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Comparative analysis of optimal damped and undamped passive filters using MIDACO-solver

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A B S T R A C T

Harmonic pollution is one of the challenging problems facing power networks recently due to the widespread non-linear loads and inverter-based renewables. In this regard, this work presents the optimal design of damped and undamped passive filters using a solver called Mixed-Integer Distributed Ant Colony Optimisation (MIDACO). This solver is employed to obtain an optimal design strategy for single-tuned passive power filters by investigating three primary criteria – minimisation of active power losses of the Thevenin's resistor, maximisation of the true power factor, and maximisation of the transmission efficiency. Several constrictions associated with the designed filters have been considered, in which the global maximum or minimum criterion was attained by retaining the quality factors of the designed filters within a particular range, damping harmonic resonance, achieving a permissible range of the power factor, limiting voltage harmonic distortion by complying with IEEE Std. 519–2014 restrictions. Besides, the performance limits of capacitors operating in distorted systems have been met while complying with IEEE Std. 18–2012. Further, the results obtained using the MIDACO solver in four different case studies are compared to those obtained using particle swarm optimisation and genetic algorithm. In addition, this work depicts the damping resistor of the inductance in the single-tuned filters. The benefits and drawbacks of damping over an undamped filter are discussed. Finally, the results validate the effectiveness of the MIDACO solver employed in this paper.

1. Introduction

Recent years have witnessed an escalation in the application of non-linear loads for power systems that, unfortunately, led to different power quality issues. Some non-linear loads employed in industrial and commercial sectors include variable speed drives (VSDs), power converters, mixed inverter-based renewables [1,2], computers, and light dimmers. For instance, harmonic pollution increases power loss in electrical appliances and causes communication disruption. Consequently, these power quality and system harmonics issues have emerged as rising concerns requiring harmonic management to sustain productivity and reliability in the industrial sector [3].

Several approaches have been investigated to address issues that occur in harmonics [4–6]. In this regard, passive power filters (PPFs) appear to be highly sought to mitigate harmonics, compared to other techniques, due to their non-complicated, robust, lower cost, and maintenance-free operation. Moreover, the PPF compensates reactive power to the system, improves the power factor, and minimises active power losses [7].

The performance exerted by PPF depends on two key factors: the circuit topology and the selection of the proper parameters. Therefore, designing a PPF seems challenging due to the uncertain

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Nomenclature

f_n, f	Tuned and fundamental frequency
k, k_n, k_r	Harmonic order, tuned harmonic order and harmonic order activating resonance
R_{LK}, X_{LK}	Load resistance and reactance at the *k*th harmonic (ohms)
R_{THK}, X_{THK}	Thevenin resistance and reactance at harmonic order *k* (ohms)
R, X_L, X_C	Resistance, inductive and capacitive reactances (ohms)
V_{THK}, V_{TH}	Thevenin rms voltage at the *k*th harmonic (V)
V_{LK}, V_{CK}	Load and capacitor voltage at the *k*th harmonic (V)
V_L, V_C	Load and capacitor rms voltage (V)
V_{CP}	Capacitor peak voltage (V)
I_{SK}, I_S	Rms source current at the *k*th harmonic (A)
I_{LK}, I_L	Rms load current at the *k*th harmonic (A)
I_{CK}, I_C	Rms capacitor current at the kth harmonic (A)
P_S, P_L	Supply and load powers (W)
Q_C	Reactive power of capacitor (kVAR)
θ_K, ϕ_K	Angles of load voltage and line current (rad)
QF	Quality factor
PF, η	Power factor and transmission efficiency (%)
P_{LOSS}	Power losses of the Thevenin resistor (W)
$VTHD$	Voltage total harmonic distortion (%)
n_{pop}, k and Ω	Ant, kernel and oracle parameters.

operating conditions requiring continuous measurements [8]. Accordingly, several methods have been presented in the literature to overcome these issues [9,10].

The single-tuned PPF used in [11] was designed to mitigate the harmonics generated by the AC-DC converter-based self-excited DC shunt motor. A comprehensive parametric analysis for the single-tuned PPF was carried out in [12]. In [13], the single-tuned PPF was used to mitigate the harmonic pollution in radial distribution networks using particle swarm optimisation (PSO). In [14] the authors compared different harmonic suppression solutions employed in traction systems and found that single-tuned PPF is the most economical and effective solution. In [15], the single-tuned PPF was used to mitigate harmonics in a large industrial plant while considering the voltage sag. The authors in [16] introduced a harmonic power flow analysis for power systems using MATPOWER, using four types of PPFs. Clearly, the single-tuned PPF is widely used in transmission and distribution networks, so the optimal design of such a filter is vital for power networks and in recent power quality published works.

Apart from the single-tuned type, PPF generally is widely used to suppress harmonics in power networks. Many research efforts have been exerted to obtain the optimal design of different PPF types. For instance, an optimal design for damped third-order PPF using a multi-objective Pareto-based firefly algorithm was presented in [17]. The authors in [10] have introduced a comparative analysis of double-tuned PPF design methods using a slime mould optimisation algorithm. In [18], a novel design of fourth-order PPF was demonstrated using a crow spiral-based search algorithm.

The complexity of PPF design increases with increasing the filter order, the number of objectives and the considered constraints. The single-tuned PPF has the advantage of its more straightforward design process over other PPF types, especially if there is one dominant harmonic whose elimination improves the system's performance significantly.

This study focuses on harmonics mitigation, whereby the parameter of a single tuned filter is optimised via mixed-integer distributed ant colony optimisation (MIDACO). In fact, the scavenging behaviour of artificial ants has inspired this method by extending the mixed-integer search domains. Although this tool is relatively new in PPFs design, this solver has displayed good efficiency for the investigated engineering problem [19]. Three main objectives are investigated: maximisation of power factor, minimisation of power loss of the Thevenin's resistor, and maximisation of the transmission efficiency. Moreover, the design satisfies specific performance criteria displayed by the filter, filter values to avoid resonances, power factor range to ascertain transmission efficiency, and current and voltage individual harmonic values, following IEEE Std. 519–2014 [20]. Previously, a damped single-tuned filter has been proposed for harmonics elimination without considering the practical values of the capacitor [21].

Additionally, in this study, the manufacturer's standard values for the capacitor are considered, where the standard used is IEEE Std. 18–2012 [22]. These values are regarded as constraints, as the capacitor value should be one of the practical values in the market [23,24]. Further, a comparative study between the damped filter over the proposed undamped filter, presented in [25], is proposed in this work by depicting the damping resistor of the inductance in the single-tuned filters, whereby the benefits and drawbacks of damping over undamped filters are presented and discussed in four different case studies. Besides, the results obtained from MIDACO solver are analysed and compared with two milestone algorithms: genetic algorithm (GA) and PSO. Accordingly, the core contributions of this work can be summarized as follows:

- The optimal design of damped and undamped passive filters using MIDACO solver is presented.
- Due to the nonlinearity of the problem, three primary criteria are investigated – minimisation of active power losses of the Thevenin's resistor, maximisation of the true power factor, and maximisation of the transmission efficiency.
- Several constrictions associated with the designed filters have been considered, in which the global maximum or minimum criterion was attained.
- The practical performance limits of capacitors operating in distorted systems have been met while complying with IEEE Std. 18–2012.
- The results obtained using the MIDACO solver in four different case studies are compared to those obtained using PSO and GA.
- The benefits and drawbacks of damping over an undamped filter are discussed.
- Sensitivity analysis of the MIDACO solver has been discussed.
- The outcomes from the study displayed that the proposed approach attained better accuracy and more efficiency.

This paper is organised as follows – Section 2 describes the elementary design of single-tuned harmonic filters and their design considerations. Section 3 presents the system under study, and the optimisation problem is formulated in Section 4. Section 5 presents the MIDACO solver employed in this work. Section 6 presents the simulation results obtained and their discussions. Section 7 presents the conclusions drawn from the analysis and the possible future works.

2. Design of shunt-connected single-tuned filters

The filter possesses a non-intricate series *RLC* circuit configuration. The filter provides power loss from the resistor, *R*, commonly referred to as an intrinsic resistance to inductance. The incorporation of resistance is called 'damping' as it helps dampen resonance between the filter and the system.

2.1. Design equations

At a tuned frequency, f_n, the optimal filter can be obtained when harmonic inductive and capacitive reactance expressions are equal [26]; thus:

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

The tuned harmonic order k_n which can be formulated as [26]:

$$k_n = \frac{f_n}{f} = \sqrt{\frac{X_C}{X_L}} \tag{2}$$

where f denotes the fundamental frequency; X_L refers to the inductive reactance, $X_L = 2\pi fL$; and X_C reflects the capacitive reactance, $X_C = \frac{1}{2\pi fC}$. At the kth harmonic frequency, the total impedance can be written as [26]:

$$Z_F = R + j(kX_L - \frac{X_C}{k}) \tag{3}$$

The filter inductor quality factor, *QF*, is determined from the correlation between filter reactance and resistance. The value of the quality factor can be obtained from (4) as follows [26]:

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

where *R* dictates the peak of the harmonic impedance.

The following are several notations pertaining to *QF* of a single-tuned filter: the *QF* value is not measured regularly to determine the filtering performance. This is because the resistance values employed to alter the filter's response may incur an increased loss. A higher *QF* value indicates a sharper peak for resonance and thus results in higher frequency selectivity and enhanced harmonic attenuation. Furthermore, higher *QF* minimises passband. The best practical values for *QF* should range between 20 and 100. Nevertheless, the responses cannot be differentiated clearly, except for the peak that indicates the harmonic resonance magnitude [26].

2.2. Design considerations

The primary drawback of integrating the single-tuned filter into a power circuit is that resonances may occur in a series or parallel and may cause amplification in the current and voltage, hence may damage the circuit. The issue associated with resonances happens due to filter detuning, whereby typical operations are due to temperature, RLC manufacturer's tolerance, capacitor fuse blowing, and system variants. Consequently, tuning the filter at a range of 3 % to 10 % away from the sought harmonic frequency is advisable to hinder these two resonances [26].

3. Studied system

Fig. 1 illustrates the harmonic circuit model employed in this study that comprised a bus with linear loads, variable-quality factor-based single-tuned passive filter, and non-linear loads.

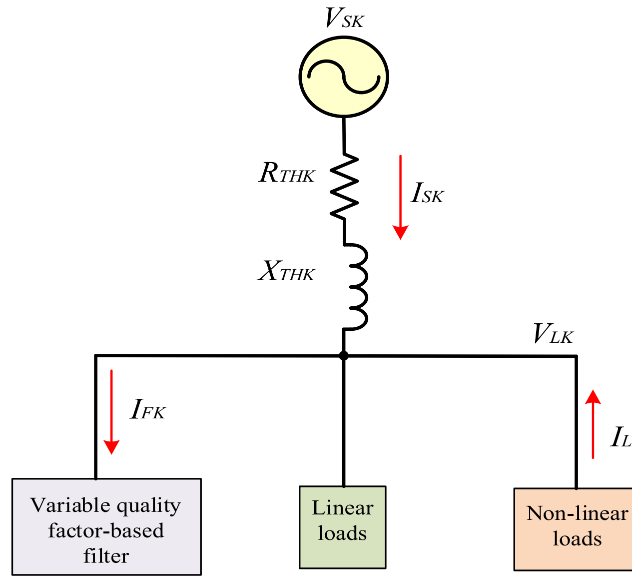


Fig. 1. Studied system.

The shunt-connected filter disallows the harmonic current source from passing through the source, whereby the filter impedance limits the harmonic current. After different mathematical modelling equations, the load power factor, *PF*, could be described as [25]:

$$PF = \frac{P_L}{I_S V_L} = \frac{\sum V_{LK} I_{SK} \cos(\theta_K - \phi_K)}{\sqrt{\sum I_{SK}^2 \sum V_{LK}^2}} \tag{5}$$

where, P_L denotes load power; V_{LK} and I_{SK} denote the load voltage and source current at the kth harmonic order, respectively. In addition, V_L denotes rms load voltage; I_S denotes rms source current; θ_K denotes angle of V_{LK}; and $\varnothing_K$ denotes angle of I_{SK}.

Apart from that, active power losses in the Thevenin's resistor, P_{LOSS}, is described below to display the filter performance [25]:

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

Additionally, the transmission efficiency is given as follows [25]:

$$\eta = \frac{P_L}{P_S} = \frac{\sum V_{LK} I_{SK} \cos(\theta_K - \varnothing_K)}{\sum V_{LK} I_{SK} \cos(\theta_K - \varnothing_K) + \sum I_{SK}^2 R_{THK}} \tag{7}$$

where P_S and R_{THK} are supply power and Thevenin's resistance at the kth harmonic, respectively. The voltage total harmonic distortion (*VTHD*) can be formulated as follows [20]:

$$VTHD = \frac{\sqrt{\sum_{K \geq 2} V_{LK}^2}}{V_{L1}} \tag{8}$$

The above indices are used to assess the filter's performance using different optimisation techniques with and without resistance that can dampen the harmonic resonance, as shown in the results section.

4. Optimisation problem

Constraint of standard value of capacitor: By adhering to IEEE Std. 18–2012, this study had set the values of manufactured capacitors in voltage and reactive power as nominal current, I_C, was less than 135 %, rated capacitor voltage, V_C, was less than 110 %, rated peak voltage, V_{CP}, was less than 120 %, and reactive power and Q_C was less than 135 % [22–24].

Constraint of QF: The *QF* for the tuning reactor was set between 20 and 100 for this problem [26].

Constraint of harmonic resonance: The occurrence of resonance in series and parallel occurred when $X_L = X_C$. Therefore, the harmonic order that activated resonance, k_r, is defined in (8), where X_{TH1} was the Thevenin reactance at the fundamental frequency [26].

$$h_r = \sqrt{\frac{X_C}{X_L + X_{TH1}}} \tag{8}$$

The circuit has the least impedance and exciting voltage in the case of the series resonance, but it could produce a high current. Contrarily, parallel resonance possesses impedance at its maximum and a small, exciting resonance current with amplified voltage. Therefore, avoiding both types of resonances is crucial through incorporating k_n constraint in (2), which should exceed k_r in (8). Furthermore, the k_n value should be tuned to 9 % from the harmonic frequency to hinder these resonances.

Constraint of VTHD: The IEEE Std.-519 recommends that maximum values for *VTHD* should be at 5 % or lower [20].

Constraint of PF: A penalty is present when *PF* dips to less than 90 % in certain appliances to ascertain efficiency of electricity usage. Therefore, a *PF* load equivalent to or higher than 90 % was weighed upon designing the filter.

Then, the problem formulation of the objective functions and constraints is listed as follows:

$$\text{Criterion 1} = P_{LOSS}(R, X_C, X_L) \tag{9}$$

$$\text{Criterion 2} = PF(R, X_C, X_L) \tag{10}$$

$$\text{Criterion 3} = \eta(R, X_C, X_L) \tag{11}$$

where $k_r < k \leq 0.9f_n$, $20 \leq QF \leq 100$, $VTHD \leq 5\%$, $PF \geq 90\%$ and capacitor following IEEE Std. 18–2012.

5. Optimisation algorithm

A method that integrates the C solver, known as the MIDACO solver, has been incorporated as a tool for optimisation to address the problem formulation depicted in (9)–(11). This solver is considered an innovative optimisation solver that merges the extended ant colony optimisation (ACO), which is of the evolutionary metaheuristics class, and the oracle penalty method to control constrictions [27]. The concept of ACO was initiated by Marco Dorigo [28], whereby mimicking the biological traits of ants appeared to be the fundamental notion. Initially, biological ants find food (F) by rummaging around their nest. Upon discovering F, a pheromone marks the trail upon returning to the nest (N) to attract other ants to locate the food source. As the old trail wafts away, new trails are continuously tinged with pheromones.

Consequently, the distance between the nest and the food source gets shorter as the trail is updated. The extended ACO metaheuristic is embedded in MIDACO solver, whereby the algorithm reflects the approximation method of stochastic Gauss. Furthermore, its approach is dictated by the 'pheromone-controlled probability functions' (PDFs) for distinct domains rather than applying the pheromone table that portrays the benefits of ACO [29]. Although the method of penalty appears non-intricate, it is challenging to obtain the desired performance. Therefore, MIDACO solver initiates a novel idea of a typical penalty, known as the 'oracle penalty method', to control constrictions [28]. This approach overcomes an issue by altering an oracle (Ω) parameter to gain better or equivalent global solutions.

Moreover, the key benefit of MIDACO solver, which resembles a black box, is that it offers its users the freedom to determine objective functions and constrictions that may appear in various forms. Additionally, this software program provides an optimal solution that is the global maximum/minimum without the need to exam-

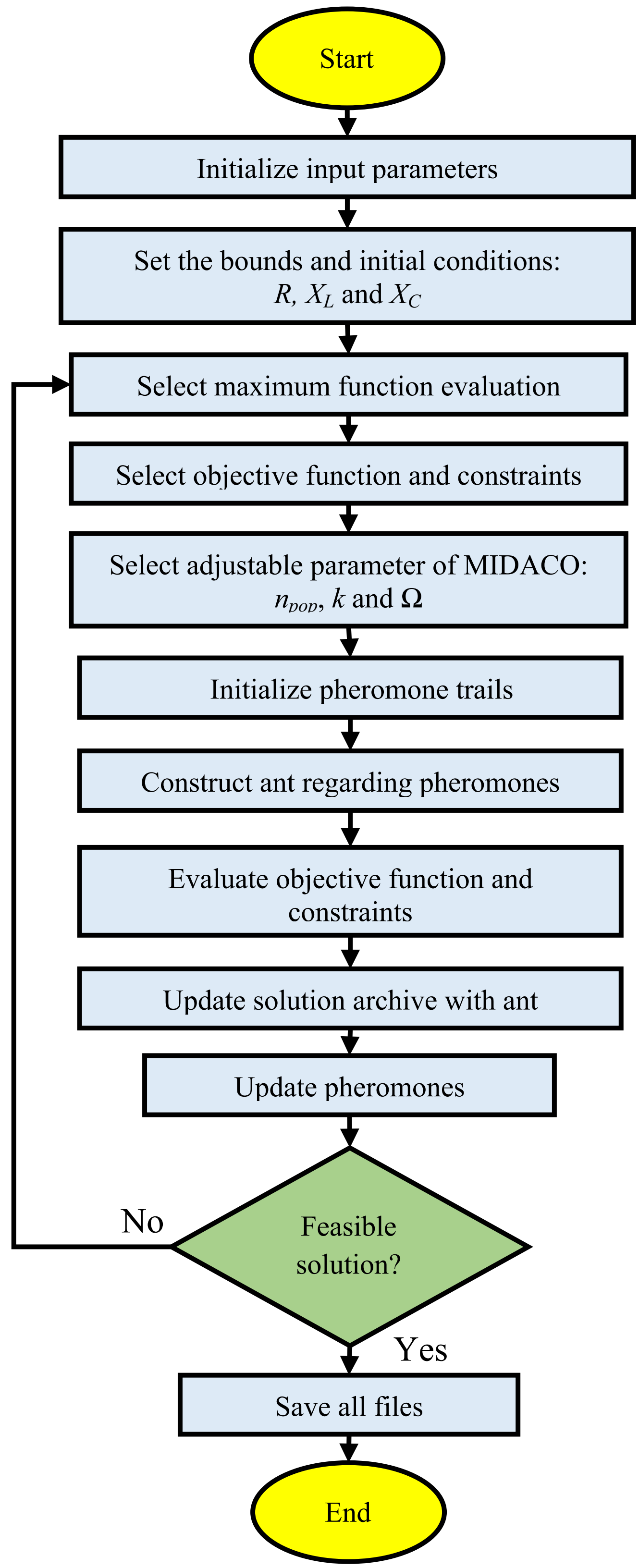


Fig. 2. The flowchart of ACO.

ine varied values in its primary settings. The flow chart of the ACO is shown in Fig. 2.

Many researchers have recently used the ACO to solve many engineering problems; for example: In [30], the ACO was used to develop enhanced torque control of switched reluctance motor drives. A cloud control system for unmanned aerial vehicles based on ACO was presented in [31]. An optimal design of gravitational sewer networks using ACO was introduced in [32]. As seen, the full potential of ACO and MIDACO is not yet exploited in electric power research, which is one of the main contributions of this research.

6. Simulation results and discussion

6.1. Results of damped single-tuned passive filter

A total of four various utility cases were simulated after the filter was designed. As such, this study set all the constant values, as shown in Table 1. The information on the studied system was retrieved from IEEE Std. 519–1992 [15], whereby all the cases employed were selected from previous publications. These included the 3-phase load power = 5100 kW, 3-phase load reactive power = 4965 kVAR, line-to-line supply voltage = 4160 V, load resistance = 1.742 Ω and load reactance = 1.696 Ω. Besides, the load current has been set to 33 A, 25 A, 8 A and 9 A at the 5th, 7th, 11th and 13th harmonics for all cases.

Table 2 presents prior and post effects, incorporating the designed filters into the method that has been proposed to determine the performance of the system. Several parameters employed to control the MIDACO solver have been set as follows: MIDACO solver dynamically adjusted n_{pop} per generation, while the maximum k was fixed at 100, and Ω = 0.

Additionally, Table 2 shows the obtained results, whereby optimal filter was attained with varying optimum solutions upon improvised power factor, minimised loss in the Thevenin's resistor and maximised efficiency. Besides, the proposed filter displayed satisfactory results with improved performance upon R, X_L, and X_C additions.

Furthermore, the decreased short-circuit capacity increased Thevenin's impedance. Such outcomes appeared to increase the active power losses and thus reduced the efficiency of transmission. Nevertheless, an increment was noted in the system's power factor primarily due to lower harmonic current. Case 1 and Case 3 exhibited the findings obtained for the varied capacities of short circuits with similar harmonics settings.

On the contrary, similar values of Thevenin's impedance exhibited decreased power factor with added harmonics voltage in the system. Such findings appeared to increase the line current that passed through the power source. When the line current was higher, the loss in Thevenin's resistor increased, and a drop in voltages was noted, indicating a slump in the efficiency of the transmission. Case 1 and Case 2 presented a similar capacity for a short circuit with varied settings for harmonics voltage.

Besides, the restrictions that limit the primary capacitors based on the practical standard were calculated, whereby the results for V_{CP}, V_C, I_C, and Q_C were in the range of 66.02 % to 69.70 %, 89.21 % to 90.63 %, 95.29 % to 101.64 %, and 84.03 % to 88.14 %, respectively. The results showed that all the capacitors embedded in the system were functioning well, following the IEEE standard.

Fig. 3 depicts the filter's impedance in the resonant circuit and the impact peak for resonance for different QF values used based on the three criteria for Case 1, where h denotes a generalised harmonic order. Integrating single-tuned filters into the system led to series and parallel resonances. The capacitance and inductance reactance values were equal in the series resonance, thus making resistance hit the local minimum at resonant.

On the other hand, the resistance was at its local maximum for parallel resonance, whereby the R value determined the resonant peak. The lower the R value, the higher the QF value, and the sharper the resonant peak, resulting in high-frequency selectivity. Nevertheless, a reduction was noted in the passband with a higher QF. It should be tuned to below the filtered harmonic to prevent any damage caused by the harmonic resonance.

6.2. Sensitivity of the MIDACO solver results

The sensitivity analysis of the MIDACO solver is shown in Table 3 for all cases, where two parameters are implemented in the proposed algorithm – ants (n_{pop}) and kernels ($kernel$). Fig. 4 (a) shows the optimal solutions obtained with different values of the oracle parameter. Besides, Fig. 4(b) shows the optimal solutions obtained by increasing the number of function evaluations. These figures validate the effectiveness of MIDACO solver in getting the global solution to the investigated problem.

6.3. Comparison with other techniques

This study presents the viability of the proposed approach by comparing its performance with two well-known optimisers, the GA and the PSO. Table 4 shows the comparison outcomes of MIDACO solver with GA and PSO. For the GA, the simulation was done using population size, crossover rate, and mutation probability, which were set to 50, 0.8, and 0.001, respectively. Furthermore, Table 4 presents the simulated results when PSO was simulated with its learning factors; cognitive and social attractions were set to 1.0 and 1.5, respectively. Besides, the velocity was controlled, while the weight of inertia was reduced from 0.9 to 0.5 linearly at iterations, and both population size and maximum iteration were set at 50 and 200, respectively. From Table 4, the results show that MIDACO solver provides better accuracy than GA and PSO, in which the outcomes of $VTHD$ seemed to not only satisfy the constraints, however, also appeared lower than the standard limit.

Table 1
Studied system.

Parameters	Cases			
	1	2	3	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
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

Table 2
Results obtained with and without the filer connection.

Settings	X_C (Ω)	R (Ω)	X_L (Ω)	PF (%)	η (%)	P_{LOSS} (kW)	$VTHD$ (%)
Case 1							
No filter	–			71.72	99.34	10.48	6.20
Criterion 1	4.43	0.011	0.217	96.24	99.63	6.15	2.48
Criterion 2	4.30	0.040	0.210	96.56	99.63	6.20	2.43
Criterion 3	4.43	0.013	0.218	96.25	99.63	6.16	2.48
Case 2							
No filter	–			71.71	99.34	10.48	8.22
Criterion 1	4.30	0.025	0.211	94.43	99.62	6.45	3.04
Criterion 2	4.43	0.029	0.219	94.27	99.62	6.47	3.13
Criterion 3	4.18	0.009	0.205	94.57	99.62	6.40	2.98
Case 3							
No filter	–			71.71	98.78	18.45	6.38
Criterion 1	4.57	0.010	0.227	97.33	99.33	11.02	1.91
Criterion 2	4.30	0.048	0.212	98.11	99.34	11.09	1.85
Criterion	4.57	0.013	0.210	97.26	99.33	11.05	1.82
Case 4							
No filter	–			71.71	98.78	18.45	8.29
Criterion 1	4.71	0.011	0.231	96.05	99.31	11.29	2.31
Criterion 2	4.30	0.043	0.212	97.27	99.32	11.27	2.21
Criterion 3	3.95	0.016	0.191	97.85	99.34	11.12	2.00

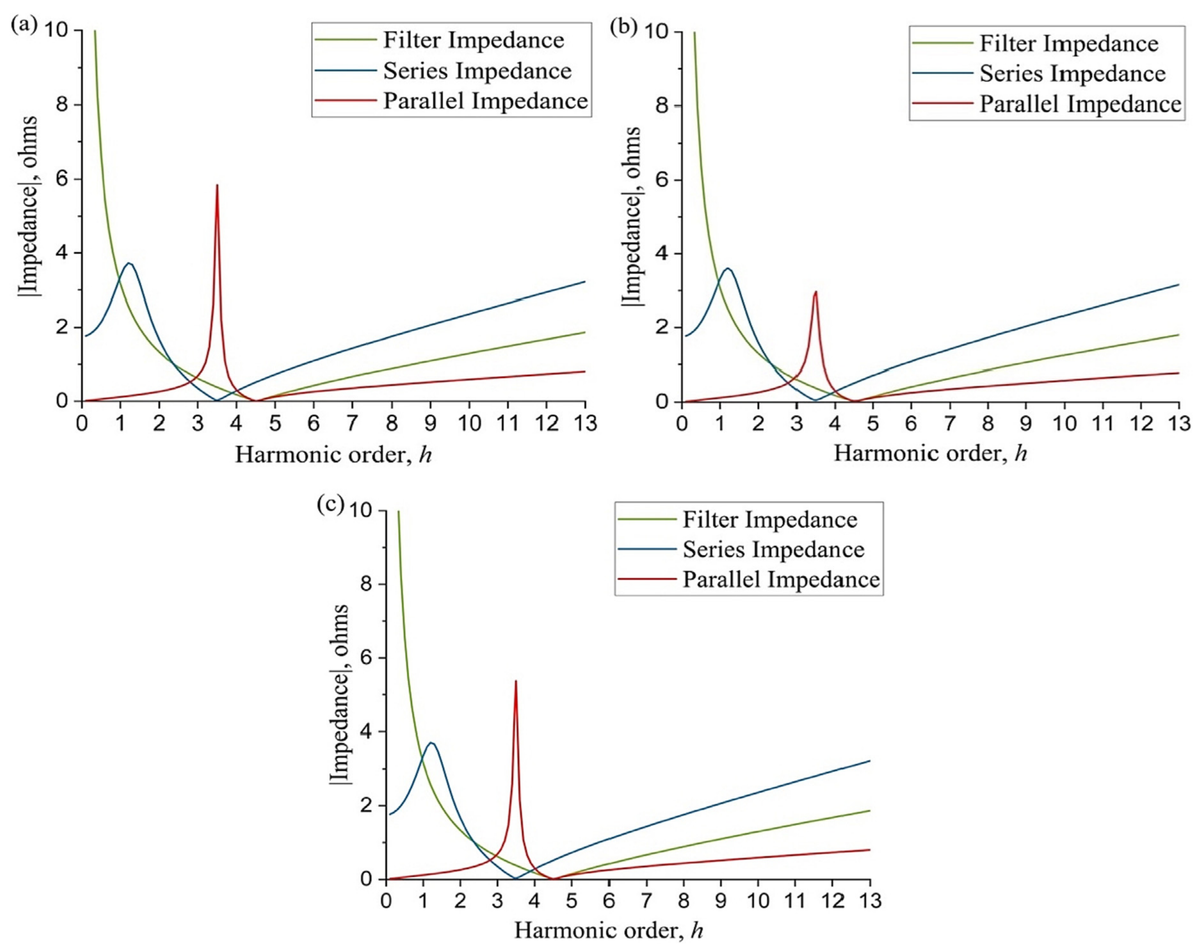


Fig. 3. Impedance resonance for case 1: (a) minimise P_{LOSS}, (b) maximise PF and (c) maximise η.

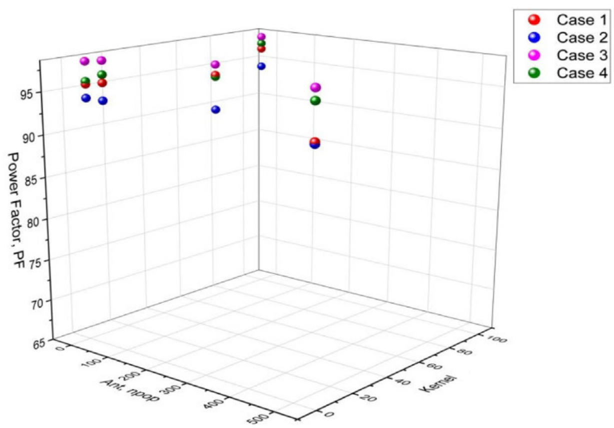
Furthermore, Table 4 exhibited that both GA and PSO provided extremely high VTHD for all cases.

Meanwhile, Table 5 presents the outcomes of statistical analysis for all the methods examined at their best run following the limits set in Criterion 2. The results showed that the proposed technique displayed a higher chance of achieving optimal global solutions upon reaching the maximum function evaluation.

6.4. Comparison of the damped and undamped filters

To further comprehend the impact of the damping resistor on the system, a comparative study between the proposed damped filter in this research and the proposed undamped single-tuned filter [25] is presented. Table 6 shows the simulated results of damped

Table 3
Sensitivity of the optimiser for all cases investigated.



Setting	n_{pop}	*kernel*	Cases			
			1	2	3	4
1	2	2	95.77	94.17	98.40	96.11
2	30	5	96.00	93.95	98.55	96.94
3	500	10	92.92	92.69	98.54	97.20
4	100	50	95.67	91.48	96.92	95.45
5	0	100	96.56	94.27	98.11	97.27

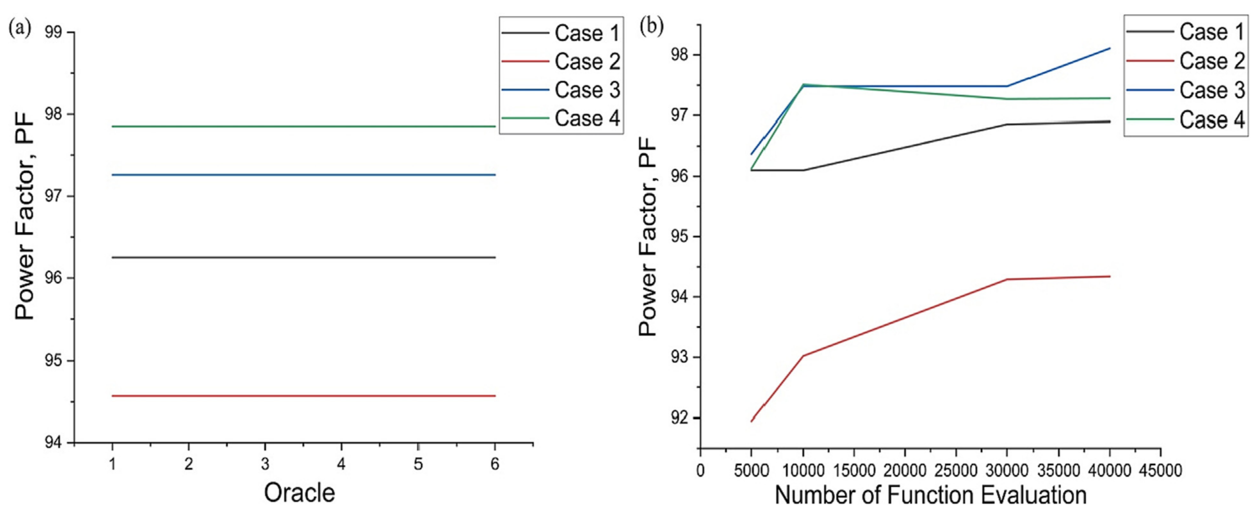


Fig. 4. Optimal solutions: (a) with different values of oracle parameter and (b) increasing number of function evaluation.

and undamped filters [25] for case 1 based on Criterion 2, which is to maximise PF.

The results presented in Table 6 validated that integrating an additional *R* resistor in the filter circuit increased power loss in the filter, thus deteriorating the system's performance. The findings also represented that reduction in *PF* led to an increment in the loss of Thevenin's resistor, which decreased the transmission efficiency and increased the *VTHD* values. Moreover, Table 6 shows that *k* seems nearer to the fifth harmonics, suggesting that the dampened filter demands more ratings for reactor current and capacitor voltage, which could end in a higher filter cost.

Additionally, Fig. 5 shows that resonance frequency is unaffected by resistance. However, the same cannot be said for the circuit's bandwidth.

The damping effect of the resistor in the parallel resonance circuit widened the band, consequently making it less adequate for a damped filter. Nonetheless, the benefit of a damped filter refers to an increment in load power consumption for the system. This is mainly due to the limited harmonic current supplied into the system and in the filter, whereby the reactor seems to limit the flow of harmonic current to the filter. Furthermore, a comparative study was performed between undamped and damped filters to determine the benefits and shortcomings of these filters. This was because the damping resistor should not be ignored, especially when designing a damped passive filter that can help damp harmonic resonance.

7. Conclusions and future works

The harmonics problem caused by non-linear loads can significantly impact electrical distributions and facilities they feed, decreasing the reliability of the power system. Therefore, to prevent the harmonics problem, it is critical to understand the causes, potential effects, and mitigation techniques during the design stage. Passive filter design is the most common type of method to solve this problem due to the design, which is simple and inex-

Table 4
Simulated results of MIDACO solver, GA and PSO.

Simulated results	MIDACO			GA			PSO		
	No. of Criterions								
	1	2	3	1	2	3	1	2	3
Case 1									
PF (%)	96.24	96.56	96.25	99.01	97.11	99.03	99.48	99.01	93.07
η (%)	99.63	99.63	99.63	99.65	99.64	99.65	99.66	99.65	99.60
P_{LOSS} (kW)	6.15	6.20	6.16	5.88	6.36	5.88	5.88	6.01	6.98
VTHD (%)	2.48	2.43	2.48	4.12	4.88	3.94	4.34	4.80	4.91
Case 2									
PF (%)	94.43	94.27	94.57	99.24	97.62	99.02	98.85	97.23	99.23
η (%)	99.62	99.62	99.62	99.65	99.64	99.65	99.65	99.64	99.65
P_{LOSS} (kW)	6.45	6.47	6.40	5.94	6.24	5.93	6.00	6.31	5.96
VTHD (%)	3.04	3.13	2.98	6.16	6.40	5.77	6.03	6.57	6.51
Case 3									
PF (%)	97.33	98.11	97.26	98.96	99.50	96.01	97.45	98.88	93.09
η (%)	99.33	99.34	99.33	99.35	99.35	99.30	99.33	99.35	99.26
P_{LOSS} (kW)	11.02	11.09	11.05	10.82	11.08	12.37	11.83	11.32	13.29
VTHD (%)	1.91	1.85	1.82	3.18	4.11	4.35	4.39	4.32	4.32
Case 4									
PF (%)	96.05	97.27	97.85	99.17	96.99	97.01	98.99	97.70	98.58
η (%)	99.31	99.32	99.34	99.35	99.32	99.32	99.35	99.33	99.34
P_{LOSS} (kW)	11.29	11.27	11.12	10.87	12.02	12.01	10.87	11.74	11.41
VTHD (%)	2.31	2.21	2.00	4.62	5.56	5.55	4.70	5.79	5.67

Table 5
Statistical measurement: Criterion 2.

Methods	Minimum value	Maximum value	Mean value	Standard deviation
Case 1				
MIDACO	95.7194	98.9827	96.5561	0.8101
GA	99.6827	99.7239	99.7117	0.0148
PSO	99.2157	99.2164	99.2162	0.0001
Case 2				
MIDACO	93.1374	98.0948	94.4083	1.0702
GA	99.3513	99.4848	99.4612	0.0442
PSO	98.2808	98.7809	98.7809	0.0001
Case 3				
MIDACO	97.5244	99.0366	98.3795	0.6781
GA	99.4642	99.8360	99.7594	0.1485
PSO	99.6648	99.6650	99.6649	0.0001
Case 4				
MIDACO	95.4917	98.1436	97.8629	0.5700
GA	99.3924	99.6656	99.5970	0.1364
PSO	99.3656	99.4423	99.4384	0.0111

Table 6
Comparison results of damped and undamped filter [25].

Filter	X_C (Ω)	R (Ω)	X_L (Ω)	*PF* (%)	η (%)	P_{LOSS} (kW)	*VTHD* (%)	k	k_r
Damped	4.30	0.040	0.210	96.56	99.63	6.20	2.43	4.53	3.64
Undamped	3.95	–	0.195	97.18	99.64	6.05	2.35	4.50	3.57

pensive. A proposed mathematical modelling technique via MIDACO solver was presented in this paper to determine the optimal passive filter to minimise the harmonics while complying with practical standards. As such, a damping resistor of the single-tuned filter was weighed in, whereby the benefits and glitches of the damping filter over the undamped filter were identified.

Moreover, the key pros and cons of damping over an undamped filter were also presented in this paper. A total of four case studies were carried out to compare this proposed technique with GA and PSO. The outcomes from the study displayed that the proposed approach recorded better accuracy and more efficiency, as the simulation findings exhibited that global maximum and minimum could be attained to satisfy all constrictions set and functions outlined. Furthermore, this study demonstrated the competency of fast convergence for the proposed technique towards obtaining the best solution to the issues highlighted. Future works will pay

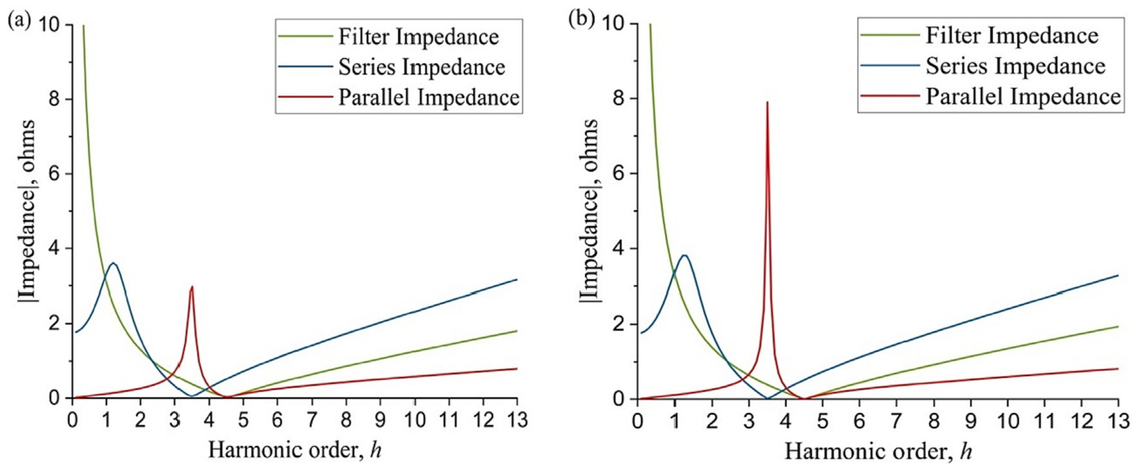


Fig. 5. Comparison of impedances resonance between (a) damped and (b) undamped filter [25] based on Criterion 2: Case 1.

attention to employing MIDACO solver in designing damped filters for mixed inverter-based renewable energy sources to optimize their performance while managing harmonics distortion.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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