Optimal Planning of Large Passive-Harmonic-Filters Set at High Voltage Level

Chih-Ju Chou, Chih-Wen Liu, *Member, IEEE*, June-Yown Lee, and Kune-Da Lee

***Abstract*—This paper proposes the optimal planning of large passive-harmonic-filters set at high voltage level based on multi-type and multi-set of filters, from which, the types, set numbers, capacities and the important parameters of filters are well determined to satisfy the requirements of harmonic filtering and power factor. Four types of filters, namely single-tuned filter, second-order, third-order and C-type damped filters are selected for the planning. Firstly, the characteristics of filters are analyzed. The cost function and the constraints of filters and system are constructed for formulating the optimization problem of the planning of filters. Secondly, the simulated-annealing (SA) algorithm for searching optimal solution of planning of filters is developed. Finally, three cases of filter planning are presented to show that the superiority and availability of the SA algorithm and proposed planning results of filters.**

***Index Terms*—High Voltage, Large Capacity, Optimal Planning, Passive-Harmonic-Filter.**

I. INTRODUCTION

THE HARMONIC components of current and voltage waves in the power system are increasing continuously due to the growing use of nonlinear loads by consumers. Many studies have shown that harmonics may produce adverse effects on power systems, communication systems, and various apparatus [1]–[3]. Now, it is an important issue that consumers should reduce their harmonic currents to satisfy some criteria of utility and prevent the system and apparatus from the damage by harmonics. Various methods can be applied to reducing the harmonic currents in consumers, in which the shunt passive harmonic filters are most often used as low cost devices and can provide the reactive power compensation to systems simultaneously.

Before applying the passive harmonic filters, the planning of filters should be drawn out first, which determines the types, set numbers, capacities and the important parameters of filters to satisfy the requirements of harmonic filtering and reactive power compensation (improvement of power factor). The filter can be set at high voltage level or low voltage level. In general, because most of nonlinear loads are set at low voltage level, and the low voltage system has a high and stable source impedance, thus the performance of harmonic filter set at low voltage level is better than that of high voltage level. When the harmonic filter with large capacity (up to 1 MVA) is required, however, the filter set at low voltage level needs tremendous investment cost and space occupation, so that the filter set at high voltage level is the preferable choice in large consumers. On the other hand, the source impedance of high voltage system is usually very low and varies complicately. The planning of filters is critical to the performances of filters, and usually single type of filter is difficult to meet the requirement of harmonic filtering at high voltage system with complex harmonic situations. This paper proposes the optimal planning of large-passive-harmonic-filters based on multi-type and multi-set of filters and considers the source impedance variation, harmonic filtering requirements and the improvement of power factor, simultaneously.

Many studies related to the planning of passive harmonic filters have been found in the literatures (e.g. [4]–[12]). The results of these studies have contributed to improvement of power factor and harmonic reduction. The compensators and filters used in these studies are LC tuned type. This paper extends the planning to other types of filters, i.e. four types of filters namely single-tuned filter, second-order, third-order, and C-type damped filters. In this paper, the planning of filters is formulated as an optimization problem with an object (cost) and some constraint functions. The object and constraint functions are constructed from the viewpoint of practical aspects and filter characteristics which will be detailed described in Sections II and III. To approach the optimal solution of the planning of filters, the solution searching algorithm based on the simulated annealing (SA) method is developed. The numerical results of case studies give comparisons between the results obtained from SA method and conventional try-and-error method. From which, the superiority and availability of SA method and proposed planning results of filters are certified.

II. CHARACTERISTICS ANALYSIS OF HARMONIC FILTERS

A. Descriptions of Filter Structures and Performances

The passive harmonics filters are composed of passive elements: resistor (R), inductor (L) and capacitor (C). The common types of passive harmonic filter include single-tuned and double-tuned filters, second-order, third-order and C-type damped filters. The double-tuned filter is equivalent to two single-tuned filters connected in parallel with each other, so that only single-tuned filter and other three types of damped filters are presented here. The ideal circuits of the presented four types of filters are shown in Fig. 1 in which both third-order and C-type damped filters have two capacitors with one in series with resistor and inductor, respectively. Two capacitors of third-order damped filter have typical same capacitance

Manuscript received November 9, 1998.

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Publisher Item Identifier S 0885-8950(00)01907-6.

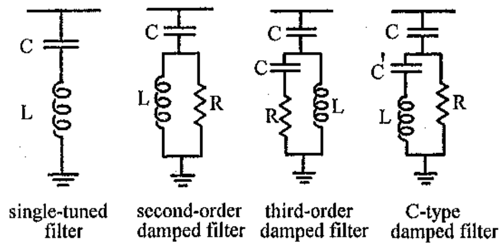

Fig. 1. Typical passive harmonic filters.

(in μF) for simplifying design and unifying stock. The capacitor C' and inductor L of C-type damped filter are designed to yield series resonance at fundamental frequency for reducing the fundamental power loss. Because single-tuned resonant filter only comprises LC components, its investment cost and power loss are lower than that of damped filters with same capacity, and easily to design. However, its performance of harmonic filtering is where general aimed to the harmonics with frequency slightly higher than the resonant frequency of filter. At high frequency, the single-tuned filter is inefficient in harmonic filtering because of the impedance of filter increasing with frequency monotonously. The low frequency harmonics will be magnified by single-tuned filter due to the impedance of filter becoming capacitive. So the single-tuned filter is only suitable to the system with simple harmonic situations, (i.e. not many large harmonics distributed on wide frequency range). On the other hand, the damped filters impedance approaches to the value of resistance at high frequency, so that they have a better performance of harmonic filtering at high frequency. The phenomenon of enlargement of low frequency harmonics will be mitigated even eliminated by the damped filters with proper parameters. Hence, the damped filters are suitable for reducing complex harmonics, i.e. many large harmonics distributed on wide frequency range. Although the above descriptions show that the damped filters are better than single-tuned filter from the viewpoint of harmonic filtering, the damped filters are usually used in cooperation with tuned filters for reducing investment and power loss, in which the tuned filters are used for filtering primary harmonics and the damped filters are used for filtering secondary harmonics.

B. Modeling and Characteristic Parameters of Harmonic Filters

The previous descriptions imply that the passive harmonic filters can be characterized by their impedance variation with frequency. The harmonic currents and voltages of a system with a nonlinear load and a harmonic filter can be analyzed approximately by using the model shown in Fig. 2(a). Where the nonlinear load is modeled as a current source of harmonic, and the system source and harmonic filter are modeled as impedance elements. The other loads will be neglected due to very large impedance compared with the impedance of source system and harmonic filter. Thus, the harmonic currents to system source

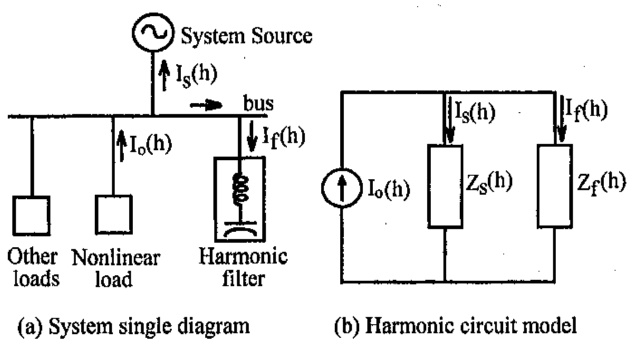

Fig. 2. Harmonic circuit model of a system with a nonlinear load and a harmonic filter: (a) system single diagram and (b) harmonic circuit model.

and harmonic filter, and harmonic voltage at system bus can be found as

$$I_s(h) = \frac{Z_f(h)}{Z_f(h) + Z_s(h)} I_0(h) \tag{1}$$

$$I_f(h) = \frac{Z_s(h)}{Z_f(h) + Z_s(h)} I_0(h) \tag{2}$$

$$V_s(h) = \frac{Z_f(h) Z_s(h)}{Z_f(h) + Z_s(h)} I_0(h) \tag{3}$$

where

$I_0(h)$ current source (in $A_{\rm rms}$) of hth order harmonic produced by the nonlinear load,

$I_s(h)$ hth order harmonic current (in $A_{\rm rms}$) to system source,

$I_f(h)$ hth order harmonic current (in $A_{\rm rms}$) to harmonic filter,

$V_s(h)$ hth order harmonic voltage (in $V_{\rm rms}$) at bus,

$Z_s(h)$ equivalent hth order harmonic impedance (in Ω) of source system,

$Z_f(h)$ equivalent hth order harmonic impedance (in Ω) of harmonic filter,

h harmonic order number (multiple of harmonic frequency, f_h to fundamental frequency, f_b)

$$h \equiv \frac{f_h}{f_b}. \tag{4}$$

Equations (1) and (3) show that the harmonic voltage and current to system source can be reduced by the harmonic filter with proper impedance at harmonic frequency. Thus, to plan a harmonic filter, we must characterize its frequency response of impedance. To this work, two parameters namely characteristic-harmonic-order, h_0 and damped-time-constant-ratio m are defined as follows for single-tuned and damped filters, respectively:

- For single-tuned filter,

$$h_0 \equiv \sqrt{\frac{X_C}{X_L}} = \frac{1}{f_b} \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

X_C: capacitive reactance (in Ω) of capacitor C at fundamental frequency,

$$X_C = \frac{1}{2\pi f_b C} \tag{6}$$

X_L: reactance (in Ω) of inductor L at fundamental frequency,

$$X_L = 2\pi f_b L. \tag{7}$$

- For damped filters,

$$h_0 \equiv \frac{X_C}{R} = \frac{1}{2\pi f_b RC} \tag{8}$$

$$m \equiv \frac{L}{R^2 C} = \frac{X_C X_L}{R^2} = h_0 \frac{X_L}{R} \tag{9}$$

where R is resistance (in Ω) of damped filter.

Refer to Fig. 1, the impedance $Z_f(h)$ of four harmonic filters with respect to harmonic order h can be derived.

- For single-tuned resonant filter,

$$Z_f(h) = j\left(hX_L - \frac{X_C}{h}\right). \tag{10}$$

- For second-order damped filter,

$$Z_f(h) = \frac{R(hX_L)^2}{R^2+(hX_L)^2} + j\left[\frac{R^2 hX_L}{R^2+(hX_L)^2} - \frac{X_C}{h}\right]. \tag{11}$$

- For third-order damped filter,

$$Z_f(h) = \frac{R(hX_L)^2}{R^2+\left(hX_L - \frac{X_C}{h}\right)^2} + j\left[\frac{R^2 hX_L - hX_L^2 X_C + \frac{X_L X_C^2}{h}}{R^2+\left(hX_L - \frac{X_C}{h}\right)^2} - \frac{X_C}{h}\right]. \tag{12}$$

- For C-type damped filter,

$$Z_f(h) = \frac{R\left(hX_L - \frac{X_L}{h}\right)^2}{R^2+\left(hX_L - \frac{X_L}{h}\right)^2} + j\left[\frac{R^2\left(hX_L - \frac{X_L}{h}\right)}{R^2+\left(hX_L - \frac{X_L}{h}\right)^2} - \frac{X_C}{h}\right] \tag{13}$$

where $j = \sqrt{-1}$.

To normalize $Z_f(h)$ with the base X_C/h_0 the normalized impedance $\hat{Z}_f(h)$ of filter is defined as

$$\hat{Z}_f(h) \equiv \frac{h_0 Z_f(h)}{X_c} = \hat{R}_f(h) + j\hat{X}_f(h) \tag{14}$$

where $\hat{R}_f(h)$ and $\hat{X}_f(h)$ are, respectively, the normalized resistance and reactance of filter with respect to harmonic order h. Substituting (10)–(14) and using parameters (h_0 and m) to relate the R, X_L, and X_C, we can obtain the normalized-impedance expressions of each filter in Fig. 1, which are listed in Table I.

TABLE I
EXPRESSIONS OF NORMALIZED-IMPEDANCE OF HARMONIC FILTERS
($\bar{h} = h/h_0$)

$\hat{Z}_f(h,m,h_0)$ / Filters	$\hat{R}_f(h,m,h_0)$	$\hat{X}_f(h,m,h_0)$
Single-tuned filter	0	$\left(\bar{h}-\frac{1}{\bar{h}}\right)$
Second-order damped filter	$\frac{m^2\bar{h}^2}{1+\left(m\bar{h}\right)^2}$	$\frac{m\bar{h}-m^2\bar{h}-1/\bar{h}}{1+\left(m\bar{h}\right)^2}$
Third-order damped filter	$\frac{m^2\bar{h}^2}{1+\left(m\bar{h}-1/\bar{h}\right)^2}$	$\frac{m\bar{h}-m^2\bar{h}+m/\bar{h}}{1+\left(m\bar{h}-1/\bar{h}\right)^2}-\frac{1}{\bar{h}}$
C-type damped filter	$\frac{\left(m\bar{h}-\frac{m}{h_0^2\bar{h}}\right)^2}{1+\left(m\bar{h}-\frac{m}{h_0^2\bar{h}}\right)^2}$	$\frac{m\bar{h}-\frac{m}{h_0^2\bar{h}}}{1+\left(m\bar{h}-\frac{m}{h_0^2\bar{h}}\right)^2}-\frac{1}{\bar{h}}$

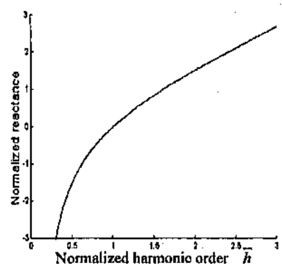

Fig. 3. Normalized harmonic impedance of single-tuned resonant filter.

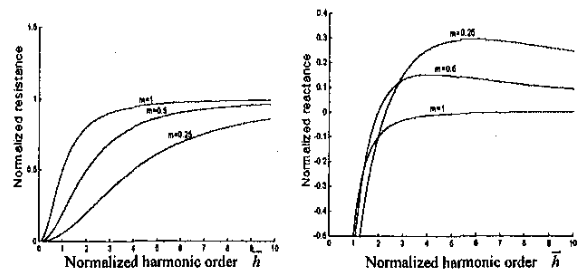

Fig. 4. Normalized harmonic impedance of second-order damped filter.

According to the expressions in Table I, the frequency response curves of filter impedances with various parameter values are drawn in Figs. 3–6 for the four filters in Fig. 1, respectively, where the impedances and harmonic orders are all in normalized values. The curves are independent of the parameter h_0 except that of C-type damped filter. Just as the descriptions above, these figures indicate that the impedance of single-tuned filter increase with harmonic order monotonously, and the damped filters approach to a resistance (R) at high harmonic order ($h \gg h_0$). In general, the system source impedance is inductive at high frequency, the damped filters with small parameter, m possess better performances of harmonic filtering at

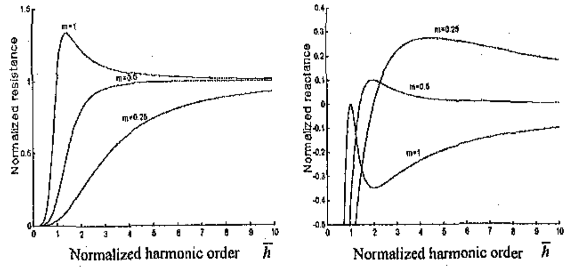

Fig. 5. Normalized harmonic impedance of third-order damped filter.

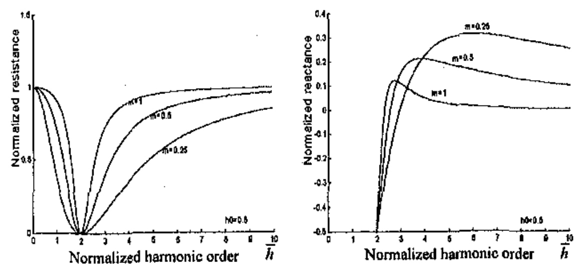

Fig. 6. Normalized harmonic impedance of C-type damped filter.

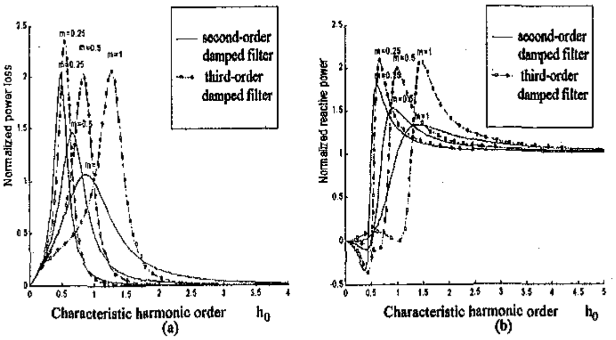

Fig. 7. (a) Normalized fundamental power losses and (b) reactive power compensations.

high frequency because of inductive impedance (see Figs. 4–6). Significant amount of fundamental power losses are found in second-order and third-order damped filter with low parameter, h_0, [see Fig. 7(a)]. This means that small m and large h_0 are preferred for a filter but this is in conflicts with (9) where m and h_0 increase with each other. Consequently, trade-off between the performance of harmonic filtering and the reduction of fundamental power losses are required by proper determining parameters m and h_0, of second-order and third-order damped filters. In addition, Fig. 7(b) indicates that both second-order and third-order damped filters have similar properties on reactive power compensations. To prevent the phenomenon of derating reactive power compensation from filters with very low h_0, we must assign the filters to high harmonics. For those low harmonics to be reduced, C-type damped filters are suitable to use due to no fundamental power loss (in ideal case) and var derating. Although C-type filters are also suitable for filtering high harmonics, second-order and third-order damped filters are still preferred for high harmonics because of some factors such as transient behavior, investment cost and protection measures of filters.

III. Problem Formulation

The problem of the planning of filters is to determine the types, set number, elements (R, L, C) and parameters (m, h_0) of filters to satisfy the requirements of harmonic filtering, power factor improvement and other conditions. Additionally, the costs of filters are taken into consideration in the planning for constructing the filters with lowest total cost. These are formulated in an optimization model with a cost function and some constraints which include harmonic filtering power factor improvement and other conditions. The constructions of cost function and constraints are described in the following subsections.

A. *Construction of the Cost Function*

In practice, the cost of a filter comprises four parts: materials, installation, maintenance, and fundamental power loss. The sum of former three parts costs is called investment cost in engineering aspect which is usually evaluated from the element values and the capacity of filter, by a linear combination with a weighting coefficient for each element and capacity of filter. The cost of fundamental power loss is also expressed as in proportion to the loss (in kW) of filter with respect to fundamental source voltage. The cost of a type of filter with multi-set is larger than that of with single set due to increases of space occupation, unit packing and installation. To this point, a set-number-multiplier larger than 1 is assigned to each type of filter to multiply the cost of filter with only one set. This set-number-multiplier is not only dependent on the set number but also the type of filter, and should be determined according to engineering judgments. In summary, the cost function, E of a planning considering four types of filters is constructed as

$$E = \sum_{i=1}^{4} \gamma_i \sum_{j=1}^{n_i} [k_1 R_{ij} + k_2 L_{ij} + k_3 C_{ij} + k_4 Q_{ij} + k_5 P_{\text{loss}\, ij}] \tag{15}$$

where R_{ij}, L_{ij}, C_{ij}, Q_{ij}, and $P_{\text{loss}\, ij}$ are the resistance (in Ω), inductance (in mH), capacitance (in μF), reactive power capacity (in kVar) and power loss (in kW) of jth filter of type i, respectively, k_1, k_2, k_3, k_4 and k_5 are cost weighting coefficients with respective to R, L, C, Q, and P_{loss}, respectively, γ_i represents the set-number-multiplier of ith type of filter, and n_i is set number of ith type of filter.

B. *Construction of Constraints*

Constraints for planning filters include the requirements of harmonic filtering, power factor improvement and other conditions which are derived as follows:

1) Requirements of Harmonic Filtering: The harmonic voltages and currents to system are, in general, restricted within the tolerable values (e.g., [13]). For individual harmonic component and the total harmonics, the constraints are proposed here with the following inequality formula,

$$\alpha_{Vm}(h) = \frac{V_{sm}(h)}{V_1} \leq \overline{\alpha}_V(h), \qquad h = 2 \cdots \tag{16}$$

$$\alpha_{Im}(h) = \frac{I_{sm}(h)}{I_1} \le \overline{\alpha}_I(h), \qquad h = 2 \cdots \tag{17}$$

$$\mathrm{THD}_V = \sqrt{\sum_h \alpha_{Vm}^2(h)} \le \overline{\mathrm{THD}_V} \tag{18}$$

$$\mathrm{THD}_I = \sqrt{\sum_h \alpha_{Im}^2(h)} \le \overline{\mathrm{THD}_I} \tag{19}$$

where

- $V_{sm}(h)$ the maximum magnitude of hth order harmonic voltage at system bus (V_{rms}), [see (20)]
- $I_{sm}(h)$ the maximum magnitude of hth order harmonic current to system source (A_{rms}), [see (21)]
- V_1 the magnitude of fundamental voltage at system bus (V_{rms}), $V_1 = V_s(1)$,
- I_1 the magnitude of fundamental current in system (A_{rms}), $I_1 = I_s(1)$,
- $\alpha_{Vm}(h)$ the maximum distortion factor of hth order harmonic voltage at system bus,
- $\alpha_{Im}(h)$ the maximum distortion factor of hth order harmonic current to system source,
- $\overline{\alpha}_V(h)$ the upper limits (tolerable values) of $\alpha_{Vm}(h)$,
- $\overline{\alpha}_I(h)$ the upper limits (tolerable values) of $\alpha_{Im}(h)$,
- THD_{Vm} the maximum total harmonic distortion factor of voltage at system bus,
- THD_{Im} the maximum total harmonic distortion factor of current in system,
- $\overline{\mathrm{THD}_V}$ the upper limits (tolerable values) of THD_{Vm},
- $\overline{\mathrm{THD}_I}$ the upper limits (tolerable values) of THD_{Im}.

$V_{sm}(h)$ and $I_{sm}(h)$ are calculated from the following equations:

$$V_{sm}(h) = |I_0(h)| \left(\text{Max of} \left|\frac{Z_f(h) \cdot Z_s(h)}{Z_f(h) + Z_s(h)}\right|\right) \tag{20}$$

$$I_{sm}(h) = |I_0(h)| \left(\text{Max of} \left|\frac{Z_f(h)}{Z_f(h) + Z_s(h)}\right|\right) \tag{21}$$

$$Z_f(h) = \frac{1}{\displaystyle\sum_{i=1}^{4}\sum_{j=1}^{n_i} \frac{1}{Z_{fij}(h)}} \tag{22}$$

where $Z_{fij}(h)$ is the hth order harmonic impedance of jth filter of type i. The notation "Max of" means taking the maximum value of its behind formula where $Z_f(h)$ and $Z_s(h)$ may vary due to the deviations of filter elements and system variation.

2) Power Factor Improvement: The power factor of system should be improved in accordance with utility regulations. Moreover, high power factor with lagging characteristic is preferred for preventing over compensation. Thus, the total reactive power from all filters to system must be restricted within the range as the following equation,

$$\underline{Q} \le \sum_{i=1}^{4}\sum_{j=1}^{n_i} Q_{ij} \le \overline{Q} \tag{23}$$

where

- $\underline{Q}$ the lower limit of total reactive power specified by the tolerable lowest power factor (kVar),
- $\overline{Q}$ the upper limit of total reactive power specified by the highest lagging power factor for preventing over compensation (kVar).

3) Other Conditions:

a) Inductive Constraints: We restrict each filter being inductive to its corresponding harmonics to be filtered, and the resultant impedance of all filters must be also inductive to those critical harmonics which may induce harmonic resonant on system. Thus, we have the following constraint equations:

$$X_{fij}(h_k) > 0, \qquad \text{for all } k \tag{24}$$

$$X_f(h_m^*) > 0, \qquad \text{for all } m \tag{25}$$

where

- $X_{fij}(h_k)$ the reactance of jth filter of type i with respect to its kth corresponding harmonic current with order h_k to be filtered,
- $X_f(h_m^*)$ the resultant reactance [i.e., reactive part of $Z_f(h^*)$], of all filters with respect to mth critical harmonic current with order h_m^*.

b) Element Constraints: Every element value of filter must be larger than its lower limit for keeping the deviation from manufacture within the tolerance. Thus, we have the following constraint equations

$$\underline{R} \le R_{ij}, \quad \underline{L} \le L_{ij}, \quad \underline{C} \le C_{ij} \tag{26}$$

where $\underline{R}$, $\underline{L}$, and $\underline{C}$ are the lower limits with respect to the filter elements of resistor, inductor, and capacitor, respectively.

IV. The Proposed Planning Method

To approach the optimal solution of the planning of filters, the solution searching algorithm based on the simulated annealing (SA) optimization technique and a perturbation mechanism for generating a new solution are developed in the following subsections.

A. Simulated Annealing Optimization Technique and Solution Algorithm

The SA optimization technique is developed from the concept of annealing process of crystallization in physical system [14], [15]. Procedure of SA is shown in following steps (pseudo code).

1) Obtain an initial solution S
2) Attain an initial temperature $T > 0$
3) While not yet frozen do the following
    3.1) Perform the following until balance
        3.1.1) Generate a random neighbor S' from S
        3.1.2) If feasible
            3.1.21) Calculate the increment cost ΔC
                $\Delta C = \cos\ t(S') - \cos\ t(S)$
            3.1.22) If $\Delta C \le 0$, Let $S = S'$ (downhill move)
                If $\Delta C \ge 0$ then (uphill move)
                Let $S = S'$ with probability $\exp(-\Delta C/T)$
    3.1.22) Let $T = \alpha \cdot T$ (cooling down), $\alpha < 1$
4) Return S.

SA is a powerful general purpose optimization technique, i.e., it can be used for any optimization problem to get global

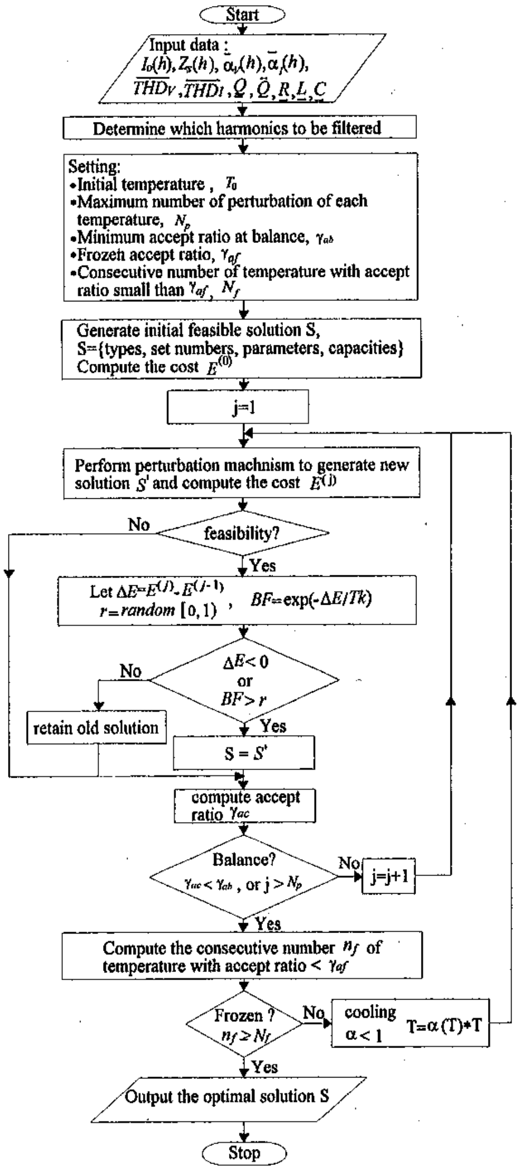

Fig. 8. Solution algorithm of the planning of filters based on SA.

optimal solution rather than local optimal solution by other greedy searching techniques [14], [15]. The solution algorithm based on SA for the planning of filters is shown in Fig. 8. The perturbation mechanism for generating a new feasible solution is illustrated in the following subsection.

B. Perturbation Mechanism in SA for Generating a New Solution

According to the results of characteristics analysis of harmonic filters in Section II, the filters to be selected in the planning should follow the following rules:

1) The single-tuned filters should be first selected, and if not feasible, the damped filters are involved in harmonic filtering with single-tuned filters under following regulations:
   - For high order harmonic band, second-order and/or third-order damped filters are involved.
   - For low-order harmonic band, the C-type damped filters are involved.
   - For the harmonic band covering low and high orders, C-type, second-order and third-order damped filters are all possible involved.

2 The type and set number of above filters are selected randomly and with capacity varying discretely.

3 All parameters (h_0, m) of filters are varied discretely with step size 0.001.

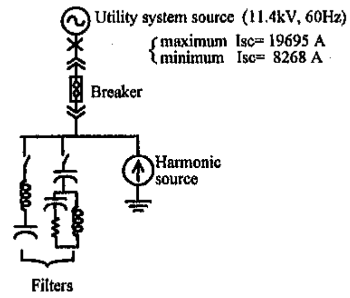

Fig. 9. System for case studies.

TABLE II
HARMONIC CURRENT AND VOLTAGE DISTRIBUTION WITHOUT FILTERS AND UTILITY TOLERANCES

Harmonic orders	Harmonic current (A)			Harmonic voltages (V) to neutral			Utility tolerances		
							Currents(A)		Voltages(v)
	Case1	Case2	Case3	Case1	Case2	Case3	Case1	Case2 and 3	All cases
2	7.02	19.2	9.45	11.18	30.57	15.05	8.28	15.58	197.5
3	8.64	36.8	15.6	20.63	87.88	37.26	33.1	62.33	197.5
4	5.92	5.41	3.77	18.85	17.23	12.0	8.28	15.58	197.5
5	45.8	98.0	62.7	182.3	390.1	249.6	33.1	62.33	197.5
7	19.0	18.0	21.0	105.9	100.3	117.0	33.1	62.33	197.5
11	15.4	14.2	19.4	134.9	124.3	166.9	16.6	31.17	197.5
13	9.4	12.6	17.0	97.28	130.4	175.9	16.6	31.17	197.5
17	0	0	16.0	0	0	216.5	12.43	23.38	197.5
19	0	0	15.5	0	0	234.4	12.43	23.38	197.5
THD	6.55	7.04	4.92	4.11	6.86	7.42	5	5	5

V. CASE STUDIES

A. System Descriptions and Associated Data

A 11.4 kV, 60 Hz system with harmonic source shown in Fig. 9 is to be studied with three cases of the planning of harmonic filters, where the harmonic current and voltage distributions without filters with respect to three cases are listed in Table II. The utility harmonic tolerances of each case are also listed in Table II, in which the tolerances of each harmonic component and total harmonic distortions (THD's) are based on ANSI/IEEE Std. 519-1992 [13]. The table shows that the current THD's of cases 1 and 2 and voltage THD's of both cases 2 and 3 exceed the tolerances. In addition, the second-order harmonic current and fifth-order harmonic voltage in case 2, and the fifth, 17th, and 19th order harmonic voltages in case 3 also exceed the tolerances. The load demands (fundamental power) of case 1 is 14 590 kW with lagging power factor 0.892, and both

TABLE III
COST WEIGHTING COEFFICIENTS AND SET-NUMBER-MULTIPLIERS

	λ_i / set no.	Single-tune λ_1	Second-order damped λ_2	Third-order damped λ_3	C-type damped λ_4
set-number-multipliers	1	1	1	1.2	1.2
	2	1.2	1.4	1.6	1.6
	3	1.6	1.8	2.0	2.0
	4	2.0	2.2	2.4	2.4
	5	2.4	2.5	2.8	2.8
Cost-weighting coefficients		k_1 =5(pu/ Ω), k_2 =3(pu/ mH), k_3 =2(pu/ μF), k_4 =0.1(pu/ $kVAR$), k_5 =0.1 (pu/ kW).			

TABLE IV
PLANNING RESULTS OF FILTERS BY SA METHOD

Cases	element / filters	Resistor R(Ω)	Inductor L(mH)	Capacitor C (uF)	Capacitor C' (uF)	Capacities Q(kVAR)	Total cost (pu)
Case1	single-tuned filter 1		15.37	20.27		1039	546
		Parameter: h_0 =4.75					
	single-tuned filter 2		16.45	29.61		1559	
		Parameter: h_0 =3.8					
Case2	single-tuned filter		4.32	72.24		3713	5429
		Parameter: h_0 =4.75					
	C-type damped filter	51.84	8.21	302.4	857.0	14815	
		Parameters: h_0 =0.338 m =0.010					
Case3	single-tuned filter		3.67	105.42		5364	4466
		Parameter: h_0 =4.30					
	3-rd damped filter	15.37	4.30	35.68		1788	
		Parameters: h_0 =16.8 m =0.510					
	C-type damped filter	40.44	15.25	218.95	461.39	10727	
		Parameters: h_0 =0.60 m =0.043					

cases 2 and 3 20 000 kW with lagging power factor 0.65. The utility system short circuit current may vary from 8268 to 19 695 A with assumptions of pure reactive and frequency independent inductance. The cost weighting-coefficients ($k_1 \sim k_5$) and the set-number-multipliers ($\lambda_1 \sim \lambda_5$) in the cost function (15) are listed in Table III, in which the type numbers 1, 2, 3 and 4 are, respectively, the type numbers of single-tuned, second-order, third-order, and C-type damped filters. All elements (R, L, C) of filters are assumed having $\pm 3\%$ deviation, and the minimum element values are: $\underline{R} = 0.01\ \Omega$, $\underline{L} = 0.01$ mH, $\underline{C} = 0.01\ \mu$F. The planning of the filters of each case must satisfy the requirements of utility criterion of harmonic tolerances and the power factor improvement between lagging 0.95 and 0.99. The fundamental frequency variation is assumed from 59–61 Hz.

B. Numerical Results and Comparisons

The planning results of filters of the three cases by SA method are shown in Table IV. Table V shows the harmonic distributions with filters, in which all harmonic components and THD's of voltage and current are within the utility tolerances. The power factors of the three cases are all improved to 0.95 (lagging). The comparisons between SA method and conventional try-and-error method on the planning results of single-tuned filters of case 1 are shown in Table VI. The total cost by SA method is less than by conventional try-and-error method mainly due to different capacities allocations to two filter sets.

TABLE V
HARMONIC CURRENT AND VOLTAGE DISTRIBUTIONS WITH FILTERS AND COMPARISONS WITH UTILITY TOLERANCES

harmonic orders	Harmonic currents(A)			harmonic voltages(V) to neutral			utility criterion (tolerances) currents(A)		utility criterion (tolerances) voltages(V)
	Case1	case2	case3	case1	case2	case3	case1	case2 and 3	All cases
2	7.26	9.33	8.52	11.56	14.85	13.56	7.78	10.7	197.5
3	9.90	35.1	19.4	23.64	83.82	46.33	31.1	42.6	197.5
4	4.19	8.45	6.22	13.34	26.91	19.81	7.78	10.7	197.5
5	26.7	30.3	35.2	106.3	120.6	140.1	31.1	42.6	197.5
7	16.1	12.0	14.0	89.72	66.87	78.01	31.1	42.6	197.5
11	13.6	10.2	13.4	119.1	89.32	117.3	15.6	21.3	197.5
13	8.35	9.37	12.1	86.41	96.97	125.2	15.6	21.3	197.5
17	0	0	11.3	0	0	152.9	11.67	16.0	197.5
19	0	0	10.8	0	0	163.4	11.67	16.0	197.5
THD(%)	4.80	4.82	4.68	3.11	3.20	4.99	5	5	5
Power factors: 0.95 lagging for all cases									

TABLE VI
COMPARISONS BETWEEN SA METHOD AND CONVENTIONAL TRY-AND-ERROR METHOD ON THE PLANNING RESULTS OF SINGLE-TUNED FILTERS OF CASE 1

Methods / Set Number	SA-method L(mH)	SA-method C(uF)	SA-method Q(kVAR)	SA-method Cost(pu)	Conventional (try-and-error method) L(mH)	Conventional C(uF)	Conventional Q(kVAR)	Conventional Cost(pu)
1	15.38	20.27	1039	190.6	8.86	35.2	1805	277.5
	Parameter: h_0 =4.75				Parameter: h_0 =4.75			
2	16.45	29.61	1558	264.4	32.3	15.0	793	206.5
	Parameter: h_0 =3.8				Parameter: h_0 =3.8			
Total cost	455*1.2=546 pu				484*1.2=580.8 pu			

It is noted that the case 1 has simple harmonic spectrum with fifth-order harmonic current to be filtered. Two single-tuned filters are capable to filter harmonic and compensate reactive power. Although we aim to fifth-order harmonic current, the enlargement of fourth-order harmonic current should be suppressed by a fourth-order filter to satisfy utility criterion. In case 2, a low (second)-order harmonic current should be filtered. In this case the single-tuned filter is used for filtering fifth-order harmonic current but enlarge the second-order harmonic current. If another single-tuned filter is used for filtering second-order harmonic current, the system will be over compensated. Thus, the program approach to a C-type damped filter. Case 3 also has only a fifth-order harmonic current to be filtered but its high order (17th and 19th orders) harmonic voltages should be suppressed. A single-tuned filter and a third-order damped-filter are selected for filtering fifth-order harmonic current and high-order harmonic voltages larger than order 17, respectively, but the low order harmonic enlargements are inevitable, so that a C-type damped filter is necessary to suppress second-, third-, and fourth-orders of harmonics currents within utility tolerances. The third-order damped filter may be substituted by the second-order damped filter if the cost-weighting coefficient k_5 is defined smaller than 0.1 (pu/kw). The spectrums of the normalized resultant impedance magnitude seen from harmonic source based on system impedance magnitude for three cases are shown in Fig. 10, from which no resonant point (frequency with infinite

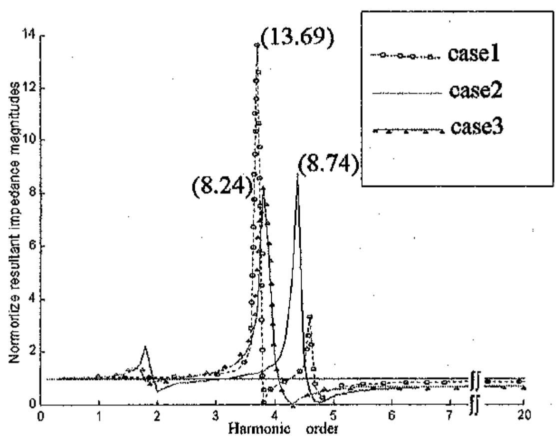

Fig. 10. Spectrums of normalized resultant impedance magnitudes seen from harmonic source.

impedance) can be found over all harmonic distributions. Moreover, there are no harmonic currents on critical point (frequency with largest normalized resultant impedance) and the harmonic currents near the critical point are under controlled. Hence, the system in all three cases is impossible to have resonance when filters are on line.

VI. Conclusions

This paper has analyzed the characteristics of four types of filters: single-tuned filter, second-order, third-order and C-type damped filters, where we defined the parameters characteristic-harmonic-order h_0 and damped-time-constant-ratio m to characterize the filters' impedances, power losses and reactive power compensation and to describe the performances of harmonic filtering and power factor improvements. The optimization model of the planning of filters and its solution algorithm based on simulated annealing method have been developed, from which we can obtain the types, set number, capacities, parameters, and element values of filters with minimum cost to satisfy the requirements of harmonic filtering, power factor improvements, and other constraints. The presented three case studies with different harmonic distributions and power factors have shown that the promising planning results of filters can be obtained by using the proposed method. In summery, the single-tuned filters are enough to filter the simple harmonic distribution with harmonic order about greater than 4 and to improve the power factor. But it is also necessary to use C-type damped filters to suppress low order (about small than 4) harmonic distributions over tolerance, and to use second-order or third-order damped filters for filtering complex high order harmonic distributions.

VII. Further Studies

The works of the planning of filters are the foundation for the following further studies:

i) To determine the commercial specifications of the units of filter elements (R, L, C). A filter element may be composed of many units with small rating in series and/or parallel manner to fit high voltage and high current requirements. Where the performances of protection devices of each unit should be considered, e.g., the protection performances of the internal fuses of capacitor units are very concerned to determine the series and parallel number, and voltage and current rating of capacitor units.

ii) To determine the protection scheme and coordination setting list for the protection of whole filters, the system load variation, operation schedule and procedure of filters, interlock relationships and relay characteristics should be taken into consideration.

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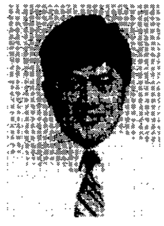

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