

Multi-objective Optimization of Double-Tuned Filters in Distribution Power Systems Using Non-Dominated Sorting Genetic Algorithm-II

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Abstract

Passive filters are commonly used for harmonic mitigation and power factor correction in industrial power systems supplying non-linear loads. This paper firstly employs optimal design of two damped double-tuned filter schemes to minimize the filter and system's line loss while the individual and total harmonic distortion limits of the IEEE 519 standard and desired interval of the displacement power factor as constraints. For the solution of the formulated multi-objective optimization problem, Non-Dominated Sorting Genetic Algorithm (NSGA-II) is used. The results show that both schemes have the same fundamental frequency reactive power compensation, the line loss reduction and voltage regulation capabilities for the typical industrial power system with distorted background voltage and non-linear loads. On the other hand, it is also observed that the first studied scheme has considerable lower loss, while the second one has considerably higher current harmonic mitigation capability.

1. Introduction

Harmonic distortion is one of the significant power quality problems which lead to extra losses, overheating and reduced loading capacity in cables, transformers, and induction machines, malfunction of protective relays and electronic circuits, resonance problems among the inductive equipment and shunt capacitors. Harmonics also cause poor power factor levels, poor efficiency and low distributed generation hosting capacity levels in the systems [1, 2].

In the literature, to reduce the adverse effects of harmonics on power systems, passive and active filters are used. Active filters have superior performance on harmonic mitigation and reactive power compensation when compared to the passive filters. However, in today's power systems, passive filters are much employed than active ones since they have considerably lower costs, simpler construction, and different design configurations that can provide different impedance-frequency characteristics.

Passive filters design is usually handled as an optimization problem to guarantee that the desired objectives are met, no

violation of constraints took place, and that filter power loss and cost are not oppositely affected due to the design conditions.

Although single-tuned filter or a group of single-tuned filters are widely used in practice, they can cause resonance problems in the system. On the other hand, high-pass filters can dampen harmonic resonance that may occur between the system and filter, but with less harmonic mitigation capability and more power loss than tuned filters. Some high-pass filters have no (such as C-type filters) to few (such as third-order damped filters) power losses at the fundamental frequency compared to the conventional first-order and second-order filters [3]. In view of that, damped double-tuned filters have recently been considered in a few studies as promising schemes that can combine between tuned and damped filter advantages [4-7]. However, their design algorithms are still under discussion in the literature. Accordingly, this paper presents optimal design of two different schemes of damped-type double-tuned passive filter. A typical distribution system with background harmonic voltage distortion and a group of linear and nonlinear loads are considered in the analysis results. The objective of the optimal filter designs is to minimize both the system's transmission line loss and filter's loss simultaneously, while conserving the individual and total harmonic distortion limits of IEEE Std. 519, as well as achieving an acceptable range of the load power factor. Non-Dominated Sorting Genetic Algorithm (NSGA-II) [8, 9] is employed for the solution of the formulated optimization problem. The results of both schemes are comparatively evaluated by regarding various performance criteria.

2. Harmonic Suppression Using Damped Type Double-Tuned filter

In this section, the working principles, design expressions, optimal design problem formulation and optimization algorithm of the damped double-tuned filters are presented.

2.1. Operating Principle of the Double-Tuned Filters

A double-tuned filter, ignoring the parasitic resistance of inductors and capacitors, can be provided by series connection of two inductor and capacitor groups. The first group is formed by their series connection, while the other group is formed by

their parallel connection, as shown in Fig. 1(a).

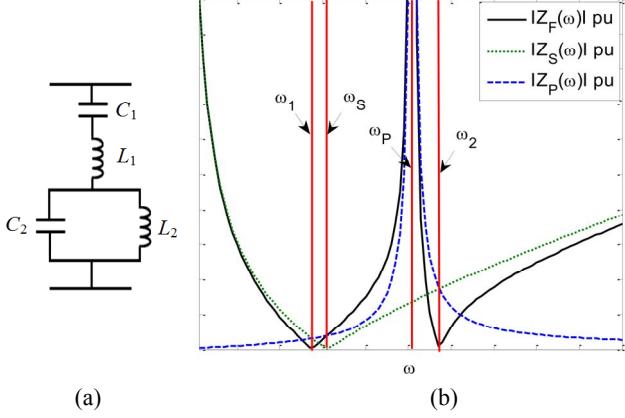


Fig. 1. Double-tuned filter: (a) Equivalent circuit, and (b) Impedance- angular frequency response

For any angular frequency (ω), impedance of the series connected inductor and capacitor (L_1C_1), Z_S , is expressed as given in Eq. (1), and its series resonance angular frequency (ω_S), which lead to zero series impedance, *i.e.* $Z_S=0$, is given as:

$$Z_S(\omega) = j \left(\omega L_1 - \frac{1}{\omega C_1} \right) \quad (1)$$

$$\omega_S = \frac{1}{\sqrt{L_1 C_1}} \quad (2)$$

Also, impedance of the parallel connected inductor and capacitor (L_2C_2), Z_P , is expressed as given in Eq. (3), and its parallel resonance angular frequency (ω_P), which lead to infinite parallel impedance, *i.e.* $Z_P=\infty$, is given as:

$$Z_P(\omega) = -j \left(\omega C_2 - \frac{1}{\omega L_2} \right)^{-1} \quad (3)$$

$$\omega_P = \frac{1}{\sqrt{L_2 C_2}} \quad (4)$$

Hence, the total impedance of the filter (Z_F), which is expressed in Eq. (5), has two resonance angular frequency (ω_1 and ω_2), thus

$$\begin{aligned} Z_F(\omega) &= Z_S(\omega) + Z_P(\omega) \\ &= j \frac{\omega^4 L_1 L_2 C_1 C_2 - \omega^2 (L_1 C_1 + L_2 C_2 + L_1 C_2) + 1}{\omega C_1 (\omega^2 L_2 C_2 - 1)} \quad (5) \end{aligned}$$

The series, parallel, total impedance-angular frequency characteristics are illustrated in Fig. 1(b). One can see from this figure that $|Z_S|$ is nil at its resonance angular frequency denoted as ω_S , whilst $|Z_P|$ is extremely high at its resonance angular frequency denoted as ω_P , and $|Z_F|$ is nil at its two resonance angular frequencies denoted as ω_1 and ω_2 .

On the other hand, there are various configurations of damped type double-tuned filter in the literature [7]. In this study, two configurations, given in Fig. 2, are considered. Impedance of both schemes can be expressed in (6) and (7) for

Types 1 and 2 of damped double-tuned filter, respectively.

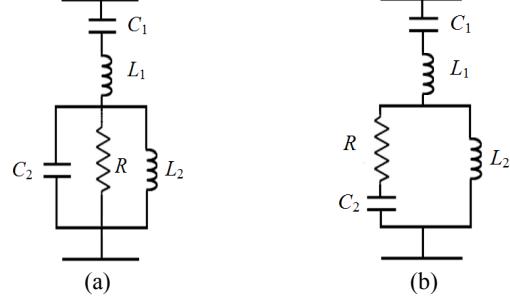


Fig. 2. Two schemes of the damped type double-tuned filter: (a) Type 1, and (b) Type 2

$$Z_F(\omega) = j \left(\omega L_1 - \frac{1}{\omega C_1} \right) + \frac{1}{\frac{1}{j\omega L_2} + j\omega C_2 + \frac{1}{R}} \quad (6)$$

$$Z_F(\omega) = j \left(\omega L_1 - \frac{1}{\omega C_1} \right) + \frac{1}{\frac{1}{j\omega L_2} + \frac{1}{R - j \frac{1}{\omega C_2}}} \quad (7)$$

Furthermore, for Type 1 and 2 damped double-tuned filters, the impedance-angular frequency characteristics are shown in Fig. 3.

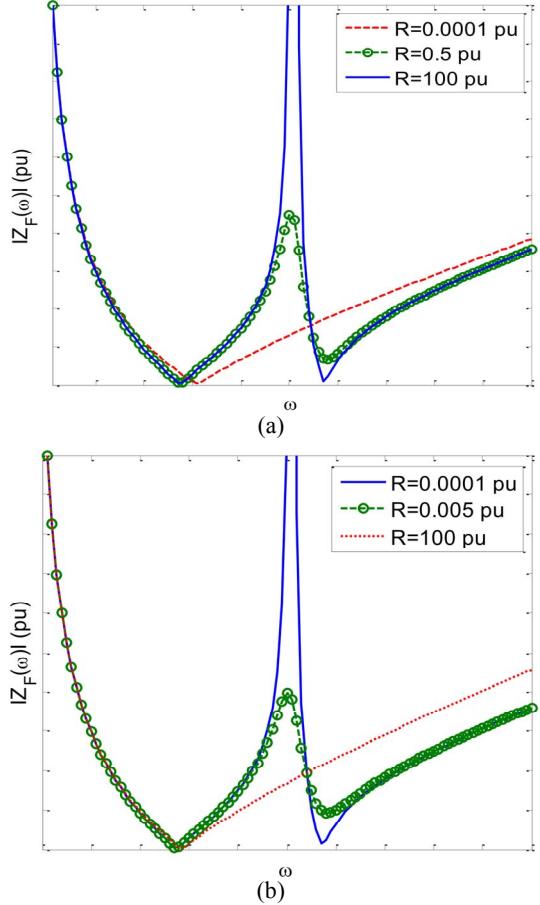


Fig. 3. The impedance-angular frequency characteristics of the damped type double-tuned filter: (a) Type 1, and (b) Type 2

It can be clearly mentioned from Fig. 3(a) that Type 1 filter (DDT₁) acts like single-tuned and double-tuned filter for considerable low and high resistance values, respectively. Fig. 3(b) shows that the Type 2 (DDT₂) filter acts like single-tuned and double-tuned filter for considerable high and low resistance values, respectively. Besides, the same figures also pointed out that the proper value of the resistance can reduce the sharpness of the double tuned filter at ω_P .

2.2. Double-Tuned Filter's Design Expressions

Design expressions of the filters are derived below. Firstly, equating Eq. (5) to zero to find its roots (ω_1 and ω_2), one can get

$$\omega^4 L_1 C_1 L_2 C_2 - \omega^2 (L_1 C_1 + L_2 C_2 + L_2 C_1) + 1 = 0 \quad (8)$$

Solving Eq. (8) based on the equivalence between double-tuned filter and two parallel single-tuned filters, and using Vieta's formulas that express relations between the coefficients and roots of a polynomial [6, 10-13], Eq. (9) is established:

$$\omega_1^2 \omega_2^2 = \frac{1}{L_1 C_1 L_2 C_2} \Rightarrow \omega_1 \omega_2 = \left(\frac{1}{\sqrt{L_1 C_1}} \right) \left(\frac{1}{\sqrt{L_2 C_2}} \right) = \omega_s \omega_p \quad (9)$$

From (9), one can find ω_s , as follows:

$$\omega_s = \frac{\omega_1 \omega_2}{\omega_p} \quad (10)$$

Hence, substituting (2) and (4) into (8); then

$$\frac{\omega^4}{\omega_s^2 \omega_p^2} - \omega^2 \left(\frac{1}{\omega_s^2} + \frac{1}{\omega_p^2} + \frac{C_1}{C_2} \left(\frac{1}{\omega_p^2} \right) \right) + 1 = 0 \quad (11)$$

At ω_1 , the relation between C_1 and C_2 , based on (11) is expressed as:

$$\frac{C_1}{C_2} = \frac{\omega_1^4 - \omega_p^2 \omega_1^2 - \omega_s^2 \omega_1^2 + \omega_p^2 \omega_s^2}{\omega_s^2 \omega_1^2} = \frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_s^2} - 1 \quad (12)$$

At fundamental frequency, i.e. $\omega = \omega_F$, $Z_F(\omega_F)$ can be written in terms of fundamental frequency supply voltage (V_1) and filter's fundamental frequency reactive power (Q_F) as;

$$Z_F(\omega_F) = -j \frac{V_1^2}{Q_F} \quad (13)$$

Also from (5), $Z_F(\omega_F)$ can be expressed as:

$$Z_F(\omega_F) = j \frac{\omega_F^4 L_1 C_1 L_2 C_2 - \omega_F^2 L_1 C_1 - \omega_F^2 L_2 C_2 + 1 - \omega_F^2 L_2 C_1}{\omega_F C_1 (\omega_F^2 L_2 C_2 - 1)} \quad (14)$$

By equating the right hand sides of (13) and (14); and using the expressions of ω_s and ω_p , one can get;

$$\frac{\omega_F^4}{\omega_s^2 \omega_p^2} - \omega_F^2 \left(\frac{1}{\omega_s^2} + \frac{1}{\omega_p^2} + \left(\frac{C_1}{C_2} \frac{1}{\omega_p^2} \right) \right) + 1 = -\frac{V_s^2}{Q_F} \quad (15)$$

$$C_1 = -\frac{Q_F}{V_s^2} \left(\frac{\omega_F^4 - \omega_F^2 \left(\frac{\omega_p^2}{\omega_s^2} + 1 + \left[\frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_s^2} - 1 \right] \right) + \omega_p^2}{\omega_F (\omega_p^2 - \omega_F^2)} \right) \quad (16)$$

Therefore, from (12) and (16), the expressions of C_1 and C_2 can be written as follows:

$$C_1 = \left[\frac{\omega_F^4 - \omega_F^2 \left(\frac{\omega_1^2 + \omega_2^2}{\omega_s^2} \right) + \omega_p^2}{\omega_F (\omega_p^2 - \omega_F^2)} \right] \left(\frac{Q_F}{V_s^2} \right) \quad (17)$$

$$C_2 = C_1 \left(\frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_s^2} - 1 \right)^{-1} \quad (18)$$

Additionally, from (2) and (4), L_1 and L_2 can be expressed as follows:

$$L_1 = \frac{1}{\omega_s^2 C_1} \quad (19)$$

$$L_2 = \frac{1}{\omega_p^2 C_2} \quad (20)$$

Finally, one can formulate ω_1 , ω_2 , and ω_P in terms of ω_F , as follows:

$$\omega_1 = h_1(\omega_F), \omega_2 = h_2(\omega_F), \text{ and } \omega_p = m(\omega_F) \quad (21)$$

where h_1 and h_2 , are the tuning harmonic orders, and m is the parallel resonance harmonic order.

2.3. Formulation of the Optimal Filter Design Problem

In this paper, two kinds of double-tuned damped filters are employed for harmonic mitigation and power factor correction of the system shown in Fig. 4. Fig. 4(a) shows the single-line diagram of the system, where the system has a consumer with three-phase linear and nonlinear loads, the supply line, and the passive filter has to be connected to the load bus. The system can be simulated by using its single-phase equivalent circuit given in Fig. 4(b). In the equivalent circuit, background harmonic voltage and the harmonic currents generated by the non-linear loads are modelled as voltage and current h th harmonic sources (V_{sh} and I_{Lh}).

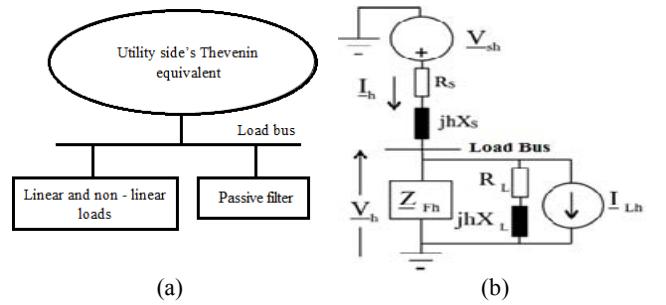


Fig. 4. System under study: (a) Single-line diagram, and (b) Equivalent circuit

In the equivalent circuit, the linear load, supply line and the filter are expressed as h th harmonic impedances denoted as \underline{Z}_{Sh} , \underline{Z}_{Lh} and \underline{Z}_{Fh} , thus

$$\underline{Z}_{Sh} = R_S + jhX_S \quad (22)$$

$$\underline{Z}_{Lh} = R_L + jhX_L \quad (23)$$

$$\underline{Z}_{Fh} = j \left(\omega_h L_1 - \frac{1}{\omega_h C_1} \right) + \frac{1}{\frac{1}{j\omega_h L_2} + j\omega_h C_2 + \frac{1}{R}} \quad \text{for DDT1} \quad (24)$$

$$\underline{Z}_{Fh} = j \left(\omega_h L_1 - \frac{1}{\omega_h C_1} \right) + \frac{1}{\frac{1}{j\omega_h L_2} + \frac{1}{-j\frac{1}{\omega_h C_2} + R}} \quad \text{for DDT2} \quad (25)$$

where ω_h is h th harmonic angular frequency, R_S and X_S are the fundamental resistance and reactance of the supply line impedance, and R_L and X_L are the fundamental resistance and reactance of the load impedance. Based on the basic circuit theorems, for h th harmonic order, expressions of the line current and load bus voltage can be expressed as follows, where the subscript ($_h$) denotes phasor values of the respective expressions. Also, \underline{Z}_{FLh} represents the parallel equivalent impedance of \underline{Z}_{Fh} and \underline{Z}_{Lh} .

$$I_h = \frac{V_{Sh}}{\underline{Z}_{Sh} + \underline{Z}_{FLh}} + \frac{\underline{Z}_{FLh}}{\underline{Z}_{Sh} + \underline{Z}_{FLh}} I_{Lh} \quad (26)$$

$$V_h = V_{Sh} - I_h \underline{Z}_{Sh} \quad (27)$$

Voltage and current total harmonic distortions, denoted as $THDV$ and $THDI$, can be found by using Eqs. (28) and (29):

$$THDV = \frac{\sqrt{\sum_{h \geq 2} V_h^2}}{V_1} \cdot 100 \quad (28)$$

$$THDI = \frac{\sqrt{\sum_{h \geq 2} I_h^2}}{I_1} \cdot 100 \quad (29)$$

where V_1 and I_1 are the rms voltage and current at the fundamental harmonic, and V_h and I_h are the h th harmonic rms voltage and current, respectively. Also, in terms of the fundamental harmonic active power ($P_1 = V_1 I_1 \cos(\phi_1)$) and fundamental harmonic apparent power ($S_1 = V_1 I_1$), the displacement power factor (DPF) can be obtained as:

$$DPF = \frac{P_1}{S_1} \quad (30)$$

Finally, the expression of the line loss (ΔP_L), filter loss and (ΔP_F) can be written, as follows:

$$\Delta P_L = 3 \sum_{h \geq 1} I_h^2 R_S \quad (31)$$

$$\Delta P_F = 3 \sum_{h \geq 1} \frac{V_h^2}{Real(\underline{Z}_{Fh})} \quad (32)$$

In this work, the two double-tuned damped type filters are designed to minimize ΔP_L and ΔP_F , simultaneously. The individual (CIHD_{hMax} and VIHD_{hMax}) and total harmonic distortion (THDI_{Max} and THDV_{Max}) limits of the IEEE 519 standard and desired interval of DPF (between 90% lagging and 100%) are taken as constraints. In addition to that, parallel resonance harmonic order (m) should be between h_1 and h_2 . As a result, for the studied system, which is considered a benchmark system in many previous studies [14], the problem formulation of the filters design is proposed as given below.

Find: Q_F , h_1 , h_2 , m , and R parameters of the filter to minimize the following objective functions.

$$\text{Minimize} \begin{cases} \Delta P_L = f_1(Q_F, h_1, h_2, m, R) \\ \Delta P_F = f_2(Q_F, h_1, h_2, m, R) \end{cases} \quad (33)$$

Subjected to the following constraints:

$$\begin{aligned} 90\% &\leq DPF(Q_F, h_1, h_2, m, R) \leq 100\%, \\ THDI(Q_F, h_1, h_2, m, R) &\leq THDI_{Max}, \\ THDV(Q_F, h_1, h_2, m, R) &\leq THDV_{Max}, \\ CIHD_h(Q_F, h_1, h_2, m, R) &\leq CIHD_{h,Max}, \\ VIHD_h(Q_F, h_1, h_2, m, R) &\leq VIHD_{h,Max}, \\ h_1 &< m < h_2. \end{aligned} \quad (34)$$

2.4. Solution Algorithm of Optimal Design Problem

Non-Dominated Sorting Genetic Algorithm (NSGA-II) is a multi-objective optimization algorithm developed by N. Srinivas and K. Deb [8, 9]. It provides a set of solutions, so-called 'non-dominated solutions,' which further to be plotted in the Pareto plot, while the remaining solutions, so-called 'dominated solutions,' are discarded. Its main advantages are the low computational speed, less complexity, applicability in a wide range of problems, real valued representation, and fast convergence to the solution.

The search algorithm can be summarized as below:

Step 1: Create an initial parent population (P_t) of size Z .

Step 2: Sort P_t based on non-domination procedure.

Step 3: Assign a rank based on non-domination level for all non-dominated solutions (1 is the best level).

Step 4: Tournament selection, recombination, and mutation operators are to be used to create an offspring population (Q_t) of the same size Z .

Step 5: Starting from the 1st generation to the last generation, perform the following procedure:

- Create a combined population R_t of size Z_t by combining P_t and Q_t .
- The combined population R_t is sorted according to the non-domination procedure to identify all the non-dominated fronts (Fr_1, Fr_2, \dots).
- Further, the new parent population P_{t+1} , is formed by adding solutions from the first ranked non-dominated front till exceeding the population size Z , then some of the lower ranked non-dominated solutions will be rejected. This is achieved using crowded comparison operator based on the crowding distance (CD). By definition, CD is the average distance of two solutions

- on either side of a particular solution along each of the objectives.
- Finally, the newly generated population of size Z is used for performing the selection, crossover, and mutation operations to create the new offspring population, Q_{t+1} of the same size Z .

Step 6: Repeat Step 5 till reaching the maximum number of iterations.

3. Analysis Results

The studied system has a rated three-phase supply voltage and short circuit power as 4.16 kV and 150 MVA, respectively. In the uncompensated case of the system, three-phase fundamental frequency active (P_1) and reactive (Q_1) powers, DPF , and ΔP_L measured at the load bus are 5.1 MW, 4.965 MVAr, 71.65%, and 31.7406 kW. The R_S , X_S , R_L and X_L values of the system's single-phase equivalent circuit are 0.0115, 0.1154, 1.742, and 1.696 Ω , respectively. Source background harmonic voltages are 76, 48, 24 and 12 volt for the 5th, 7th, 11th, and 13th harmonic orders, respectively. As well, harmonic load currents are 99.56, 44.79, 19.91, and 9.95 ampere for the same harmonic orders, respectively. The $THDV$ and $THDI$ values are 6.061% and 10.263%, respectively. With respect to IEEE Std. 519, the $THDV$ and $THDI$ of the system should not exceed 5% and 8%, respectively. Also, for all harmonic orders, $VIHD_{hMax}$ is 3%. In addition, $CIHD_{hMax}$ is 7% for the 5th and 7th harmonic orders, and 3.5% for the 11th and 13th harmonic orders. Consequently, two schemes of the damped type double-tuned filter are optimally designed for harmonic mitigation, fundamental frequency power factor correction, and electric loss reduction.

The optimal designs of the proposed filter types are indicated in Table 1 and the power quality parameters calculated after both filters are individually connected to the load bus are shown in Table 2.

Table 1. Parameters of the optimal filter designs

Parameters	Type 1	Type 2
Q_F (kVAr)	1428.42	1414.05
C_1 (mF)	0.8176	0.8110
L_1 (mH)	0.8604	0.9177
C_2 (mF)	11.5984	5.5763
L_2 (mH)	0.0295	0.0643
h_1	3.6812	3.482
h_2	5.615	5.631
m	5.446	5.3144
R (Ω)	7.3185	0.1

Table 2. Power quality parameters of the compensated system

Parameters	Type 1	Type 2
DPF (%)	99.941	99.939
$THDV$ (%)	3.6443	3.6270
$THDI$ (%)	7.0805	6.6370
V_1 (kV)	2.391	2.391
ΔP_L (kW)	17.2697	17.2603
ΔP_F (kW)	0.0274	0.3164

For individual harmonic distortion limits, both types' results are well below the standard values. In addition, it is clearly seen from Table 2 that both schemes achieve almost the same DPF ,

ΔP_L , $THDV$ and V_1 values around 99.94%, 17.26 kW, 3.60% and 2.391 kV, respectively. This means that for the studied benchmark system, both provides the same fundamental frequency reactive power compensation, the transmission loss reduction and voltage profile improvement properties. However, this is not the case for $THDI$ and ΔP_F . For both filter types, the achieved ΔP_F values are 0.0274 and 0.3164 kW, and the achieved $THDI$ values are 7.0805% and 6.6370%, respectively. Thus, one can see that first type provides lower filter loss, while the second type provides better current harmonic mitigation.

The Pareto fronts of non-domination populations' results of the multi-objective optimization for both filter types are shown in Fig. 5. The x -axis represents the first objective function (ΔP_L), and the y -axis represents the second objective function (ΔP_F).

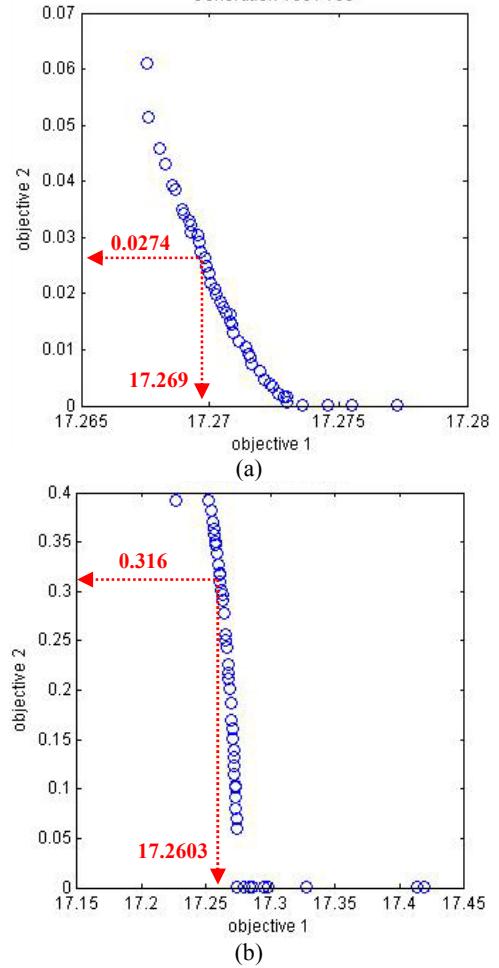


Fig. 5. Pareto fronts representing the non-dominated solutions: (a) Type1, and (b) Type2

4. Conclusions

Because of their various advantages, double-tuned filters are widely used in power systems. This paper presents a simple algorithm for determining the optimal parameters of the double tuned filter using NSGA-II as a multi-objective optimizer. In this algorithm, minimization of the transmission line power losses and filter's losses are selected as optimization's objectives in order to comprise between results of both schemes

of the damped double-tuned filter. In addition to the filter parameters constraints, the individual and total harmonic distortion limits of IEEE Standard 519 and the desired range of the displacement power factor are taken as constraints.

The results obtained from the considered industrial power system with the background voltage harmonic distortion and harmonic currents injected by the nonlinear loads; show that both filter types have the same fundamental frequency reactive power compensation, transmission loss reduction, and voltage regulation capabilities. However, the first type of the damped double-tuned filter provides better loss reduction compared to the second type, while the second type provides better current harmonic mitigation capability.

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