REDUCING HARMONIC DISTORTION AND CORRECTING POWER FACTOR IN DISTRIBUTION SYSTEMS

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ABSTRACT

This paper 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.

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

INTRODUCTION

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 [1]), 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 [2-4]. 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 stepwise, 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. 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.

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 $T=\alpha*T$ (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

$$\Delta \mathbf{C} = \mathbf{cost(S') - cost(S)},$$

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 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. 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. Fig. 1 depicts a flow chart showing the major steps of the SA algorithm.

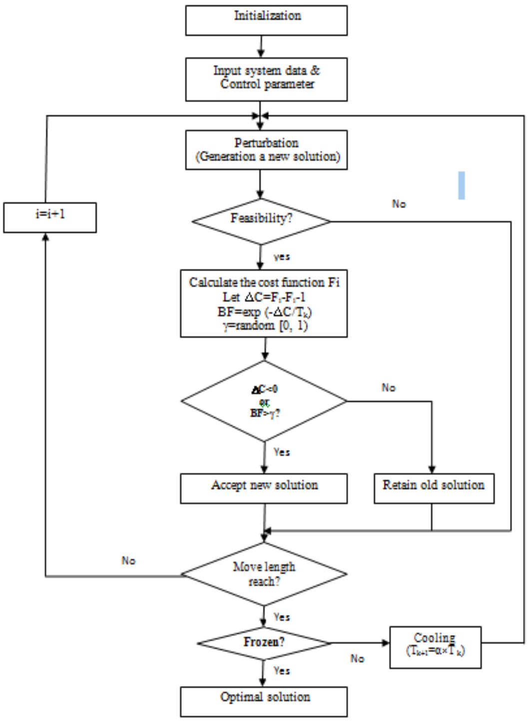

Fig. 1 The flow chart of the SA algorithm

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.

1. *Objective Function*

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

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

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.

2. *Constraints*

The following constraints are considered:

- **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:

$$Q_{com} = Px(\tan(\cos^{-1} pf_0) - \tan(\cos^{-1} pf_1)) \qquad (2)$$

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

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

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

$$Q_{fh} = Q_{com}\, x \,\frac{I_h}{\sum I_h}, \quad \text{h=2, 3,...} \qquad (4)$$

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.

$$Q_c = \frac{h^2}{h^2-1} Q_f$$
$$Q_c = Q_c - Q_f$$
$$Q_c = \frac{1}{h^2} Q_c$$

- **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,

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

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

- **Operation Constraints**

The operational constraints can generally comprise of the following:

$$THD_v \leq THD_v^{max}$$
$$THD_1 \leq THD_1^{max}$$
$$V^{min} \leq V_i \leq V^{max} \qquad \text{i=1,2,.......m}$$

Where:

$\mathbf{V_i}$ is the voltage on bus i, m is the total number of bus in the system, **THDV,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 $THDV^{min}$,I^{max}, correspond to the permissible minimum and maximum limit of voltage, and THD (specified by IEEE Std. 519), respectively.

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.

a) 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. Therefore, the parameter KC and KL are constructed by looking up tables in the computer program.

b) 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

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

c) 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.g. 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.

d) Cooling Schedule

SA algorithm analogs to the cooling down process of material crystallize. 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.

e) 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 nk, 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 Tk+1=α(Tk)*Tk, 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).

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 11/6.6kV, loading 3150kVA, 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 I
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	4.8	2.9	2	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 [5] 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.

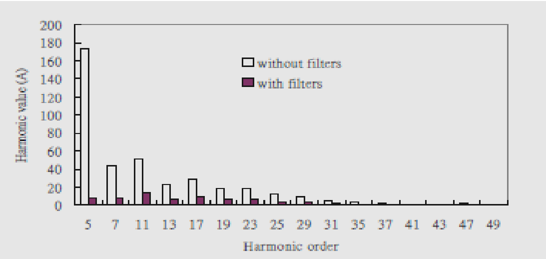

Fig. 2 A single-tuned filter tuned to the 5th order Harmonic

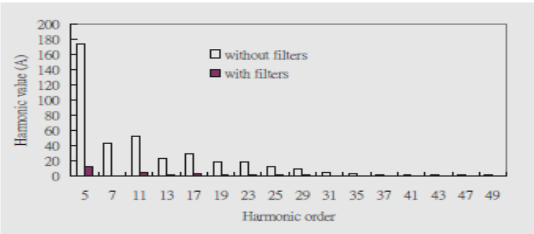

Fig. 3 A single-tuned filter tuned to the 7th order Harmonic

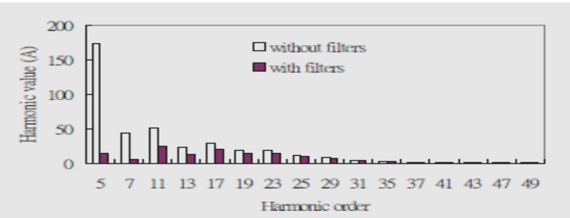

Fig. 4 Two single-tuned filters tuned to the 5th and 7th, respectively

TABLE II
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%
QC5	2200kVA	1696.06kVA	1420kVA
QL5	99.593kVA	80.154kVA	67.215kVA
C5	488.456uf	375uf	313.9144uf
L5	0.861mh	0.887mh	4.5654mh
QC7	1800kVA	1293.24kVA	330kVA
QL7	42.63kVA	31.1823kVA	7.9776kVA
C7	417.934uf	300uf	76.5419uf
L7	0.550mh	0.566mh	2.222mh

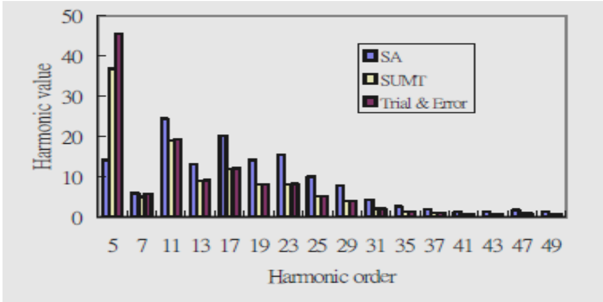

Fig. 5 Comparison of simulation results on the three Methods

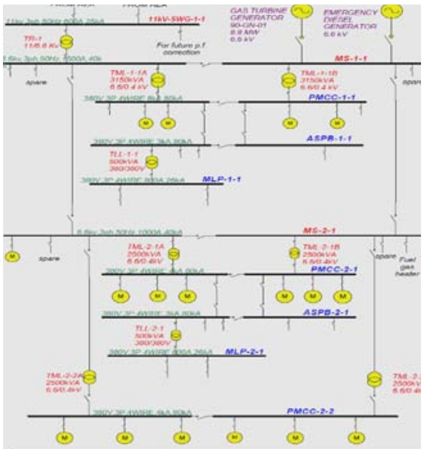

Fig. 5 single line diagram of case study

CONCLUSION

This work presents designing the power harmonic filters in Egypt 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 11kV industrial distribution system with highly promising results.

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