Optimal Single Tuned Damped Filter for Mitigating Harmonics using MIDACO

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***Abstract*— This paper presents new method employing Mixed Integer Distributed Ant Colony Optimization to optimize the sizing parameters of single tuned damped filter in the nonsinusoidal system. The proposed method obtain the optimum value of inductance and capacitance along with the resistance of the inductor where the global minimum and maximum is achieved after considering the nonlinear loads, the voltage total harmonic distortion based on IEEE Std. 519-2014, the filter values which would introduce resonance and the quality factor of the tuning reactor. The optimal design of the single tuned damped filter is introduced and compared with the previous published filter.**

Keywords*— *Power system harmonics; single tuned damped filters; Mixed Integer Distributed Ant Colony Optimization (MIDACO); damping; filtering; power quality;

I. Introduction

Power system harmonics is an electrical pollution that has been occurred in the power system where the distorted waveforms has become a growing concern for engineers to the power quality problem, harmonic pollution and interference problems due to the increasing number of nonlinear loads. For example; rectifier, uninterruptible power supplies and other devices using solid state switching [1]-[2].

Among the numerous solutions [3]-[7], the most ideal to solve the harmonics problem in the power system is passive harmonic filter [8]-[9]. Generally, single tuned filter is type of passive shunt filter that is common used to mitigating harmonics because the method is effective and economical. It has been recommended for nonlinear loads because it can eliminate harmonics and in the same time correcting the power factor [10].

There are several techniques that have been used for the design of passive filter which are experimental procedures [11], network synthesis [12] and optimization tools [13]-[15]. In this paper, the first application of Mixed Integer Distributed Ant Colony Optimization (MIDACO) is presented to find ideal solutions of single tuned damped filters for mitigating harmonics.

Three different criteria where the optimization maximized the power factor, minimized the losses power in Thevenin's resistor and maximized the transmission efficiency are discussed. In general, the method considers the load being nonlinear, the total voltage harmonic distortion based on IEEE Std. 519-2014 [16], the quality factor of the tuning reactor and the series or parallel resonance when adding the filter into the system.

This paper generalizes the method taking into consideration the nonlinearity of the loads, the total voltage harmonic distortion based on IEEE Std. 519-2014 [16], the quality factor of the tuning reactor, the series or parallel resonance when adding the filter and the effect of the Thevenin's impedance on the load voltage. A detailed comparison between proposed method and previous published technique has been discussed where the examples adopted from IEEE Std. 519-1992 publication [17].

II. Single Tuned Damped Filter

The most common shunt filter use for mitigating harmonics is single tuned damped filter. It consist a series of Resistor (R), Inductor (L) and Capacitor (C) where resistor is the losses in the inductor.

Practically, the power losses in the capacitor are negligible. Nonetheless, the power losses in the inductor must be taking into consideration where the adding of series resistance is known as damping [2]. The total impedance of the filter branch can be expressed as

$$Z_F = R + j(X_L - X_C) \tag{1}$$

where the inductance is given by $X_L = 2\pi fL$ and the capacitance is $X_C = 1/2\pi fC$

The filter is said to be ideal when it is tuned to the frequency which the inductor and capacitor of the filter have equivalent reactance and pure resistance [8]. The tuning frequency is given by

$$f_n = \frac{1}{2\pi\sqrt{\frac{L}{C}}} \tag{2}$$

The relationship of the filter reactance and resistance determines the inductor quality factor, Q_F of the filter at the tuned harmonic order, h.

$$h = \frac{f_n}{f_1} = \sqrt{\frac{X_C}{X_L}} \tag{3}$$

Where subscript "1" refer to the 1st harmonic order or fundamental component.

If X_0 is the filter reactance at its tuned frequency

$$X_0 = hX_L = \frac{X_C}{h} = \sqrt{\frac{L}{C}} \tag{4}$$

Then, Q_F gives the quality factor

$$Q_F = \frac{X_0}{R} = \frac{\sqrt{\frac{L}{C}}}{R} \tag{5}$$

The quality factor, Q_F indicates the performance of the inductor in the power system where it relates to the energy losses. In the circuit, the energy losses are mainly caused by the built in resistance in the inductor where the value of the resistance determines the minimum or maximum of the impedance at resonant. The lower the resistance, the high value of Q_F, thus the circuit has high frequency selectivity [18].

Additionally, the sharpness of the tuning can be defines from the bandwidth and expressed as

$$B = \frac{f_n}{Q_F} \tag{6}$$

Therefore, the bandwidth is proportional to the quality factor wherein the frequency selectivity of filter is decided on the quality factor.

In the power system, the most important side effects when adding a single tuned damped filter are the occurrence of series or parallel resonance. The harmonic activating resonance can be expressed as

$$h_r = \sqrt{\frac{X_C}{X_L + X_{TH1}}} \tag{7}$$

In series resonance, the circuit has minimum impedance and a small exciting voltage but results in high current. Conversely, parallel resonance has maximum impedance and small exciting current but results in a large voltage. Therefore it is suggested to avoid both series and parallel resonance because both resonances can cause damage in the circuit [2].

III. OPTIMIZATION PROBLEM

Fig.1 shows the configuration of the single tuned damped filter with the study system. The filter which provides low impedance is connected in shunt with the linear and nonlinear loads. This is to prevent the harmonic currents, I_{LK} from entering the source system and restricted to go into the filter impedance [2].

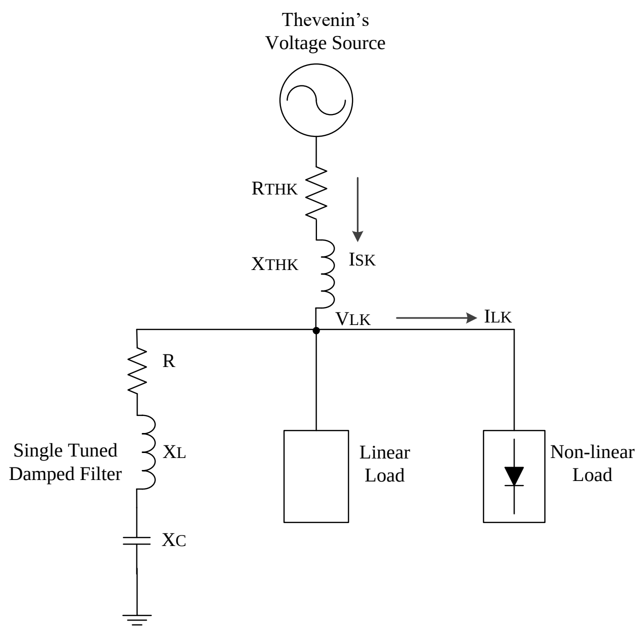

Fig. 1. The system under study

In this study, three different criteria have been presented to analyze the system performance:

The maximizing power factor, PF is given as

$$PF = \frac{P_L}{I_S V_L} = \frac{\sum_K V_{LK} I_{SK} \cos(\theta_K - \phi_K)}{\sqrt{\sum_K I_{SK}^2 \sum_K V_{LK}^2}} \tag{8}$$

The minimizing losses in Thevenin's resistor, P_{LOSS} is given as

$$P_{Loss} = \sum_K I_{SK}^2 R_{THK} \tag{9}$$

The maximizing the transmission efficiency, η is given as

$$\eta = \frac{P_L}{P_S} = \frac{\sum_K V_{LK} I_{SK} \cos(\theta_K - \phi_K)}{\sum_K V_{LK} I_{SK} \cos(\theta_K - \phi_K) + \sum_K I_{SK}^2 R_{THK}} \tag{10}$$

Where θ_K is *k*th harmonic angle of load voltage and $\emptyset_K$ is the *k*th harmonic angle of line current.

Besides, the total harmonic voltage distortion (VTHD) has been introduced to recognize harmonic component where VTHD at the load terminals can be expressed as

$$\mathrm{VTHD} = \frac{\sum_{K>1} V_{LK}^2}{V_{L1}} \tag{11}$$

Although there is no national standard limit for total harmonics distortions, but IEEE Std. 519-2014 provides suggested acceptable harmonic distortion for power system.

The constraints considered in the optimization problem are:

- *Harmonic resonance constraint* where the tuning frequency below 3%-10% from the harmonic to be filtered is selected [8].
- *Harmonic resonance constraint* where the value of h which is always greater than harmonic order activating resonance, h_r.
- *Quality factor* of the tuning reactor is specified to $20 \leq Q_F \leq 100$.
- *IEEE Std. 519-2014* According to IEEE Std. 519-2014, the maximum total voltage harmonics distortion is 5% or less [16].
- *Load power factor* is equal or greater than 90%

The different criteria, such as power factor PF, losses in Thevenin's resistor P_{LOSS} and transmission efficiency η are expressed using (8)-(10). Thus, the objective functions and constraints to find the optimal design of single tuned damped filter is given as

Maximize $\mathrm{PF}(R, X_C, X_L)$
Minimize $P_{LOSS}(R, X_C, X_L)$
Maximize $\eta(R, X_C, X_L)$

Subject to:

- $20 \leq Q_F \leq 100$
- $h \leq 0.9 f_n$
- $h > h_r$
- $\mathrm{VTHD} \leq 5\%$
- $\mathrm{PF} \geq 90\%$ (12)

MIDACO will be used as an optimization tool where the software implements Ant Colony Optimization with Oracle Penalty Method to reach the global optimum solutions of the parameters single tuned damped filter satisfying the constraints [19]. The advantage of the method is that the concept gives user a complete freedom to define and calculate objective functions and constraints in different form without any restrictions.

IV. Results and Discussion

In this study, there are four different cases were simulated. The inductive three-phase load power and reactive power given is 5100kW and 4965kVAR respectively. The 60-cycle voltage source is line to line 4.16kV with displacement power factor of 0.717. All the data were primarily taken from IEEE Std. 519-1992 publication [17] and given in the Table I below.

TABLE I
Four Cases System of Industrial Plant

Parameters & Harmonics	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Short Circuit, MVA	*150*	*150*	*80*	*80*
R_{TH1} (Ω)	0.01154	0.01154	0.02163	0.02163
X_{TH1} (Ω)	0.1154	0.1154	0.2163	0.2163
R_{L1} (Ω)	1.742	1.742	1.742	1.742
X_{L1} (Ω)	1.696	1.696	1.696	1.696
V_{S1} (kV)	2.4	2.4	2.4	2.4
V_{S5} (%)	5	7	5	7
V_{S7} (%)	3	4	3	4
V_{S11} (%)	2	2	2	2
V_{S13} (%)	1	1	1	1
I_{L5} (A)	33	33	33	33
I_{L7} (A)	25	25	25	25
I_{L11} (A)	8	8	8	8
I_{L13} (A)	9	9	9	9

TABLE II
Simulated Results of the Proposed Filter

Criteria	**X_C (Ω)**	**X_L (Ω)**	**R (Ω)**	**PF (%)**	**η (%)**	**P_{LOSS} (kW)**
Case 1						
Min P_{LOSS}	3.81	0.1838	0.01	97.16	99.63	6.10
Max PF	3.39	0.1441	0.03	96.06	99.64	6.40
Max η	3.82	0.1858	0.02	97.24	99.64	6.13
Case 2						
Min P_{LOSS}	3.68	0.1629	0.01	93.68	99.61	6.59
Max PF	3.78	0.1690	0.04	93.92	99.61	6.65
Max η	3.61	0.1754	0.02	94.84	99.62	6.48
Case 3						
Min P_{LOSS}	3.89	0.1918	0.01	98.88	99.35	10.87
Max PF	3.74	0.1647	0.03	98.82	99.35	11.05
Max η	3.87	0.1833	0.01	98.82	99.35	10.91
Case 4						
Min P_{LOSS}	3.99	0.1964	0.02	97.83	99.33	11.15
Max PF	3.59	0.1747	0.04	98.08	99.33	11.37
Max η	3.26	0.1569	0.01	97.32	99.33	11.49

Table II show summary of the simulated results of the proposed technique for the nonlinear loads to find optimal value of R, X_L and X_C based on the problem formulation given in (18). The filter performance show that different optimal solution is achieved satisfying all different criteria and constraints involved.

The results from Table II show that higher short circuit capacity for same harmonics condition effects to low power factor because high short circuit has small Thevenin impedance which allows more harmonic current drive to the system. However, small values of Thevenin resistor results to the lower power losses, therefore increasing the overall transmission efficiency; refer to Case 2 and 4.

Besides, the results also show that different value of harmonics will affects the same system; refer Case 1 and 2. The additional of voltage harmonics increased of the line current which results to lower power factor and consequently increased the losses in Thevenin resistor. The losses are also mainly caused by the value of resistance in the filter which overall results to lower transmission efficiency.

TABLE III
Comparison Results of VTHD with Filter [20].

Criteria	VTHD (%)	
	Proposed Filter	*Filter [20]*
Case 1		
Min P_{LOSS}	2.22	4.56
Max PF	1.71	4.59
Max η	2.26	4.51
Case 2		
Min P_{LOSS}	2.27	7.29
Max PF	2.38	7.13
Max η	2.70	7.20
Case 3		
Min P_{LOSS}	1.71	4.03
Max PF	1.40	12.01
Max η	1.60	4.21
Case 4		
Min P_{LOSS}	2.07	4.07
Max PF	1.90	8.85
Max η	1.72	4.01

Table III shows the comparison results of VTHD for the proposed filter with filter [20]. From the result, it proved the proposed filter has better performance compare to filter [20] where all the resultant of VTHD values for all cases is below maximum total voltage harmonics distortion as suggested by IEEE Std. 519-2014 [16].

V. CONCLUSION

The present method was developed to optimize the parameters of the single tuned damped filter having constrained nonlinear problems. The results of this research show that global maximum and minimum can be achieved by using Mixed Integer Distributed Ant Colony Optimization satisfying different criteria of the objective functions while taking into consideration few constraints. The performance of the proposed method is acceptable where it provides solution accuracy and the effectiveness of the developed algorithm proved when it can reach optimal solution for all cases that has been tested. This main contribution from the methodology is the assurances convergence to get the best solution in less iteration satisfying the objective functions and complying with the IEEE Std. 519-2014. There is continuing research to consider the value of manufacturer's standard capacitor into the studies where new solution and modification algorithm to include the practical values of capacitor has to be found.

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