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A Stochastic Optimization Method Applied for Single Tuned Passive Filter Planning

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Abstract—**Power system harmonics is one of the power quality problems. This study proposed an optimal single-tuned filter to eliminate harmonics in the power system using an optimization tool known as Mixed Integer Distributed Ant Colony Optimization. Two objective functions have been considered: the total of harmonic voltage distortions and transmission losses. The global maximum and minimum were achieved by maintaining the desired range of power factor, the quality factor is maintained within a specific range, avoiding harmonic resonance, and ensuring that capacitors and harmonic voltage do not violate IEEE standards. On a comprehensive passive filter design, this study also presents the advantages of multi-objective approaches over single-objective optimization using the proposed technique.**

Keywords— Power quality, harmonic filter, optimization, extended ant colony

I. INTRODUCTION

Harmonics in the power system have been observed since the 1920s and early 1930s when distorted waveforms with high frequencies were observed on transmission lines [1]. Most facilities use power electronically controlled devices, which change the pure sinusoidal power of alternating current (AC) [2]. As nonlinear loads and sensitive electronic equipment become more common, harmonic problems become more prevalent and will continue to be a challenge for engineers in the future [3].

There are several techniques to reduce harmonics, such as passive power filter (PPF) [4,5], active power filter (APF) [6,7], shifting transformer [8,9], isolation transformers [10,11], and others [12]. However, PPF is one of the many techniques used to eliminate harmonics because it is simple, robust, economical, and almost free for maintenance operation [13]. The reactive compensation by the PPF has become an advantage for the utility and users, where the filter increases the power factor and reduces the power losses. Nevertheless, it can cause harmonic resonance when the filter is integrated into the circuit, which can damage the circuit as a whole.

In recent years, PPF design methods inspired by nature, such as adaptive bacterial foraging optimization, adaptive carrier frequency optimization, artificial bee colony, genetic problem, and particle swarm optimization have been numerous in the power system. With the inspiration from the scavenging behaviour of artificial ants, Mixed Integer Distributed Ant Colony Optimization (MIDACO) was proposed in its algorithm to extend the mixed integer search domains [14,15]. Previously, a single tuned filter has been proposed using MIDACO for harmonics elimination using different objective functions and constraints for single [16,17] and multi-objective optimization [18]. Besides, the previous works also used only a single value of seed during simulation, which resulted in the algorithm behaving in a deterministic manner.

This research presents the application of MIDACO in passive filter design. The system performances of four different scenarios were evaluated in this study, which focused on single-objective and multi-objective optimization. During simulation, a stochastic approach is used where each scenario was run with 100 numbers of different seeds to allow random initialisation for the algorithm. Two objective functions have been considered: the total of harmonic voltage distortions and the resistor losses of the impedance of Thevenin. A comprehensive study was conducted to design the best filter while considering several significant constraints. The global minimum can be achieved by maintaining the desired range of power factor, the quality factor is maintained within a specific range, avoiding harmonic resonance, and ensuring that capacitors and harmonic voltage do not violate IEEE standards. On the Pareto front, the non-dominated solution for simulation of the multi-objective problem with different search efforts has also been investigated. The results showed that multi-objective approaches outperformed single-objective optimization on a comprehensive passive filter design using the proposed method.

II. METHODOLOGY

In this research, the circuit consists of a single-tuned filter, linear and non-linear load that are connected in shunt, as shown in Fig. 1. The filter placement in the circuit network performs as small impedance path, which allows harmonic current to go through the impedance which overall, will further reduce the voltage distortion. The total impedance, Z_F of the filter-branch can be expressed as in (1) below:

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

where the inductance is given by $X_L=2f\pi L$ and the capacitance is $X_c=1/2f\pi C$.

An ideal filter is the values of the capacitor and reactor have equal reactance at the tuned harmonic frequency, f_n.

$$f_n = h * f_0 = 1/2\pi\sqrt{LC} \tag{2}$$

where the f_n = filter resonant frequency, f_0 = fundamental frequency, C = filter capacitance and L = filter inductance.

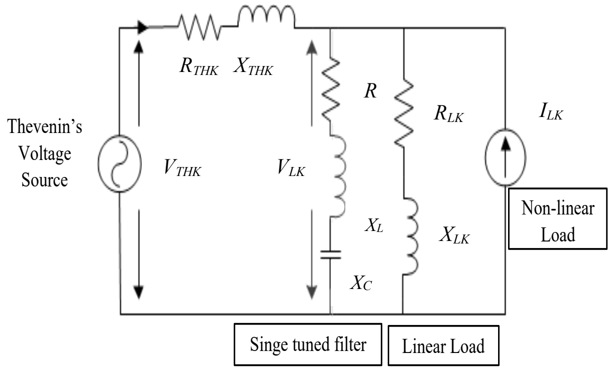

Fig. 1. System under study

According to (2), h is the tuning order and is given in (3) below:

$$h = f_n/f_0 = \sqrt{X_c/X_L} \tag{3}$$

The quality factor, *QF* in (4) defines the performance of the filter which related to the energy loss in the filter.

$$QF = 1/R\sqrt{L/C} \tag{4}$$

The optimization problem can be formalized by two objective functions: minimize the total harmonic voltage distortion and minimize the losses in Thevenin's resistor, as given in (5)–(6), described as follows:

a) Minimize Total Harmonic Voltage Distortion, THD_V.

$$THD_V = \frac{\sum_{K>1} V_{LK}^2}{V_{L1}} \tag{5}$$

where VL_K and VL_1 is the load voltage at K-th harmonics and fundamental frequency.

b) Minimize Losses in Thevenin's resistor, P_{LOSS} is given as:

$$P_{Loss} = \sum_K I_{SK}^2 R_{THK} \tag{6}$$

where Is_K and R_{THK} is the source current and Thevenin resistance at K-th harmonics.

The optimization problem also subjects to several constraints which are:

- *Capacitor limitation* following IEEE Std. 18-2012 [19].
- *Quality factor, QF* value is between 20 and 100.
- *Harmonic resonance* constraint where the harmonic order, h is tuned below 9% from the tuned frequency [20] and always greater than harmonic order activating resonance, h_r.
- *IEEE Std. 519-2014* standard where THD_V equal or less than 5% [21].
- *Load power factor* must not lower than 90%.

Hence, the objective functions and constraints can be formulated as in (7) a:

Objective 1: Minimize THD_V (R, X_C, X_L)

Objective 2: Minimize P_{LOSS} (R, X_C, X_L)

Subject to:

- Capacitor is lower than 135% of I_C, 110% of V_C, 120% of V_{CP} and 135% of Q_C.
- $20 \leq QF \leq 100$
- $h \leq 0.9 f_n$
- $h > h_r$
- $THD_V \leq 5\%$
- $PF \geq 90\%$ (7)

where I_C, V_C, V_{CP} and Q_C is current, voltage, peak voltage and reactive power for capacitor, respectively.

MIDACO will be used as an optimization tool, with the software combining Ant Colony Optimization with the Oracle Penalty Method to find the global optimum solutions while satisfying the constraints. In contrast to the single-objective optimization which usually results to single solution as global optimum, multi-objective optimization results to set of non-dominated solutions or known as Pareto-optimal which represents a trade-off curve (Pareto front) between the individual objectives. To solve multi-objective problems, MIDACO specifically used the concept of *Utopia-Nadir-Balance* where the algorithm is based on a combination of a decomposition of the original multi-objective problem into a series of single-objective problem. MIDACO acts as a black box optimizer where it allows the objective function and constraints to be represented and formulated in maximum possible freedom without any restrictions. The advantage of the method is that the concept allows user a complete freedom to define and calculate objective functions and constraints in different form without any restrictions [14,15].

III. SYSTEM UNDER STUDY

There are four industrial plants with random harmonics that have been studied, in which the examples of the calculation for short circuit parameters are adopted from the IEEE 519-1992 system. A 60 Hz fundamental frequency supply bus voltage determined at 4.16 kV (line-to-line). The settings for three-phase load power is set to 5100 kW and three-phase load reactive power is set to 4965 kVAR. Then, the calculations to find the short circuit and load parameters are performed and presented in Table 1.

TABLE I. SYSTEM UNDER STUDY

Parameters & Harmonics	**Scenario I**	**Scenario II**	**Scenario III**	**Scenario IV**
MVA_{SC}	150	150	80	80
R_{TH1} (Ohm)	0.01154	0.01154	0.02163	0.02163
X_{TH1} (Ohm)	0.1154	0.1154	0.2163	0.2163
R_{L1} (Ohm)	1.742	1.742	1.742	1.742
X_{L1} (Ohm)	1.696	1.696	1.696	1.696
V_{S1} (Volt)	2400	2400	2400	2400
V_{S5} (%V_{S1})	5	7	5	7
V_{S7} (%V_{S1})	3	4	3	4
V_{S11} (%V_{S1})	2	2	2	2
V_{S13} (%V_{S1})	1	1	1	1
I_{L5} (Ampere)	33	33	33	33
I_{L7} (Ampere)	25	25	25	25
I_{L11} (Ampere)	8	8	8	8
I_{L13} (Ampere)	9	9	9	9

IV. RESULTS AND DISCUSSION

The performance for the uncompensated system is shown in Table II below. The results showed that the system without filter has poor performance with the THD_V greater than 5% which exceed the IEEE 519-2014 standard [21].

TABLE II. THE NUMERICAL RESULTS FOR UNCOMPENSATED SYSTEM

Parameters	**Scenario I**	**Scenario II**	**Scenario III**	**Scenario IV**
PF (%)	71.72	71.71	71.71	71.71
η (%)	99.34	99.34	98.78	98.78
P_{LOSS} (kW)	10.48	10.48	18.45	18.45
THD_V (%)	6.20	8.22	6.38	8.29

Table III summarized the simulated results after including single tuned filter into the system. The best value of R, X_C and X_L were found by using the proposed method in which these results will be used for evaluating the overall performance. In this simulation, the controlling parameters of MIDACO were set to: 1) the number of ants will change dynamically for every generation; 2) kernel is fixed to 100 and 3) oracle set to default. For each objective, the algorithm was run with 100 different SEED parameter and the best solution out of a reasonable number of runs was chosen.

TABLE III. THE RESULTS FOR SINGLE-OBJECTIVE OPTIMIZATION

No. of Scen.	X_C **(Ω)**	***R*** **(Ω)**	X_L **(Ω)**	***PF*** **(%)**	**η (%)**	P_{LOSS} **(kW)**	THD_V **(%)**
Minimize THD_V							
I	3.54	0.143	0.0121	95.74	99.63	6.31	1.63
II	3.18	0.145	0.0068	93.00	99.61	6.74	2.20
III	3.04	0.125	0.0062	97.06	99.33	11.63	1.09
IV	3.48	0.145	0.0071	97.49	99.33	11.32	1.39
Minimize P_{LOSS}							
I	3.43	0.169	0.0077	97.05	99.64	6.15	2.17
II	3.75	0.185	0.0085	95.03	99.62	6.38	2.84
III	4.06	0.176	0.0121	98.34	99.34	10.94	1.45
IV	3.85	0.181	0.0084	97.87	99.34	11.11	1.86

From Table III, the results showed that the optimal filter obtained proved the validity and effectiveness of this proposed solver with an enhancement in the power factor and transmission efficiency as the losses in the resistor of Thevenin impedance and total harmonic voltage distortion reduced. When comparing Table III with the uncompensated system in Table II, the proposed filter showed satisfactory improvement in the entire performances. While the increasing value of *PF* will result from the increasing value of η which overall decrease the P_{LOSS} and THD_V.

In addition, the reduce in short circuit capacity will increase the Thevenin impedance. With the increasing number of resistors in the Thevenin impedance, the losses are also increasing, which results in the decrease of transmission efficiency. Nevertheless, the power factor is increased because less harmonic current will flow to the source system which also results in improvement of the THD_V. Please refer to the results for Scenario I and III in Table III.

In contrast, the same value of Thevenin' impedance with additional supply voltage harmonics in the system will reduce the power factor, which results in increasing value of THD_V because of the additional line current passes through the source. Due to the increasing number of the line current, the losses in the source impedance and the voltage drop will increase while the transmission efficiency will decrease. Refer the results for Scenario I and II in Table II.

Table IV summarized the simulated results for the multi-objective problem after including damped single tuned filter into the system. The controlling parameters were set same as single-objective optimization. The setting for the adjustable parameter of multi-objective problem were set to default setting where PARATEMOX=1000 and EPSILON=0.001. In this simulation, MIDACO will focus its search effort on the part of the Pareto front, which offers a best equally balanced trade-off between all objectives by setting the parameter BALANCE=0.

TABLE IV. THE RESULTS FOR MULTI-OBJECTIVE OPTIMIZATION

No. of Scen.	X_{CF} **(Ω)**	R_{DF} **(Ω)**	X_{LF} **(Ω)**	***PF*** **(%)**	**η (%)**	P_{LOSS} **(kW)**	THD_V **(%)**
I	3.78	0.0083	0.1802	97.09	99.64	6.10	2.17
II	4.06	0.0090	0.1982	94.67	99.62	6.39	2.91
III	3.78	0.0083	0.1827	98.94	99.35	10.89	1.63
IV	3.92	0.0087	0.1902	97.89	99.34	11.08	2.00

From Table IV, the results show that the ideal damped filter is successfully obtained while considering two objective functions concurrently subject to the constraints involved. By comparing Table IV with the results of single-objective optimization in Table III, the overall performance of the multi-objective optimization is satisfied with providing enhanced to the power factor, transmission efficiency as well as the losses in the resistor of Thevenin impedance. However, the value of THD_V is slightly higher for multi-objective optimization comparing to the single-objective problem. Because of the objective when maximizing THD_V is conflicting with the objective when minimizing P_{LOSS}. Thus, improvement of P_{LOSS} results to worsening THD_V. However, although there is a slight increase in the results of THD_V, but overall THD_V is still below than 5% which is below than suggested standard by IEEE 519-2014.

Fig. 2 is added to illustrate the impedance resonance for Scenario I, which has been recommended in this research in order to avoid any series or parallel resonance. The graph of the response is assessed and evaluated as follows:

- The series or parallel resonance can happen because of the interaction between the impedance at the source and the loads.
- The impedance is at the lowest point when the reactance of inductance is equal to the capacitance for the series resonance, thus canceling each other out. However, the impedance is at maximum for parallel resonance.
- For both resonances, the frequencies after the tuning are increased along with the impedance.

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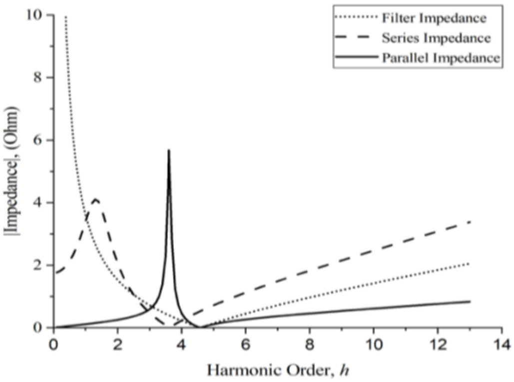

Fig. 2. Impedance response for Scenario I

- It is vital to consider detuning effects when designing this type of filter. This is clearly shown in the sharp increase of in impedance in Fig.2 where the parallel resonance causes a sudden increase in voltage.
- This can also happen to series resonance where the small value of resistance at resonance wills results in the current flowing through the circuit to be dangerously high.
- Overall, the design of a de-tuned filter to avoid series or parallel resonance is very important to protect the circuit from damage.

Table V indicates the limitations of the proposed main capacitors in the filter to follow the IEEE Std. 18. From the table, the results showed that all capacitors are capable of operating below the standard limitation.

TABLE V. THE CAPACITOR LIMITATION

No. of Scenarios	I_C (%)	V_C (%)	V_{CP} (%)	Q_C (%)
I	114.06	104.07	78.85	115.38
II	113.14	105.11	78.42	116.97
III	113.17	105.12	78.43	116.99
IV	113.17	105.12	78.43	117.00
IEEE Standard	135	110	120	135

Next, Table VI displays the effect of tuning the parameter of ants and for multi-objective optimization. Only these two parameters are varying in five different settings, while other parameters are set with the same setting.

TABLE VI. THE IMPACT OF ANTS AND KERNEL PARAMETER

No. of Set	Parameters		*PF* (%)			
	Ants, n_{pop}	*Kernel, k*	*I*	*II*	*III*	*IV*
1	2	2	84.90	94.33	98.81	96.12
2	30	5	96.27	94.43	97.99	96.87
3	500	10	93.53	90.27	97.17	93.24
4	100	50	90.16	92.61	97.27	97.74
5	0	100	97.09	94.67	98.94	98.94

From Table VI, the results showed that the optimal value of a solution could be reached by increasing the number of the kernel. This confirms that a large kernel provides the solution for the proposed method from getting stuck in local optimum and provides a higher chance for it to reach its global optimum. However, tuning the ants and kernel parameters might significantly reduce the performance. Overall, the result showed that Setting 5, which was the setting used for the base scenario is the best setting for ant and kernel to get the best solutions.

Table VII shows the impact of varying BALANCE parameter on the optimal solutions where this parameter only assigned to non-priority between objectives. In contrast to the results in Table VI, a more exceptional epsilon tolerance for the Pareto dominance filtering was used to create the plots in Fig. 3 until Fig. 7, which generally results generally in more display of non-dominated solutions. For this simulation, the EPSILON parameter is set to 0.0001.

TABLE VII. THE IMPACT OF BALANCE PARAMETER

Parameters	No. Set of BALANCE Parameter				
	0	*1.0*	*2.0*	*0.91*	*0.18*
X_{CF} (Ω)	3.78	3.54	3.32	3.78	3.78
R_{DF} (Ω)	0.0083	0.0069	0.0070	0.0080	0.0083
X_{LF} (Ω)	0.179	0.1345	0.1482	0.1503	0.1796
PF (%)	97.06	95.08	96.16	95.50	97.07
η (%)	99.64	99.62	99.63	99.63	99.64
P_{LOSS} (kW)	6.11	6.38	6.27	6.30	6.10
THD_V (%)	2.15	1.57	1.80	1.66	2.15

From Table VI, the results show five different set simulation with different BALANCE parameter where each of the simulations will results in different optimal solutions of the optimization. The BALANCE parameter is set to zero for the first setting, indicating that the Pareto front is searching for the best equally balanced trade-off between both objectives. When the BALANCE parameter is set to 1.0 or 2.0, MIDACO is assigned to only search for the first and second objectives, respectively. The search effort in settings 4 and 5 represents some unequal priority between objectives. According to the table, the optimal filter can be obtained with different optimal solutions while simultaneously considering two objective functions, where the BALANCE parameter is significant and has a high impact on each of the solutions. Fig. 3-7 clearly show the impact of different BALANCE parameters on the shape of the Pareto front for all five settings in Table VI.

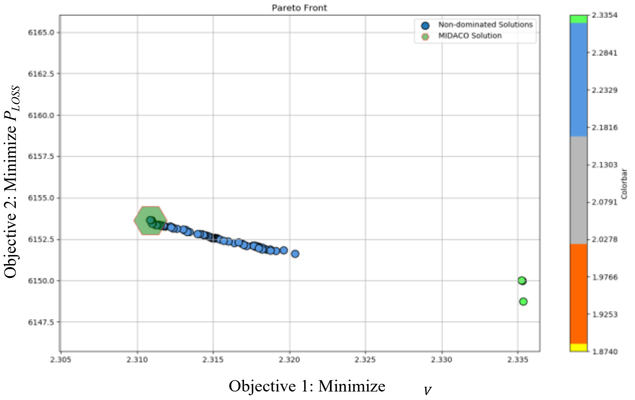

Fig. 3. The non-dominated solutions when BALANCE parameter set to 0

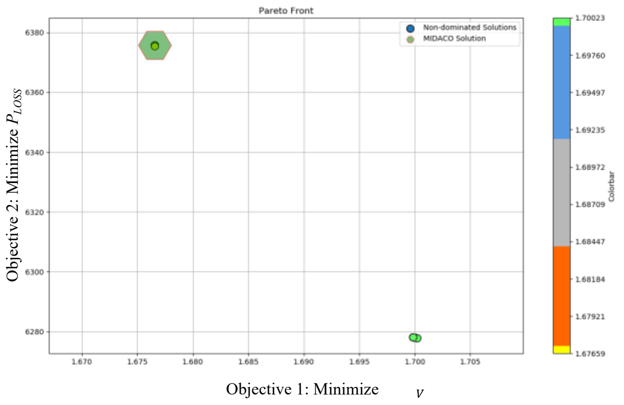

Fig. 4. The non-dominated solutions when BALANCE parameter set to 1.0

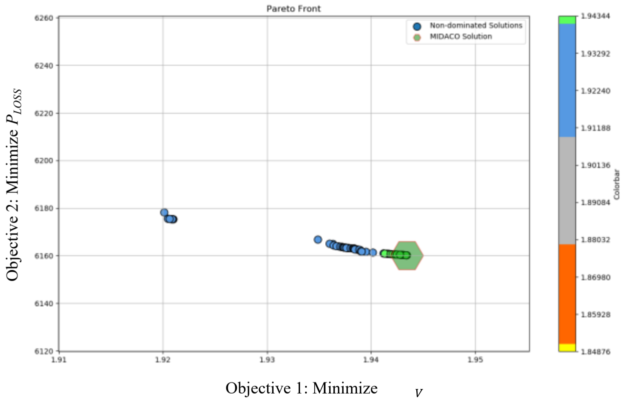

Fig. 5. The non-dominated solutions when BALANCE parameter set to 2.0

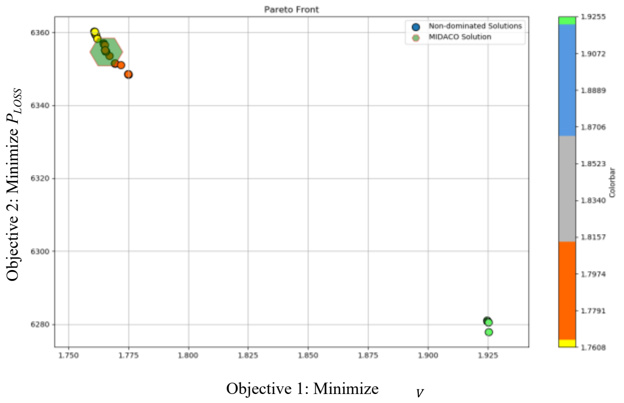

Fig. 6. The non-dominated solutions when BALANCE parameter set to 0.91

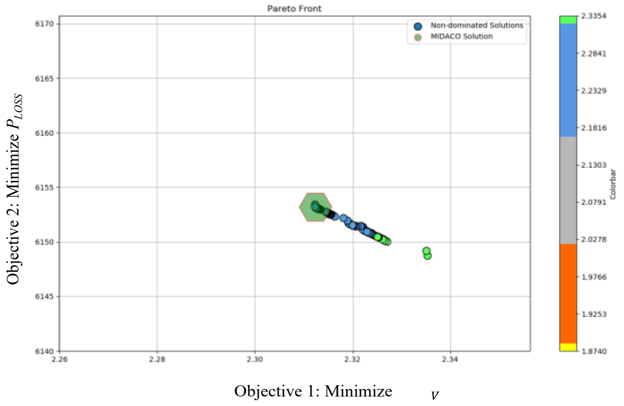

Fig. 7. The non-dominated solutions when BALANCE parameter set to 0.18

V. CONCLUSION

This research has raised the importance of harmonics in the power system, which mainly because of the growth of the non-linear loads usage. The electrical pollution caused by power system harmonics such as voltage or current distortions and resonances has become a severe problem. This may result in the malfunctions, overvoltage or overcurrent of the facility. The main aim of this research is an implementation of a metaheuristic optimization algorithm, Mixed Integer Distributed Ant Colony Optimization (MIDACO), for the design of single tuned passive harmonic filters. The designs for both filters considered the parameters of the filters, which can avoid the harmonic resonance, at least to a minimum of 90% limit of power factor. In contrast, the voltage total harmonic distortion must not be greater than 5% to follow IEEE Std. 519-2014 and the capacitor value based on IEEE Std. 18-2012. Four scenarios have been tested and the results were achieved, satisfying two objective functions and the involved constraints. The results of this investigation present the importance of adding a single tuned filter into an existing network. Besides, the study has also focused on solving the multi-objective problem. The results showed that using the proposed method, multi-objective approaches outperformed single-objective optimization on a comprehensive passive filter design.

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