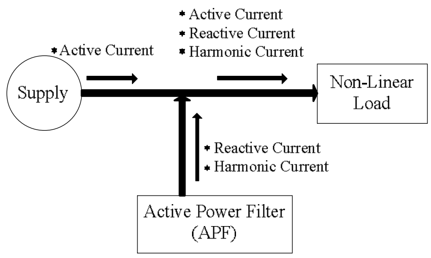

Fig. 1. Connection of shunt active filter with nonlinear load

Therefore, the resulting total current drawn from the main AC is sinusoidal. The APF should generate satisfactory reactive and harmonic current to compensate the nonlinear loads in the line. In this paper, power filter comprises two main parts: the passive part, which is an *RL* branch in series with a harmonic load, and the active part, which is in parallel with the grid. The passive part smoothes the load current, whereas the active part injects a current into the grid to cancel the harmonic distortion and reactive power part of the load current, such that the grid supplies only the real part of the load current in the fundamental frequency. Figure 2 shows the schematic model of the simulated system developed in MATLAB. The model comprises a three-phase source voltage, a six-pulse rectifier that feeds an *RL* DC load and a pure APF with additional AC line inductor. This load creates a large amount of harmonics, whereas the filter reduces both the harmonic and reactive parts of the current.

As it is shown in Fig. 2, a full bridge rectifier is used to maintain the DC link voltage at a constant value in order to proper compensation of harmonic current and reactive power.

The current control of the universal bridge is realized by measuring the load current (I_L) and eliminating the real part of current at fundamental frequency (I_D). The resultant component, $I_R=I_L–I_D$, (what is left after elimination) will be the reference for a hysteresis current controller that controls the parallel branch current towards the connection node with the grid. Thus, the grid only has to supply the direct component (I_D) of the fundamental load current, whereas the universal bridge generates the rest (I_R) [30-31]. In analytical concept, the Fourier cosine transform yields:

$$\begin{aligned} A &= \int_0^T I_L(t).\cos(\omega t)dt, \quad B = \int_0^T I_L(t).\sin(\omega t)dt, \\ C &= \int_0^T V_L(t).\cos(\omega t)dt, \quad D = \int_0^T V_L(t).\sin(\omega t)dt, \end{aligned} \tag{1}$$

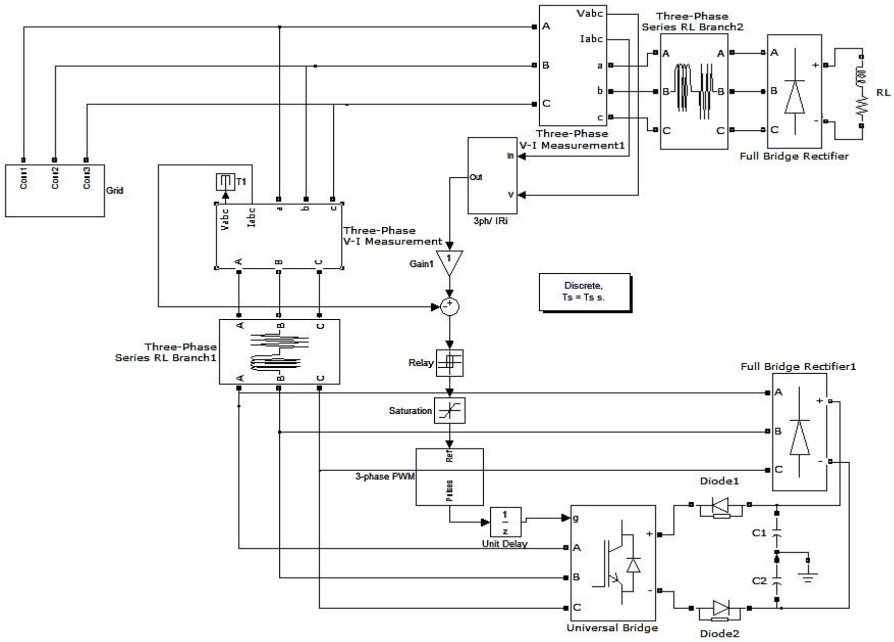

Fig. 2. The system configuration with APF.

where, V_L is the grid voltage. Considering the following definitions:

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

The current I_D can be reconstructed as following:

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

Based on the above relation in a three-phase system, the currents can be expressed as:

$$\begin{aligned} I_{D1} &= K_1\cos(\varphi_1)\sin(\omega t + \beta_1) \\ I_{D2} &= K_2\cos(\varphi_2)\sin(\omega t + \beta_2 + \frac{2\pi}{3}) \\ I_{D3} &= K_3\cos(\varphi_3)\sin(\omega t + \beta_3 - \frac{2\pi}{3}) \end{aligned} \tag{4}$$

The values of K, φ and β should be separately calculated for each phase. Figure 3 shows the diagram of generating I_D for 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.

As a result, the reference currents of the filter are derived as follows:

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

where, I_{Ri} and I_{Li} are the reference and load currents for phase i, respectively.

Eventually, the gating signals for the universal bridge are obtained by comparing the actual filter currents with the reference current templates those are determined from (5).

2.2. Optimization problem

The optimization problem for APF seeks four optimum variables, including series inductance, parallel inductance, output amplitude and bandwidth of the hysteresis current controller and three objectives which are

i) To minimize current THD.

ii) To maximize power factor (PF).

To minimize the universal bridge current (the amplitude of the IGBT bridge current).

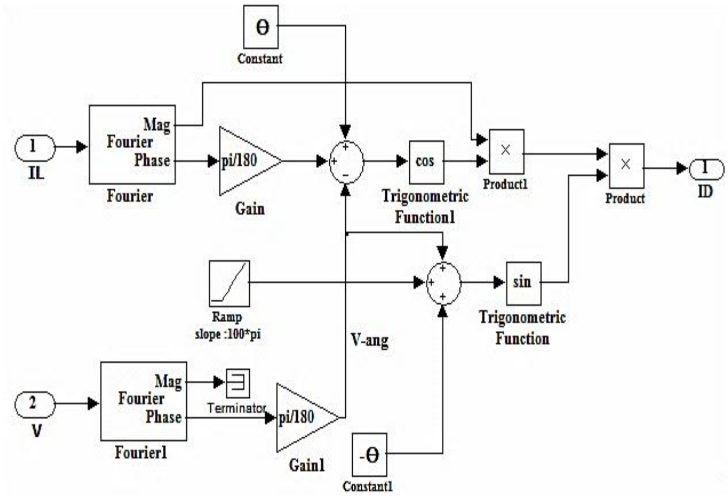

Fig. 3. Block diagram for generating I_D.

3. MULTIOBJECTIVE OPTIMIZATION PROBLEM FORMULATION

A multi-objective optimization problem can generally be expressed as [32]:

Minimize:

$$f(x) = (f(x), \dots f_i(x), \dots f_k(x)) \quad (6)$$

subject to:

$$x = (x_1, x_2, \dots x_n) \in X \;\&\; y = (y_1, y_2, \dots y_k) \in Y$$

where,

f(x): vector of the objective functions to be minimized

x: vector of design variables

X: parameter space

y: objective vector

Y: objective space

In the APF optimization problem, the vector of variables is regarded as:

$X = [x_1\ x_2\ x_3\ x_4]$

where, x_1 is half of the hysteresis current controller bandwidth; x_2 is the output amplitude of the hysteresis current controller; and x_3 and x_4 are the inductance of the series and parallel inductors in *mH*, respectively. All variables range is [0 5], except x_1 which range is [0.01 5]. This is because a very small value of the hysteresis bandwidth causes a very high switching frequency that is not desirable. The objective function vector is defined as:

$J = [j_1\ j_2\ j_3]$

where, j_1 is the THD of the current supplied by the grid; j_3 is the IGBT bridge current amplitude; and j_2 is a transformation of PF, such that larger values of PF make smaller values of j_2. Here, j_2 is defined as $j_2 = 10^{20(1.15-PF)}$.

This definition is empirical and novel in that it facilitates sufficient sensitivity for values of PF near one, such that separate objective function weights are not required. To solve the APF design problem, two different multi-objective optimization techniques are applied: NSGA-II [7, 8] and SPEA2 [10].

3.1. NGSA-II optimization technique

NSGA-II [7, 8] is capable of identifying a better spread of solutions and obtaining a non-dominated front compared with previous techniques. The NSGA-II algorithm includes the following main steps:

i) A random parent population, *P* is generated.

ii) The parent population is sorted based on non-domination.

iii) Fitness is assigned, and an offspring population, *Q* is created by using binary tournament, recombination and mutation.

iv) Parent and offspring populations are combined to form a combined population, *R* with size *2N* (except first period).

v) *R* is sorted based on non-domination: *R*= {*F1*, *F2*, …}.

vi) New parent population is formed according to domination and crowding distance.

vii) If the maximum number of generations is reached, then stop; else, go to step ii.

The NSGA-II procedure is shown in Figure 4. More details on the algorithm, including non-dominated and crowding distance sorting, are given in [18].

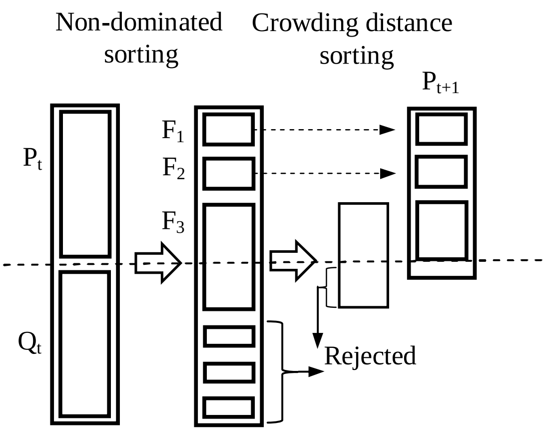

Fig. 4. NSGA-II optimization technique.

3.2. SPEA2 optimization technique

SPEA [10] is a relatively recent technique for finding or approximating the Pareto-optimal set for solving multi-objective optimization problems. In [12, 13], SPEA shows excellent performance compared with other multi-objective evolutionary algorithms and is therefore used as a point of reference in several recent investigations [11]. Furthermore, SPEA has been used in different applications [9]. In this paper, an improved version called SPEA2 [10] is used for finding optimal solution in the HPF application. The SPEA2 algorithm is described as follows:

Step 1: **Initialization**: An initial population, P_0 is generated, and the empty archive (external set) $\mathbb{P}_0 = \Phi$ at $t = 0$ is created.

Step 2: **Fitness assignment**: The fitness values of individuals in $\boldsymbol{P}_t$ and $\mathbb{P}_t$ are calculated.

Step 3: **Environmental selection**: All non-dominated individuals in $\boldsymbol{P}_t$ and $\mathbb{P}_t$ are copied to $\mathbb{P}_{t+1}$. If size of $\mathbb{P}_{t+1}$ *exceeds* $\mathbb{N}$, $\mathbb{P}_{t+1}$ is reduced using the truncation operator; otherwise, if the size of $\mathbb{P}_{t+1}$ is less than $\mathbb{N}$, $\mathbb{P}_{t+1}$ is filled with dominated individuals in $\boldsymbol{P}_t$ and $\mathbb{P}_t$. $\mathbb{N}$ is the archive size.

Step 4: **Termination**: If $t \geq T$ or another stopping criterion is satisfied, then ***A* (non-dominated set)** is fixed as the set of decision vectors represented by the non-dominated individuals in $\mathbb{P}_{t+1}$; then, stop. *T* is the maximum number of generations.

Step 5: **Mating selection**: Binary tournament selection with replacement on $\mathbb{P}_{t+1}$ is performed to fill the mating pool.

Step 6: **Variation**: Recombination and mutation operators are applied to the mating pool, and $\boldsymbol{P}_{t+1}$ is set to the resulting population. The generation counter $(t = t + 1)$ is incremented, and Step 2 is repeated.

In contrast to SPEA, SPEA2 uses a fine-grained fitness assignment strategy that incorporates density information. Furthermore, the archive size is fixed, that is, whenever the number of non-dominated individuals is less than the predefined archive size, the archive is filled by dominated individuals. 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 that has similar features but does not lose boundary points. Finally, another difference from SPEA is that only members of the archive participate in the mating selection process [10].

4. RESULTS

The APF optimization problem is solved using two optimization techniques, described in the previous section, by taking into account the following assumptions and considerations:

i) The techniques are run for 50 iterations and the termination tolerance on *x* and *J* is set to 10^{-6}.

ii) For both techniques, forward type finite differences are used to estimate gradients, and variable changes are limited between 10^{-8} and 0.1.

iii) For NSGA-II, the crossover function is of the scattered type on 80% of the population and the migration is performed in the forward direction on 20% of the population according to the Gaussian function. The selection type is of the uniform stochastic function and the mutation type is Gaussian.

iv) For SPEA2, the selection type is tournament using two individuals and the recombination and mutation probability (both for variables and individuals) is set to 1%. The variable swap probability is 0.5%.

v) For both techniques, at the end of the optimization process and from the Pareto optimal set (resultant set of solutions shown in Figs. 5 and 6 and considering the preferences in the objectives, a single solution is selected. In the Pareto optimal set for the NSGA-II and SPEA2 techniques, 21 and 50 solutions were generated, respectively.

vi) The most prominent disadvantage of the this approach is that it is time-consuming, meanwhile, depends on the multi-objective optimization techniq-ues, the running time increases when the number of iterations increases.

Figures 7 and 8 show harmonic spectrum of grid current phase ‘*A*’ obtained from each of the techniques.

Simulations in MATLAB environment were carried out on the proposed system, as shown in Fig. 2. The system parameters are given in Table 1. Figures 9 and 10 show the main currents, load voltages as well as load and filter currents for each phase of the two different techniques used in the filter design. Table 2 presents the statistical results for comparing the results of two optimization techniques after 50 iterations. Comparing the results of Figures 9 and 10 as well as those in Table 2, both techniques yield a THD of less than 1.2%, a PF greater than 0.998, and the IGBT bridge current of less than 15 A. The better results relative to the objective functions, which are reducing current THD, reactive power, and IGBT bridge current, are achieved by using the SPEA2 technique.

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 T_s	1 µs

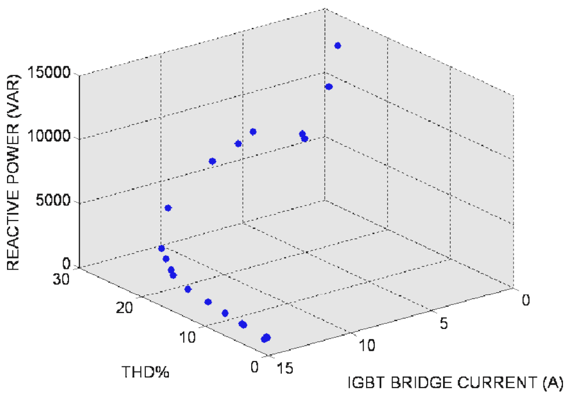

Fig. 5. Pareto optimal set (NSGAII technique).

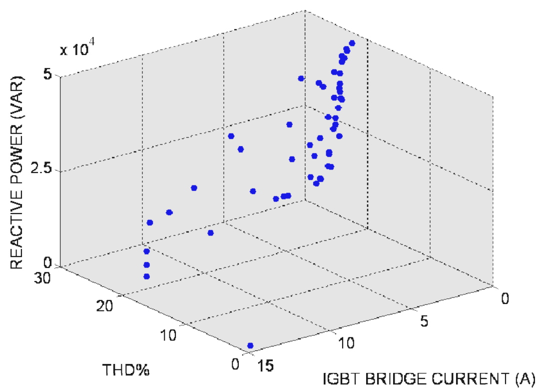

Fig. 6. Pareto optimal set (SPEA2 technique).

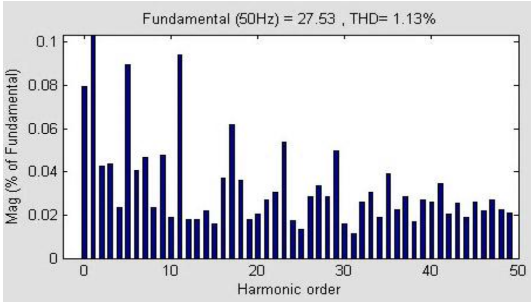

Fig. 7. Harmonic spectrum of grid current phase 'a' for NSGA-II technique.

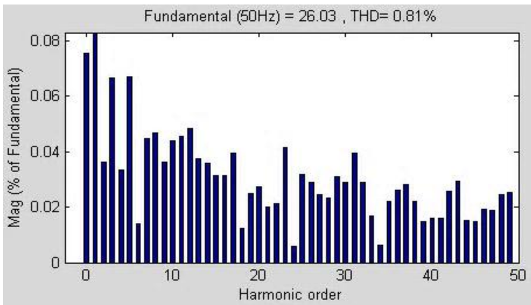

Fig. 8. Harmonic spectrum of grid current phase 'a' for SPEA2 technique.

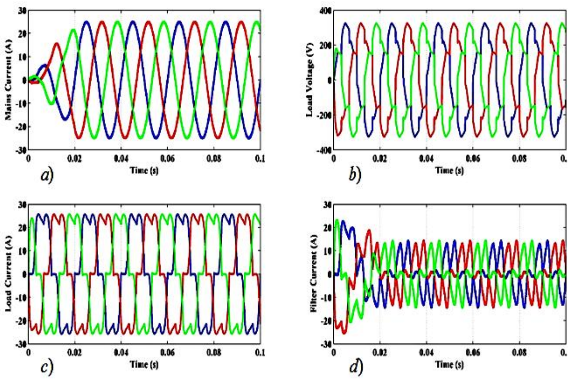

Fig. 9. The results of NSGA-II technique.

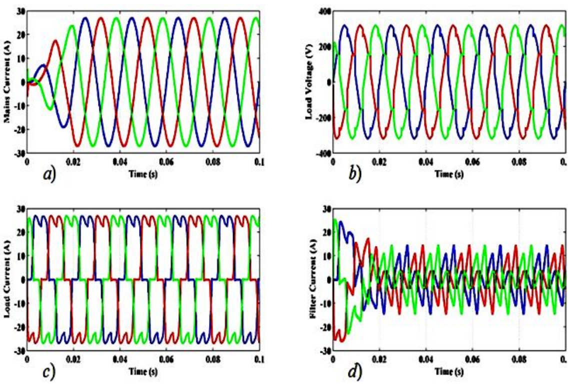

Fig. 10. The results of SPEA2 technique.

Table 2. Results Comparison.

	NSGA-II	SPEA2
x_1 (Hys. BW)	0.103	0.017
x_2 (Hys. Amp.)	2.144	2.353
x_3 (Ser. mH)	1.525	3.378
x_4 (Par. mH)	2.557	2.767
j_1 (THD %)	1.13	0.81
j_2 $(10^{20(1.15-PF)})$	1003.05 (PF=0.999)	1001.53 (PF=0.999)
j_3 (I_{Max} A)	14.818	14. 576

5. CONCLUSIONS

This paper presented an optimal APF filter design method to compensate current harmonics and the reactive power of a nonlinear load simultaneously. Two multi-objective optimization techniques have been studied and applied to the APF design problem, aiming at finding the optimized values of the hysteresis controller parameters used in the current generator. The test results proved that two multi-objective optimization techniques, namely, NSGA-II and SPEA2 techniques are effective in solving the APF design problems. Among these techniques, the SPEA2 exhibited the better performance relative to the objectives. Considering hysteresis controller parameters as optimization variables, the quality of the optimization result is greatly improved.

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