Design of Filters for Reducing Harmonic Distortion and Correcting Power Factor in Industrial Distribution Systems

Ying-Tung Hsiao

Department of Electrical Engineering
Tamkang University
Tamsui, Taipei, Taiwan 251, R O.C.
E-mail: hsiao@mail.tku.edu.tw

Abstract

This work presents a method capable of designing power filters to reduce harmonic distortion and correct the power factor. The proposed method minimizes the designed filters' total investment cost such that the harmonic distortion is within an acceptable range. The optimization process considers the discrete nature of the size of the element of the filter. This new formulation is a combinatorial optimization problem with a non-differentiable objective function. In addition a solution methodology based on an optimization technique - simulated annealing is proposed to determine the size of filters with minimum cost. The proposed technique is compared with the sequential unconstrained minimization technique in terms of performance and investment cost, via the industrial distribution system.

Key Words: Harmonics, Filter, Power Quality, THD, Optimization

1. Introduction

Increasing concern over the harmonic (voltage or current distortion) problem stems from the growing numbers and power ratings of the highly non-linear power electronic devices used in controlling power apparatuses in industrial distribution systems. Harmonic in power systems shortens the equipment's life expectancy and can interfere with communication lines and sensitive equipment. The filter design has become essential for industrial distribution systems. This work examines the feasibility of designing a filter size such that the total investment cost, (in which unacceptable voltage profiles must be correct and harmonic must be reduced within the permissible maximal value e.g. IEEE Std. 519 [4]), is keep at a minimum.

Designing a harmonic filter has conventionally been by a trial and error approach. Various formulations for a more systematic approach to design harmonic filters have been developed in the decade [1-3,5-8,10,12-14]. Although effective in eliminating the harmonic, some of these methods did not consider the cost of filter elements. Moreover, other related investigation did not address whether or not the issue of the filters can adhere to the industrial specifications.

The harmonic filter design problem has a partially discrete, partially continuous formulation with a non-differentiable nonlinear objective function. The non-differentiable nature, originating from a circumstance in which the cost of capacitors is step-wise, makes most nonlinear optimization techniques difficult to apply. This type of problems has generally been tackled by heuristic or approximate techniques.

Consequently, those solution algorithms generally achieve local optimum rather than global optimum.

A technique base on Simulated Annealing (SA) is employed to circumvent this problem. SA algorithm is a highly effective general-purpose technique for resolving combinatorial optimization problems. A previous study demonstrated that this algorithm asymptotically converges to the global optimal solution with the probability one [11].

This paper formulates the design harmonic filter problem by taking practical aspects of the element of filters and proposing operational constraints. Simulation results obtained from an industrial distribution system demonstrate the effectiveness of the proposed method.

2. Simulated Annealing

This algorithm is based on the analogy between the simulation and the annealing process used for crystallization in physical systems [9].

The following displays a pseudo code of the SA algorithm.

procedure *SIMULATED-ANNEALING*
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 loop L times
3.1.1 Generate a random neighbor S' from S
3.1.2 If feasibility
3.1.2.1 Let ΔC = cost(S') - cost(S)
3.1.2.2 If $\Delta C \leq 0$ (downhill move)
Let S = S'
3.1.2.3 If $\Delta C \geq 0$ (uphill move)
Let S = S' with probability exp($-\Delta C/T$)
*3.2 Let T=α*T (cooling down)*
4. Return S

In condensed matter physics, annealing is a thermal treatment process capable of achieving the low energy state of material. The process involves two steps: first heating up a solid to a melting point, by cooling it down until it crystallizes into a state with a perfect lattice.

At each temperature, the present system structure S is perturbed to generate a new structure S'. Then, the effect of the perturbation is evaluated in terms of the cost ΔC = cost(S') - cost(S), where cost(S) and cost(S') are the value of the cost function before and after the move has been executed. The move is accepted and the new configuration is retained. That is if the move decreases the value of the cost function, i.e., $\Delta C<0$. Most optimization algorithms belong to the class of greedy search techniques. The main disadvantage associated with the greedy search technique is that it frequently gets stuck at local optima rather than at global optima.

However, the SA can get out of a local optimal solution in the following manner (acceptance criterion): at first, the Boltzman term, exp ($-\Delta C/T$), is calculated, where the control parameter T is the "temperature". A random number Υ is then selected from uniform distribution in the interval of [0,1]. If $\Upsilon \leq$ exp ($-\Delta C/T$), the new structure is accepted; otherwise, the new move is discarded and the structure before this move is used for the next step. Due to the probabilistic selection rule, SA can always get out of a local optimal and proceed to the global optimal solution.

The feasibility checking step is used to check the new structure after a perturbation whether the constraints are satisfied or not. If all of the constraints can be satisfied, then go on next step; otherwise, the move is discarded and the structure before this move is used for next iteration.

The final solution's quality and the convergence speed of the SA algorithm depend on the choices of the initial temperature T in conjunction with the design of the cooling schedule. The temperature is initially set to a large value so that the probability of accepting "up-hill" moves is close to 1; it is then slowly decreased towards "frozen". In other word, the temperature T_k is lower when the number of moves (move length) reaches a preset value. In the cooling process, $T_{k+1} = \alpha \bullet T_k$, where α is smaller than but close to 1. Typical values lie between 0.8 to 0.99.

Stop criterion: (i) If the sampled mean values of cost function do not markedly change or (ii) the acceptance rate of moves for a temperature is sufficiently small (e.g., less than 1%) at five successive temperatures, then the annealing process is considered "frozen", and the global optimal structure is attained. Figure 1 depicts a flow chart showing the major steps of the SA algorithm.

3. Problem Formulation

We consider the filter design problem as identifying the size of filters with minimum cost in conjunction with operation constraints to effectively suppress harmonics.

Filters can be classified as active and passive. Although the active filters can effectively enhance the quality, they are expensive. This paper employs single tuned passive filter structures, owning to the advantages of a simple structure, low cost and easy design.

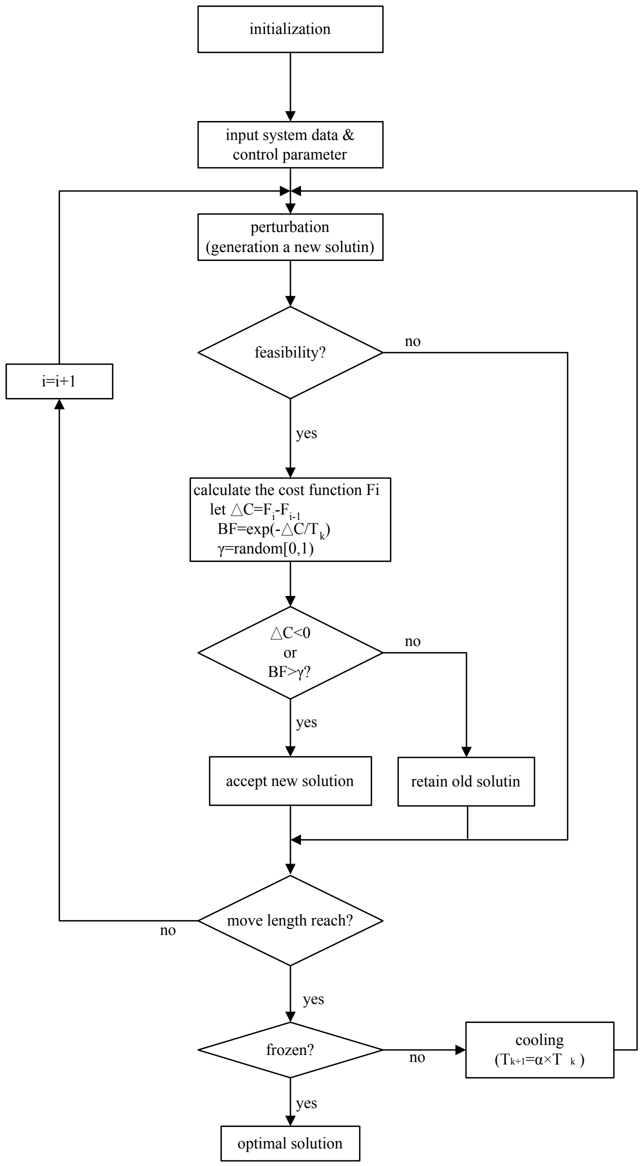

Figure 1. The flow chart of the SA algorithm

3.1 Objective Function

The objective function considered in this problem is the cost of filters which has two components, purchase cost and installment cost:

$$F = \sum\left(K_{Ch} \cdot Q_{Ch} + K_{Lh} \cdot Q_{Lh}\right) + K_I \qquad (1)$$

where K_{Ch} and K_{Lh} represent the unit cost of the capacitor and inductor, respectively. Also, Q_{Ch} and Q_{Lh} denote the kVA size of the capacitor and inductor, respectively for h'th harmonic filter. Moreover, K_I is the installment cost.

3.2 Constraints

The following constraints are considered:

3.2.1 Power Factor Correction

The harmonic filters can also provide a large percentage of reactive power for the power factor correction. When the capacitor, Q_{com} kVA, is installed in a system with a real power load P kW, the power factor can be improved from pf_0 to pf_1, where

$$Q_{com} = P \times \left(\tan\left(\cos^{-1} pf_0\right) - \tan\left(\cos^{-1} pf_1\right)\right) \quad (2)$$

The capacity of a single-tuned filter can be set to

$$Q_f = Q_{com} \quad (3)$$

For multiple parallel single-tuned filters, the capacitor corresponding to the h'th harmonic filter can be distributed approximately by

$$Q_{fh} = Q_{com} \times \frac{I_h}{\sum I_h}, \; h = 2, 3, \ldots \quad (4)$$

where I_h denotes the h'th harmonic current and Q_{fh} represent the capacity of the h'th harmonic filter. Also, the filter capacity Q_{fh} contains the capacity of capacitor Q_C, and inductor Q_L. They have the following relationships.

$$Q_C = \frac{h^2}{h^2 - 1} Q_f \quad (5)$$

$$Q_L = Q_C - Q_f \quad (6)$$

$$Q_L = \frac{1}{h^2} \cdot Q_C \quad (7)$$

3.2.2 Low and Upper Bound Limits of the Filter's Capacity

If the reactive VArs supplied by the filters exceed the system demand, the problem of system over voltage arise, which tends to occur at the light-load condition. Owing to this reason, the filter capacitors are selected such that the reactive power supplied by them does not exceed a specified value,

$$Q_{com}^{min} \le Q_f \le Q_{com}^{max} \quad (8)$$

where Q_{com}^{min} and Q_{com}^{max} denote the minimum and maximum bounds on the compensation.

3.2.3 Operation Constraints

The operational constraints can generally comprise of the following

$$THD_V \le THD_V^{max} \quad (9)$$

$$THD_I \le THD_I^{max} \quad (10)$$

$$V^{min} \le V_i \le V^{max} \qquad i = 1, 2, \ldots, m \quad (11)$$

where V_i is the voltage on bus i, m is the total number of bus in the system, $THD_{V,I}$ are the total harmonic distortion of voltage and current, respectively (a detail definition of the THD can be found in [1]), V^{min}, V^{max} and $THD_{V,I}^{min,max}$ correspond to the permissible minimum and maximum limit of voltage, and THD (specified by IEEE Std. 519), respectively.

In summary, the problem formulation of design single-tuned filters is summarized as

$$\min_{c,L} \; F = \sum_h (K_C \cdot Q_{Ch} + K_L \cdot Q_{Lh}) + K_I \quad (12)$$

subject to

$$Q_{com}^{min} \le Q_f \le Q_{com}^{max} \quad (13)$$

$$Q_C = \frac{h^2}{h^2 - 1} Q_f \quad (14)$$

$$Q_L = Q_C - Q_f \quad (15)$$

$$THD_V \le THD_V^{max} \quad (16)$$

$$THD_I \le THD_I^{max} \quad (17)$$

$$V^{min} \le V_i \le V^{max} \qquad i = 1, 2, \ldots, m \quad (18)$$

4. Implement of SA to Design Filters

This section presents a solution algorithm for designing harmonic filters to determine the size of the filters with minimum cost.

An algorithm designed as the basis of SA consists of four important elements: (1) configuration space, (2) perturbation mechanism, (3) an objective function and (4) a cooling schedule.

4.1 Objective Function

The objective function used in the problem of design filters is the cost function of filters. The cost of C and L is generally not a smooth function and not proportional to their sizes. Therefor, the parameter K_C and K_L are constructed by looking up tables in the computer program.

4.2 Configuration Space

Configuration space is the set of allowed system configurations. Design of configuration space is critical to the iterations' efficiency and the final solution's quality. Properly designing configuration space requires good engineering judgment.

If the upper and lower limit of filter capacity on capacitor is Q_{com}^{min} and Q_{com}^{max}, respectively, then the solution space of Q_f can be reduced to

$$\{ Q_{com}^{min} \le Q_f \le Q_{com}^{max} \}$$

4.3 Perturbation Mechanism

New filter configuration is generated from the current configuration via a perturbation mechanism. Four types of moves are devised to implement the perturbation mechanism.

add/subtract move: add or subtract a preset realistic step size of capacitor or inductor (e.g., 30 kVA) into the current configuration.

multiplication move: add or subtract a positive integer multiple of a standard size of capacitor or inductor (e.q. 3*30 kVA) into the current configuration.

synchronous move: the change size of capacitor or inductor in the filter is changed synchronous in a move.

asynchronous move: the change size of capacitor or inductor in the filter is changed independently at a move.

4.4 Cooling Schedule

SA algorithm analogs to the cooling down process of material crystallize. Low speed cooling down generates a perfect crystal; otherwise, it will fall to drawback. The cooling schedule is crucial for both the iterations' overall efficiency and the final solution's quality. High temperature stage initially employs a high speed cooling down to enhance the annealing efficiency and at low temperature stage employs a low cooling schedule to upgrade the solution's quality. The cooling schema generally corresponds to the rule: $T_{k+1} = \alpha(T_k)*T_k$ where $\alpha(T_k)$ is adjust to a higher value to avoid becoming stuck at a local optimal configuration at low temperature stage. Otherwise, the $\alpha(T_k)$ is adjusted to value to increase the convergence speed.

Solution Algorithm

Step 1.Input the system data and control parameter.
Input the system data (e.g., the system configuration and measured harmonic data) and control parameters (e.g., the initial temperature and cooling rate)

Step 2.Generate a feasible solution.
(1) Randomly select a configuration from the configuration space.
(2) Perform harmonic power flow equation to check constraints. If any constraint is violated, go to (1). Otherwise, proceed to (3).
(3) Calculate the cost function.

Step 3. Design a suitable cooling schedule.

Step 4. At each temperature T_k, for move= 1, 2, ..., n_k, do step 5-7.

Step 5. Obtain a new feasible configuration.
(1) Generate a new configuration using a perturbation mechanism.
(2) Execute the harmonic power flow equation and check the constraints. If any constraint is violated, go to (1). Otherwise, proceed to (3).
(3) Calculate the cost function.

Step 6.Update the system configuration.
Retain the new configuration or restore to the previous configuration based on the acceptance criterion (described in the section of II simulation annealing).

Step 7.Check the stop criterion for each temperature.
If the number of perturbations is not less than n_k, go to the next step. Otherwise, go to step 5.

Step 8.Check the stop criterion.
If the stop criterion is not satisfied, then the system is not yet frozen. Perform the cooling schedule, i.e. Allow $T_{k+1}=\alpha(T_k)*T_k$, then return to step 5. Otherwise, proceed to the next step.

Step 9.Print out the optimal results.

Output of the above solution algorithm yields the size (capacity) of the elements of the single-tuned filters (i.e. Q_C and Q_L).

5. Numerical Results

Numerical results in this section demonstrate the satisfactory performance of the proposed method. The test system is a factory with a main transformer of 69/3.3kV, loading 4410kW, and power factor 0.76. There is one harmonic source. Table 1 displays the measured harmonic currents; the current total harmonic distortion is 12.62%.

Table 1. Harmonic Current at PCC of the Test System

Order, h	5	7	11	13	17	19	23	25
Ih(A)	173	44	52	23	29	19	19	12
Order, h	29	31	35	37	41	43	47	49
Ih(A)	9.0	4.8	2.9	2.0	1.3	1.3	1.8	1.4

Three cases have been considered. In the first and second cases, a single-tuned filter was design to tune the frequency of the 5th and 7th order harmonics, respectively. Regarding the third case, two single-tuned filters were design to reduce the harmonics. Figure 2, 3 and 4 present the simulation results for the three cases, respectively.

Moreover, Table 2 and Figure 5 summarizes the results by using the SA, trial and error, as well as the sequential unconstrained minimization technique (SUMT) method [10] to reduce harmonics for case 3.

Above results confirm that the proposed SA method is better than the other two methods in terms of total harmonic distortion. Also, the SA method can attain a minimum cost of filters. Besides SA method, the other two method do not use industrial specification bank size for the Q_C. The cost of filters (by order) should be higher than that of SA method.

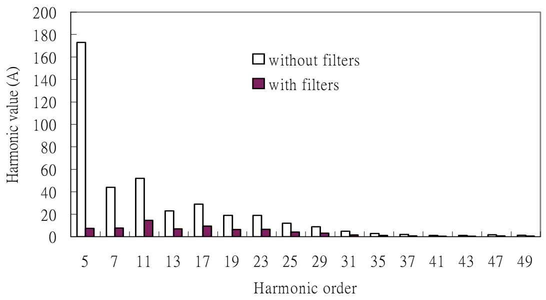

Figure 2. A single-tuned filter tuned to the 5th order harmonic

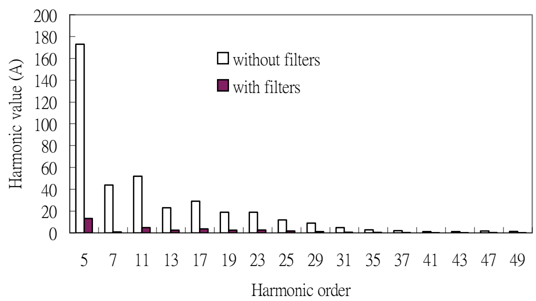

Figure 3. A single-tuned filter tuned to the 7th order harmonic

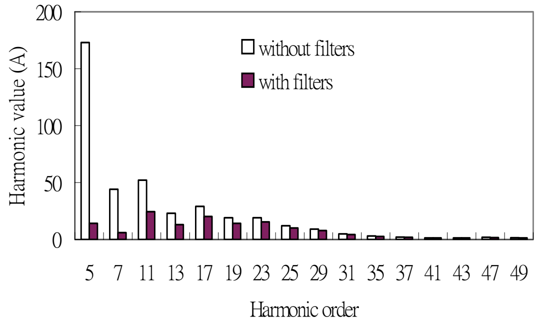

Figure 4. Two single-tuned filters tuned to the 5th and 7th, respectively

Table 2. Simulation results of the three methods on case 3

Methods	**Trial and Error**	**SUMT**	**SA**
total cost (NT$X1000)	51.76	39.29	24.02
THD_V	0.519%	0.494%	0.415%
THD_I	3.540%	3.045%	2.695%
Q_{C5}	2200kVA	1696.06kVA	1420kVA
Q_{L5}	99.593kVA	80.154kVA	67.215kVA
C_5	488.456uf	375uf	313.9144uf
L_5	0.861mh	0.887mh	4.5654mh
Q_{C7}	1800kVA	1293.24kVA	330kVA
Q_{L7}	42.63kVA	31.1823kVA	7.9776kVA
C_7	417.934uf	300uf	76.5419uf
L_7	0.550mh	0.566mh	2.222mh

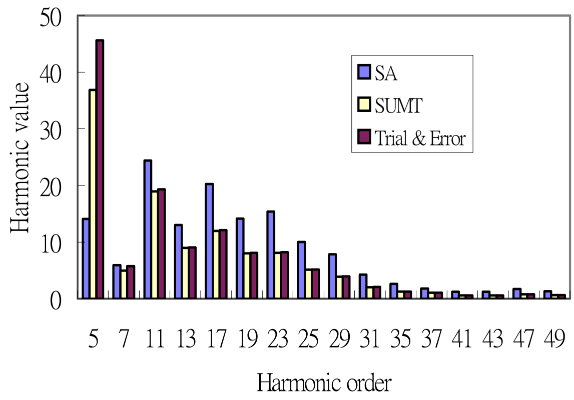

Figure 5. Comparison of simulation results on the three methods

6. Conclusion

This work presents a novel means of designing the power harmonic filters in lieu of concerns to satisfy the safety constraints and incur a minimum purchase and installment cost. The problem of designing filters is formulated as a non-differentiable optimization problem while considering the practical aspects of filters. Moreover, a solution algorithm based on SA is derived to find the optimal solution. This solution algorithm is appropriate for distribution power systems and has been implement into a software package and tested on a 69kV industrial distribution system with highly promising results.

Acknowledgment

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC 90-2213-E-032-018.

References

[1] Arrillaga, J., Bradley, D. A. and Bodger, P.S., *Power System Harmonic*, John Wiley & Sons, U. S. A. (1985).

[2] Baghzouz, Y. and Ertem, S., "Shunt capacitor sizing for radial distribution feeders with distorted substation voltage," *IEEE Trans. on Power Delivery*, Vol. 5, pp. 650-657 (1990).

[3] Chou, C. J., Liu, C. W., Lee, J. Y. and Lee, K. D., "Optimal planning of large passive-harmonic-filters set at high voltage level," *IEEE Trans. on Power Systems*, Vol. 15, pp. 433-439 (2000).

[4] Duffey, C. K. and Stratfort, R. P., "Update of harmonic standard IEEE-519: IEEE recommended practices and requirements for harmonic control in electric power systems," *IEEE Trans. on Industry Applications*, Vol. 25, pp. 1025-1034 (1989).

[5] Gonzalez, D. A. and Mccall, J. C., "Design of filters to reduce harmonic distortion in industrial power systems," *IEEE Trans. on Industry Applications*, Vol. IA-23, pp. 504-511 (1987).

[6] Hartana, R. K. and Richards, G. G., "Comparing capacitive and LC compensates for power factor correction and voltage harmonic reduction," *Electric Power System Research*, Vol. 17, pp. 57-64 (1989).

[7] Iyer, S. R., Ramachandran, K. and Hariharan, S., "Optimal reactive power allocation for improved system performance," *IEEE Trans. on PAS*, Vol. PAS-103, pp. 1509-1515 (1984).

[8] Kiimbark, E. W., *Direct Current Transmission*, New York: Wiley Interscience, Ch. 8, pp. 295-391 (1981).

[9] Kirkpatrick, S. C., Gelatt, D. and Vecchi, M. P., "Optimization by simulated annealing," *Science* 220, pp. 671-680 (1983).

[10] Lin, K. P., Yang, W. T., Liu, C. W. and Lin, M. H., "Improvement of harmonic problem in the industrial distribution system," *Monthly J. of Taipower's Engineering*, Vol. 567, pp. 34-60 (1995).

[11] Mitra, D., Romes, F. and Sangiovanni-Vincentelli, A., "Convergence and finite-time behavior of simulated annealing," *Proc. of 24th Conf. on Decision and control*, pp. 761-767 (1985).

[12] Ortmeyer, T. H. and Hiyama, T., "Distribution system harmonic filter planning," *IEEE Trans. on Power Delivery*, Vol. 11, pp. 2005-2012 (1996).

[13] Peng, F. Z., Akagi, H. and Nabase, A., "Compensation characteristics of the combined system of shunt passive and series active filters," *IEEE Trans. on Industry Applications*, Vol. IA-29, pp. 144-151 (1993).

[14] Vilcheck, W. S. and Ganzalez, D. A., "Guidelines for applying shunt capacitors on industrial power systems," *Industrial Commercial Power Systems Conf.*, Denver, CO, U. S. A. (1985).

Manuscript Received: Jul. 19, 2001
and Accepted: Aug. 15, 2001