# Optimal Planning of Harmonic Filters in an Industrial Plant Considering Uncertainty Conditions

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*Abstract:* - This paper presents an integrated approach feasible direction method and genetic algorithm (FDM+GA) to investigate the planning of large-scale passive harmonic filters. The optimal filter scheme can be obtained from a system under abundant harmonic current sources where harmonic amplification problems should be avoided. The constraints of harmonics with orders lower than the filter tuned-points have been set stricter to avoid amplifying non-characteristic harmonics. In order to determine a set of weights of objective function representing the relative importance of each term, the simplest and most efficient form of triangular membership functions have been considered. The searching for an optimal solution has been applied to the harmonic problems in a chemical plant, where three 6-pulse rectifiers are used.

*Key-Words:* - **Feasible direction method, Genetic algorithm, Passive harmonic filters, Harmonic current.**

## 1 Introduction

Wanger [1] pointed out that nonlinear loads introduce harmonic currents. The IEEE Standard 519-1992 [2] provided a guideline for the limitation and mitigation of harmonics. Basic [3] proposed many solutions, such as use of higher-pulse converters, modification of electric circuit configurations, choice of transformer connections, and application of harmonic filters. Gonzalez [4] utilized passive harmonic filters suppressing the harmonic distortion. Akagi [5] also explored the idea of applying of active harmonic filters produce inverse harmonic currents to reduce levels of harmonic distortion and avoid resonant problems. The hybrid filters are composed of active and passive harmonic filters by taking benefits of both schemes proposed by Fujita [6]. In comparison, passive filters are still popular for large-size customers in several tens-MVA levels.

The genetic algorithm (GA) has been developed to mimic some processes observed in natural evolution. Holland [7] published the fundamental principles of genetic algorithms. Berizzi [8] applied the GA in locating and sizing of passive filters. While the convergent speed of GA may be slow, the feasible direction method (FDM) proposed by Zoutendijk [9] has quicker convergent characteristics. In other words, it takes less time to find the optimal solution. Wu [10] used the FDM as a gradient-based optimization approach to the harmonic filter design. The FDM has also been used in the study of short-term operation and power exchange planning by Rakic [11]. However, the main shortcoming of FDM is the trapping in local optimal solutions.

Lin [12] treated the optimal harmonic filter design as a single objective problem. However, customers have obtained more stringent requirements from electric utilities in recent years. If a filter planning wants to determine an optimal solution to satisfy many objectives, some objectives could conflict with others. Fuzzy set theory provides membership functions, which represent uncertain and subjective information. The triangular membership function is generally selected for determining a set of weights of objective function to represent the relative importance o f each term. In addition, Yager [13] proposed the centroid method to determine the geometric center of fuzzy number.

To increase convergent speed and avoid local optimal trapping, an approach of combined feasible direction method and genetic algorithm (FDM+GA) is adopted in this paper for the large-scale passive harmonic filter design problems. The basic strategy is

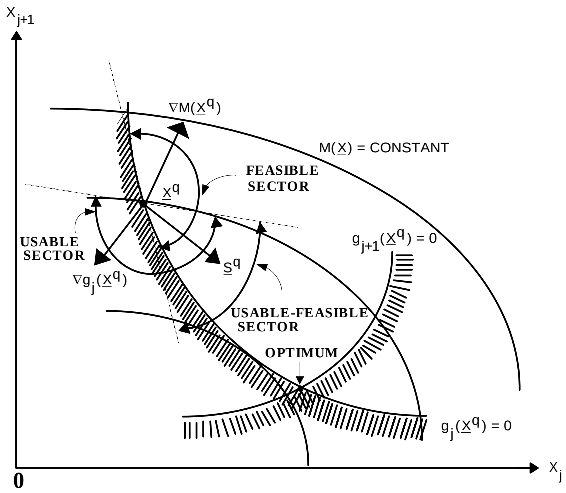


Fig. 1. Usable-feasible search direction.

that the FDM guides the search point to local optimums quickly and the GA escapes from the local optimums in order to arrive at global optimum. From the application in the passive harmonic filter design of a chemical plant, the proposed method can determine the global optimal filter sizes while satisfying all given constraints. It is noted that no harmonic amplification problem has been caused by parallel resonance. Also, the FDM+GA converges faster than the GA approach only.

## 2 FEASIBLE DIRECTION METHOD

A nonlinear constrained optimization problem can be expressed as

$$\text{Minimize } M(\underline{X}) \tag{1}$$

Subject to

$$g_j(\underline{X}) \le 0 \qquad j = 1,...,n_g \tag{2}$$

$$h_k(\underline{X}) = 0 \qquad k = 1,...,n_h \tag{3}$$

where $M(\underline{X})$ : objective function of variable vector $\underline{X}$, $\underline{X} = \left[X_1, X_2, .., X_j, .., X_D\right]^t$.

$g_j(\underline{X})$ : inequality constraints.

$h_k(\underline{X})$ : equality constraints.

The iterative method is used to obtain the solution, that is,

$$\underline{X}^{q+1} = \underline{X}^q + \alpha \underline{S}^q \tag{4}$$

where $G$ is the iteration number, $\alpha$ the scalar step size, and $\underline{S}^G = [S_1^G, S_2^G, ..., S_D^G]^t$ is the search direction vector. The FDM can be illustrated in Figure 1, where two constraint lines are given. Considering a solution $\underline{X}^G$ at step G on the constraint boundary of $g_j(\underline{X})$. We first calculate the gradient of the objective function and of the active constraint to yield the gradient vectors shown. The lines tangent to the constant objective curve and tangent to the constraint boundary are used for linear approximations at step (G+1). In order to find a search direction $\underline{S}^G$ which reduces the objective function without violating the active constraint for some finite move. Clearly, such a search direction will make an angle greater than $90^0$ with the gradient vector of the objective function. This suggests that the dot product of the $\nabla M(\underline{X}^G)$ and $\underline{S}^G$ should be negative, since the dot product is the product of the magnitudes of the vectors and the cosine of the angle between them, and this angle must exceed $90^0$ for cosine to be negative. The limiting case is when the dot product is zero, in which case the $\underline{S}^G$ vector is tangent to the plane of constant objective function. Mathematically, the usability requirement becomes

$$\nabla M(\underline{X}^G) \cdot \underline{S}^G \le 0 \tag{5}$$

A direction is called feasible if, for a small movement in that direction, any active constraint will not be violated. Thus, the feasibility requirement becomes

$$\nabla g_j(\underline{X}^G) \cdot \underline{S}^G \le 0 \tag{6}$$

Observe that the greatest reduction in $M(\underline{X}^G)$ can be achieved by finding an $\underline{S}^G$, which minimizes the quantity in equation (5), while equation (6) meets with precise equality. That is, the movement direction is both usable and feasible.

### 2.1 Unusable and feasible search direction.

**Condition 1. Without active or violated constraint**

Very often at the beginning of an optimization process, there is no active or violated constraint. The feasibility requirement is automatically met since the search can be in any direction, at least a short distance, without violating any constraint. Therefore, the search direction is simply given by

$$\underline{S}^q = -\nabla M(\underline{X}^q) \tag{7}$$

The problem now becomes determining how far the search can move in that direction. Consider the objective function and create a first order Maclaurin series approximation. That is

$$M(\underline{X}^{q+1}) = M(\underline{X}^q + \alpha \underline{S}^q) \tag{8}$$

The approximation of $M(\underline{X}^{q+1})$ is

$$M(\underline{X}^{q+1}) \cong M(\underline{X}^q) + \frac{dM(\underline{X}^q)}{d\alpha}\alpha \tag{9}$$

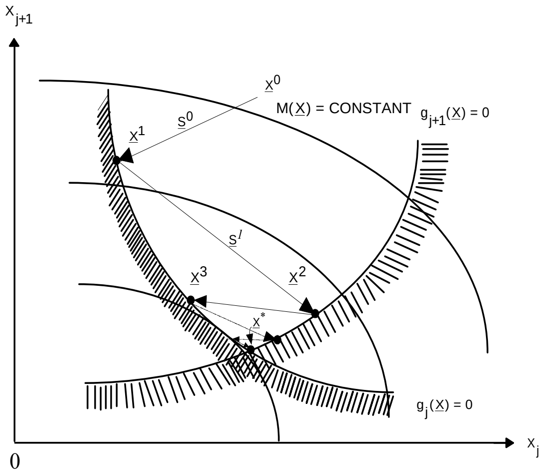

Fig. 2. Iterative process of feasible direction method.

If it is expected to reduce the objective function by 10%, the linear approximation is

$$M(\underline{X}^{q+1}) \cong M(\underline{X}^{q}) - 0.1\left|M(\underline{X}^{q})\right| \quad (10)$$

The estimated $\alpha$ should be

$$\alpha_{est} = \frac{-0.1\left|M(\underline{X}^{q})\right|}{dM(\underline{X}^{q})/d\alpha} \quad (11)$$

**Condition 2. With active constraints but without violated constraint**

The solution $\underline{X}^q$ at step q is feasible but a better design is required. It is to find a search direction $\underline{S}^q$ to reduce the objective function without violating any active constraint. To find $\underline{S}^q$, the problem can be changed to maximize $\beta$. Hence

$$\text{Maximize} \quad \beta \quad (12)$$

Subject to

$$\nabla M(\underline{X}^q) \cdot \underline{S}^q + \beta \le 0 \quad (13)$$

$$\nabla g_j(\underline{X}^q) \cdot \underline{S}^q + \theta_j \beta \le 0, \; j = 1,...,n_g \quad (14)$$

where $\theta_j$: push-off factor. It is often recommended that $\theta_j$=1 for all nonlinear constraints and $\theta_j$=0 for all linear constraints by Miura [14]. And the components of $\underline{S}^q$ should be $-1 \le S_i^q \le 1, \quad i = 1,2,..,D$.

Assume that there are some gradients of constraints that are not critical, and it is wished to estimate how far to move to make one of them critical. It is applied to a constraint by simply substituting the constraint gradient for the objective gradient. If it is to drive $g_j(\underline{X}^{q+1}) = 0$, therefore

$$g_j(\underline{X}^{q+1}) \cong g_j(\underline{X}^{q}) + \left[\frac{dM(\underline{X}^{q})}{d\alpha}\right]\alpha_j, j \in J \quad (15)$$

and an estimate of $\alpha_j$ is

$$\alpha_{est,j} = \frac{-g_j(\underline{X}^{q})}{dM(\underline{X}^{q})/d\alpha_j}, j \in J \quad (16)$$

Using the values given by equations (11) and (16), we could take the smallest positive $\alpha_{est}$ as the first estimate of how far to move to minimize $M(\underline{X}^{q+1})$.

**Condition 3. With one or more violated constraints**

If any constraint is violated, the solution at step q is not feasible. It needs to find a search direction backward to the feasible region, even if it is necessary to increase the objective function. The details of this case are described in reference by Miura [14].

## 2.2 Convergence to the optimal point

Because the optimization problem is an iterative process, a criterion is used to decide when to stop the search process. The criterion is that the absolute difference of objective functions between two steps is less than a specified tolerance, that is

$$\left|M(\underline{X}^{q+1}) - M(\underline{X}^{q})\right| \le \delta \quad (17)$$

where $\delta$ is a small positive value. A default value for $\delta$ could be 0.0001. The overall iterative process is shown in Figure 2. Figure 3 shows the triangular membership function.

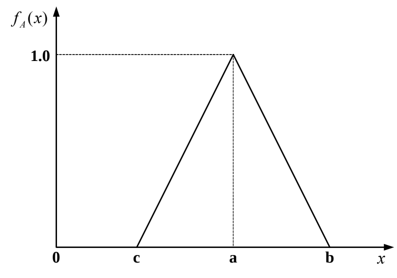

Fig. 3. A triangular membership function

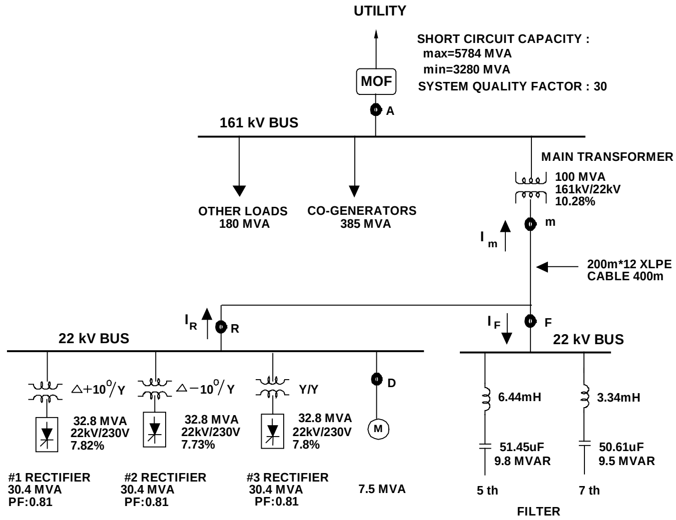


Fig. 4. System one-line diagram of the chemical plant with original filters.

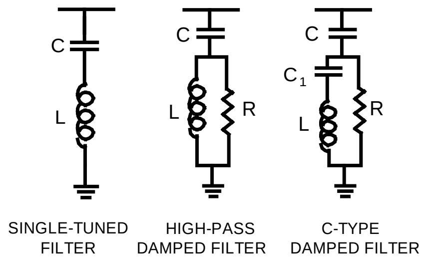


Fig. 5. Typical passive harmonic

TABLE 1. THREE RECTIFIER HARMONIC CURRENT MODES

| | Harmonic currents (A) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Order | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Mode 1 | 1493 | 16 | 18 | 12 | 196 | 5 | 136 | 17 | 18 | 7 |
| Mode 2 | 2219 | 35 | 31 | 27 | 31 | 13 | 34 | 18 | 21 | 13 |
| Mode 3 | 2219 | 40 | 37 | 35 | 64 | 14 | 44 | 20 | 24 | 15 |
| Order | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Mode 1 | 22 | 4 | 23 | 10 | 15 | 17 | 48 | 15 | 33 | 14 |
| Mode 2 | 62 | 17 | 53 | 21 | 26 | 21 | 97 | 18 | 95 | 18 |
| Mode 3 | 55 | 15 | 49 | 13 | 24 | 26 | 88 | 17 | 90 | 16 |

Table 2. Five system impedances (60Hz,Vbase=22kV,Sbase=100MVA).

| System impedance (%) | 1.39 | 1.73 | 3.05 | 5.52 | 7.62 |
|---|---|---|---|---|---|
| $R_{SYS}$ (mΩ) | 2.40 | 2.79 | 4.92 | 8.91 | 12.29 |
| $L_{SYS}$ (mH) | 0.178 | 0.222 | 0.391 | 0.708 | 0.978 |

## 3 SYSTEM UNDER STUDY

Figure 4 shows the one-line diagram of a chemical plant, where the major load consists of three 6-pulse rectifiers, each with a capacity of 30.4 MVA. The rectifiers in 18-pulse scheme have been operated for more than 25 years, so that non-characteristic harmonic currents are produced. However, these rectifiers may work in unequal loading mode. The plant has also installed $5^{th}$ and $7^{th}$ order single-tuned filters. Other loads and co-generators are connected to the primary side of the main transformer.

Three rectifier harmonic current modes could be considered as that shown in Table 1. Mode 1 is only with two rectifiers and a total load of 232 kA (DC). However, it is not a 12-pulse scheme. Mode 2 and mode 3 are with three rectifiers and a filters total load of 348 kA (DC), where the 18-pulse scheme is used. The major harmonic components are $17^{th}$ and $19^{th}$ orders. However, abundant non-characteristic harmonics are also generated. In Table 2, five system impedances are given. The base values are 161kV/22 kV and 100 MVA. The values with 1.73% and 3.05%, respectively, are calculated with the maximum and minimum system short-circuit capacities that are provided by the utility. The first value is obtained by considering the maximum system short-circuit capacity and all co-generators. The 5.52% value is obtained from the field measurement by switching the $7^{th}$ filter and comparing the bus voltage magnitudes. The last value 7.62% is calculated when the plant is disconnected from the utility and only five co-generators are under operation.

Three passive filters are shown in Figure 5. The single-tuned filters are widely used. The quality factor is assumed to be 30. The damped filters give low impedance values at higher frequencies. For the singled-tuned filter, the tuned point $h_0$ is

$$h_0 = \frac{1}{2\pi f_1 \sqrt{LC}} \tag{18}$$

Where $f_1$ is the fundamental frequency.

## 4 OPTIMAL FILTER DESIGN

(1) Solution procedure

In this paper, we first employ the FDM to determine the local optimal solution. Second, the GA escapes from the local optimums in order to arrive at global optimum. Then, expectations and standard variations of objective functions are calculated. The final solutions can be obtained when uncertainties are considered.

(2) Objective function

Harmonic filter planning can be formulated as a combined optimization problem as

$$Minimize\ M = w_1 \times I_{TDD-MOF} + w_2 \times V_{THD-bus-m} + w_3 \times P_F + w_4 \times C_F$$
(19)

Table 3. Loading and power factor at 22-kV bus.

| S (MVA) | P (MW) | Q (MVAR) | Power factor Without filter | Power factor With filters |
|---|---|---|---|---|
| 91.2 | 53.48 | 73.87 | 0.81 | 0.95 |

Table 4. Planning results of filters at the initial design point.

| | Filter | $R$ (Ω) | L (mH) | $C$ (uF) | $Q_F$ (MVA) | $h_o$ | $m$ | M(%) |
|---|---|---|---|---|---|---|---|---|
| Original filters | 5th | 0.08 | 6.44 | 51.45 | 9.8 | 4.61 | - | 12.6 |
| | 7th | 0.04 | 3.34 | 50.61 | 9.5 | 6.45 | - | |
| FDM+GA filters | 5th | 113.4 | 10 | 77.91 | 14.21 | 0.3 | 0.01 | |
| | 7th | 0.02 | 1.6 | 106.9 | 20 | 6.44 | - | 4.78 |
| | 11th | 0.008 | 0.64 | 107.3 | 19.78 | 10.1 | - | |

Table 5. Harmonic currents (A) of MOF at initial design point.

| Harmonic order | Without filter | Original filters | FDM+GA filters | Limitation |
|---|---|---|---|---|
| 2 | 16 | 17.47 | 7.53 | 22.96 |
| 3 | 18 | 23.22 | 3.42 | 91.85 |
| 4 | 12 | 27.10 | 4.03 | 22.96 |
| 5 | 196 | 138.0 | 58.17 | 91.85 |
| 7 | 136 | 60.54 | 31.15 | 91.85 |
| 11 | 22 | 9.53 | 1.15 | 45.92 |
| 13 | 23 | 10.98 | 2.70 | 45.92 |
| 17 | 48 | 24.75 | 8.14 | 32.8 |
| 19 | 33 | 17.33 | 5.99 | 32.8 |
| $TDD_I$(%) | 9.49 | 6.07 | 2.57 | 6.89 |

Table 6. Harmonic voltages (V) of 22kV side of main transformer at initial design point.

| Harmonic order | Without filter | Original filters | FDM+GA filters |
|---|---|---|---|
| 2 | 19.36 | 39.58 | 9.72 |
| 3 | 29.03 | 81.23 | 6.62 |
| 4 | 25.81 | 147.6 | 10.42 |
| 5 | 632.4 | 620.6 | 187.6 |
| 7 | 614.3 | 392.9 | 140.7 |
| 11 | 298.1 | 108.5 | 8.19 |
| 13 | 276.8 | 148.6 | 22.71 |
| 17 | 998.2 | 440.1 | 89.36 |
| 19 | 649.8 | 344.9 | 73.48 |
| $TDD_I$(%) | 6.98 | 4.35 | 1.19 |

Table 7. Comparisons of FDM+GA and GA.

| Method | M (%) | *CPU* time (sec) | $P_c$ | $P_m$ | $N_P$ |
|---|---|---|---|---|---|
| GA | 5.820 | 6.8 | 0.8 | 0.05 | 80 |
| FDM+GA | 4.153 | 2.3 | | | |

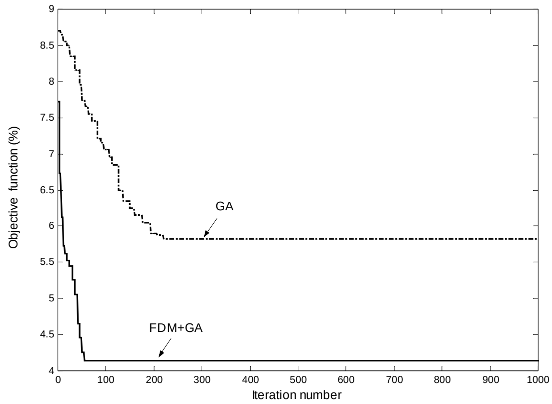


Fig. 6. Comparison of convergent characteristics

where $V_{THD-bus-m}$ = total harmonic distortion of the voltage at bus-m,

$I_{TDD-MOF}$ = total demand distortion of harmonic currents at MOF,

$P_F$ = total filter loss,

$C_F$ = the cost of total installation of LC tuned filters,

$w_1, w_2, w_3$ *and* $w_4$ = weighting factors are determined by centroid method.

**(3) Requirement of harmonic filtering**

The harmonic limitations follow with the IEEE Standard 519. However, in order to avoid harmonic amplification problems, harmonic orders below the filter tuned-point will be assigned stricter constraints. In this paper, one third of the limitation value is chosen.

**(4) Reactive power compensation**

The fundamental-frequency reactive power of each filter must be restricted, that is,

$$Q_{Fi}^{\max} \geq Q_{Fi} \geq Q_{Fi}^{\min} \quad (20)$$

where $Q_{Fi}^{min}$ and $Q_{Fi}^{max}$ are the lower and upper reactive power limits of the i$^{th}$ filter. The total reactive power compensation at bus k with n filters will be

$$Q_F^k = \sum_{i=1}^{n} Q_{Fi}^k \quad (21)$$

The engineering analysis determined that to correct the main transformer to 0.95 power factor lagging, the reactive power compensation must be performed as shown in Table 3.

**(5) Tuned point and damped time constant**

The impedance of all filters must be inductive with respect to the harmonic to be filtered to prevent harmonic amplification. For a single-tuned filter

$$a_1 h^* \le h_0 \le a_2 h^* \quad (22)$$

where $a_1, a_2 \le 1$ , and $h^*$ is the order number of harmonic to be filtered. For a high pass filter

$$1 < h_0 < h^* \sqrt{m - m^2} \text{ , } 0 < m < 1 \quad (23)$$

## 5 PLANNING RESULTS

The initial design point is assigned to be $Z_{SYS}$ =3.05% and with rectifier harmonic current mode 1. The design scheme is with a 5$^{th}$ high pass filter, a 7$^{th}$ single-tuned filter, and an 11$^{th}$ single-tuned filter. The planning results at the initial design point by the FDM+GA are shown in Table 4. The harmonic currents at MOF and harmonic voltages in the 22-kV side of the main transformer are given in Table 5 and Table 6, respectively. The design scheme by the proposed method is better. There is no harmonic amplification problem caused by parallel resonance.

Convergent speed and solution quality of the proposed method with the GA were compared in Figure 6. It shows that the FDM+GA and the GA take 51 and 219 generations to converge, respectively. The computation time is evaluated by the CPU time on a Pentium III 700MHz computer as shown in Table 7. It indicates that the FDM+GA is faster than the GA. The objective function obtained by the proposed method is lower.

## 6 CONCLUSIONS

A comprehensive planning method based on an approach of combined feasible direction method and genetic algorithm has been presented to investigate the planning of large-scale passive harmonic filters. A chemical plant is used as an example to demonstrate the proposed method. The sizes of single-tuned and high-pass filters are determined. The triangular membership function is selected for determining a set of weights of objective function to represent the relative importance of each term. From the simulation results, the proposed algorithm and probability method gave a good approach for optimal filter planning.

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