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Original Article

Application of Advanced Soft Computing Techniques for Harmonic Reduction Using Active Power Filters in Radial Distribution System

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***Abstract** - This paper addresses the use of advanced soft computing techniques, namely the Driving Training-Based Optimization algorithm (DTBO) and Coati Optimization Algorithm (COA), to reduce the harmonics through the use of Active Power Filters (APFs). Distributed Generation (DG), like Solar Photo Voltaic (SPV) gained much interest due to its advantages. However, there are issues with Power Quality (PQ), including harmonic distortion, when SPVs are integrated into the Radial Distribution System (RDS). The harmonics are injected into the RDS by Nonlinear Loads (NLs). Here, NL at two end nodes is considered in addition to Non-Linear DG (NLDG). APFs are used to decrease the harmonics to specified limits. In this instance, APFs are placed correctly to reduce harmonics and improve PQ. Within limitations on inequality, optimization seeks to minimize APF's current. DTBO optimizes the APF's size at the optimal bus location. The DTBO is inspired by natural processes and contains features that are well-balanced for both exploration and exploitation. A simulation is run on the IEEE-69 bus RDS to assess the DTBO's performance. It is compared with the recently published advanced soft computing technique COA. The simulation results confirm the stability and efficacy of the DTBO method in handling this optimization problem.*

***Keywords** - Advanced soft computing, Driving training-based optimization algorithm, Harmonics, Radial distribution system, Power system optimization.*

1. Introduction

Electrical engineering has undergone various changes thanks to Artificial Intelligence (AI) and modern soft computing methods. Power grid behavior may be predicted and optimized by AI algorithms, which lowers energy losses and increases stability. Large-scale sensor data is analyzed with the aid of machine learning to find equipment flaws and stop outages. Control systems with AI capabilities are capable of effectively integrating renewable energy sources and managing complicated energy distribution networks.

Computational technologies that model electrical systems and components, such as finite element analysis, also help with performance prediction and design optimization. Thanks to these developments, electrical engineering is evolving to become more intelligent, effective, and sustainable [1].

Today's world necessitates more and more powerful electronic devices, which has led to a growing dependence on them. Some of these devices are light-emitting diodes, dimmers, inverters, variable speed drives, constant power supplies, cell phones, and PCs. Poor Power Quality (PQ) results from them adding harmonics to the distribution system [2]. Furthermore, Distributed Generation (DG), such as solar photovoltaic and wind farms, is the primary driver of the expansion of the smart grid. It is garnering much attention due to its numerous benefits.

One of the critical tasks in the field is integrating DG with the Radial Distribution System (RDS) [3]. On the other hand, poor integration might result in PQ problems because of the converter's harmonics. A converter-based DG system that adds harmonics to the RDS is called Non-Linear DG (NLDG) [4]. However, these devices' nonlinear characteristics and NLDG lead to increased harmonic pollution. Harmonics is the main cause of poor PQ. The equipment that is affected by harmonics includes overheating, pulsating torque, noise on rotating machines, additional heating and higher dielectric stress on the capacitors, circuit breakers' ability to interrupt, the skin effect of the conductors, a reduction in lamp life, and measurement errors in instruments. As a result, suppliers' and users' worries over harmonics in PQ are spreading. The performance of distribution systems is negatively impacted by these harmonics, underscoring the importance of solving these issues [5]. Several harmonic mitigation techniques are discussed in [6]. Active Power Filter (APF) is connected in parallel with the nonlinear load, as shown in Figure 1. APF cancel harmonics at PCC. At the same node as the NL load, it injects a nonlinear current into the RDS in the opposite direction. The harmonics are, therefore, eliminated. APFs must be sized and placed precisely to ensure cost-effectiveness because their rating significantly impacts their success [7]. Moreover, meeting standard requirements for Individual and Total Harmonic Distortion in Voltage (IHDv and THDv) by IEEE standards is necessary to achieve optimal performance [8].

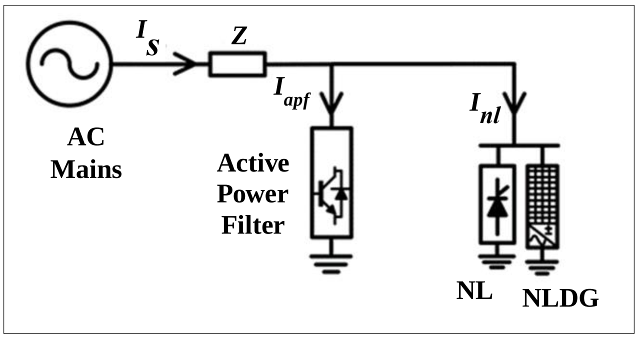

Fig. 1 APF

The precise placement and rating of APFs in RDS require careful study to determine if modern power distribution networks remain stable, dependable, and effective. As more renewable energy sources and NL are added into RDS, improving PQ and lowering harmonics become crucial. The placement and sizing of APFs can decrease harmonic distortions, lower power losses, and enhance voltage stability in RDS, all of which enhance the overall performance of the RDS. Recent studies have highlighted the significance of APF location and sizing optimization in enhancing PQ and grid dependability by emphasizing the need for more research [9].

APFs have many possible locations across the RDS. In particular, the available locations for the IEEE 69-bus RDS range from 1 APF to 68 APFs, meaning that there are 2^68 - 1 possible configurations. Finding the optimal size for each of these APFs is a major task. Moreover, APF's rating should be as low as feasible to lower its cost. An optimization strategy is needed for this. Consequently, many optimization methods have been proposed. PSO and its variants have been used [10]. Moreover, a genetic method is employed. For this problem, other algorithms are used, including a harmony search [11], firefly algorithm [12], grey wolf optimizer, and, most recently, JAYA algorithm [13].

For example, optimal- location and sizing of DG [14], location of electrical vehicle charging station, allocation of UPFC [15], reactive power dispatch, routing of wireless body sensor, and model of power scheduling. Moreover, PQ enhancement utilizing APF [9], solar irradiance forecasting, implementation of PV-wind based microgrid, UPQC using PSO-based PI tuning, fault detection in DC motor, and harmonic mitigation of solar PV are just a few of the research topics that use a variety of optimization methodologies.

The No Free Lunch Theorem (NFL) [16] states that no method can offer the optimal solutions for every optimization problem. Researchers use novel algorithms since the type of challenge might affect an algorithm's performance.

Researchers are experimenting with algorithms that draw inspiration from the process of learning to drive an effort to maximize training efficiency. The algorithms known as “Driving Training-Based Optimization (DTBO)” imitate the way teachers mentor their pupils. The program first sets fundamental parameters, much like a trainer. After that, it watches as “student” simulations run through different scenarios. The computer adjusts parameters based on these encounters, much like a teacher giving feedback. The process of iteration produces solutions that get better and better, much like a driver becomes more skilful over time. The potential uses of DTBO go beyond driving; it provides a new approach to solving challenging issues in engineering, finance, and other fields. It was recently proposed by Dehghani et al. [17] because it has shown promising results in a variety of optimization areas; this metaheuristic algorithm is an invaluable resource for scholars and practitioners across a wide range of sectors. It is widely used in engineering fields like IoT health care [18], image segmentation, optimal power flow, global MPPT of PV systems, PI-PDF controller for hybrid systems [19], and performance improvement of microgrids. These more recent applications demonstrate the flexibility and reliability of the DTBO algorithm in addressing a range of optimization problems.

The Coati Optimization Algorithm (COA) is a cooperative method that mimics the foraging habits of coatis, a South American mammal. By allowing participants to explore and share discoveries, COA effectively searches for optimal solutions in complex environments, proving adaptable to various coati behaviors and producing excellent results. It has been recently proposed by Dehghani *et al.* [20]. It has been widely used in various engineering sectors; optimizing big data [21], emotion recognition, optimal power flow, and PV cell parameter estimation.

As per the authors’ knowledge, this is the first time that the DTBO is being used to solve this nonlinear problem of placement and sizing of APF for harmonic reduction in RDS. The paper presents several key contributions related to the PQ enhancement through APFs in the presence of NL and NLDG.

The main contributions are as follows,

- Integration of DTBO with Harmonic Load Flow (HLF): The paper couples the DTBO with HLF analysis to find the proper rating of the filter. This approach considers the consequence of harmonics caused by the NL + NLDG on the system.

- Comparison of two algorithms: The paper compares and analyzes two algorithms, namely DTBO and COA, for four cases: NLs + NLDGs (without APF), APF at 27, APF at 65, and APFs at 27 and 65. The goal is to evaluate their performance in terms of finding the proper rating of the APF.
- Superiority of DTBO over COA: The computational tests demonstrate that the DTBO outperforms the COA by yielding the least APF current in all scenarios for considered data.

The DTBO is used for the first time for this problem, as per the knowledge of the authors. DTBO's performance is evaluated using computational tests, and the fitness function's best value is compared with COA. Here, the IEEE-69 RDS system is employed and simulated to find the most suitable value of APF current for considered NL + NLDG buses using DTBO and COA. This paper is structured as follows: In the next section, formulation of the problem is presented; then, analysis and discussion of results are written; and the paper is concluded in the last section.

2. Problem Formulation

This section discusses load flow with harmonics, APF, and RDS modeling, utilizing DTBO to develop an objective function to improve PQ by reducing harmonics.

2.1. Modeling of RDS, HLF, and APF

The parameters of RDS, i.e., resistance, inductance, and impedance, are modeled in a harmonic environment as per [22]. The APF is modeled as a harmonic generator, as explained in [22]. For the analysis of harmonics, the HLF approach based on network topology is employed [23]. The BIBC matrix and the BCBV matrix are the two relationship matrices that constitute the foundation of this technique.

2.2. Objective Function

An integral component of the optimization procedure is the Objective Function (OF). Finding the proper rating of APF to improve PQ is a constrained nonlinear problem. The APF current is the decision variable in this case. Because the cost of APF increases as its current rating increases, it is crucial to decrease APF's current. In order to enhance the PQ in RDS using APF, three constraints have been taken into account: (i) THDv, (ii) IHDv, and (iii) Iapf max. The first two standard limitations are mandated by IEEE Standard 519, and the third constraint depends on the NL current [8]. An objective function is illustrated as,

$$OF_{apf} = \min \sum_{m=1}^{n} \sqrt{\sum_{h=2}^{H} \left| I_{apf,m}^{h} \right|^{2}} + DP \tag{1}$$

In this equation, H represents the Highest-order harmonic, and DP denotes the Dynamic Penalty factor. m stands for the bus number, while n indicates the total number of buses.

The objective function is subjected to the following constraints,

$$OF_{apf} = \min \sum_{m=1}^{n} \sqrt{\sum_{h=2}^{H} \left| I_{apf,m}^{h} \right|^{2}} + DP \tag{2}$$

Figure 2 shows the flowchart that explains how to use DTBO to improve PQ in RDS by reducing harmonics.

This study utilizes a modified version of the IEEE-69 bus RDS [24], as depicted in Figure 3. Presumably, buses having NLs in the system are connected to the NLDGs. The NLs are characterized by a harmonic spectrum, from the 5th to the 49th, which aligns with the behavior of a six-pulse converter [2]. Specifically, the NLs are strategically located at end nodes buses 27 and 65.

2.3. Steps for Simulation

Load the relevant data, including the harmonic spectrum, from the test system first. In the following step, define the optimization settings. Proceed to step 3, where the inputs are created into a model of the harmonic environment. Step 4 should involve the HLF analysis. Step 5 should involve computing the THDv utilizing NLs + NLDGs. Before moving on to step 6, integrate the APF into the system. In step 7, incorporate the APF into the load flow harmonics. Step 8 involves figuring out the lowest feasible APF current using the DTBO. Step 9 involves setting the terminating criteria of an algorithm. Repeat these procedures for COA also.

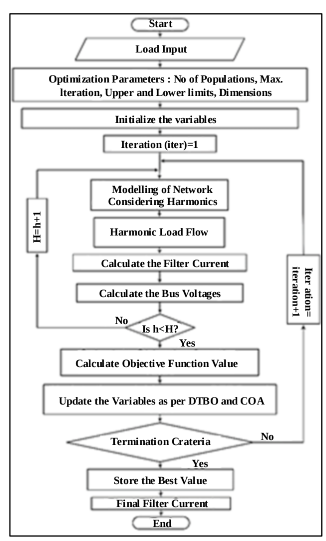

Fig. 2 Flowchart for a harmonic reduction in RDS

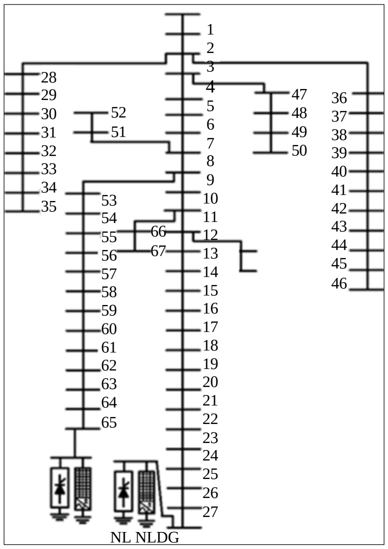

Fig. 3 IEEE-69 bus RDS with NL and NLDG

3. Results and Discussion

This section deals with the result analysis and discussion. The IEEE-69 bus system has two NLs + NLDGs at buses 27 and 65, as shown in Figure 3. Here, only two nodes have NLs + NLDGs; the harmonic influence is magnified and affects all 68 buses in the system. In the absence of an APF, HLF computes the THDv% for each bus, and Figure 4 shows the findings.

The THDv readings of forty of the sixty-eight buses (apart from the first bus, which acts as a source bus) show that harmonics extensively impact the RDS; these readings are more than 5%. Remarkably, only two buses have NLs + NLDGs, but all buses display THDv. Forty buses cannot fulfil the IEEE standard limit if their THDv is more than 5%. It displays the RDS's low PQ. There are NLs + NLDGs on buses 27 and 65. THDv values for both are 25.03% and 25.63%, respectively. Forty buses in all go over the THDv 5% limit.

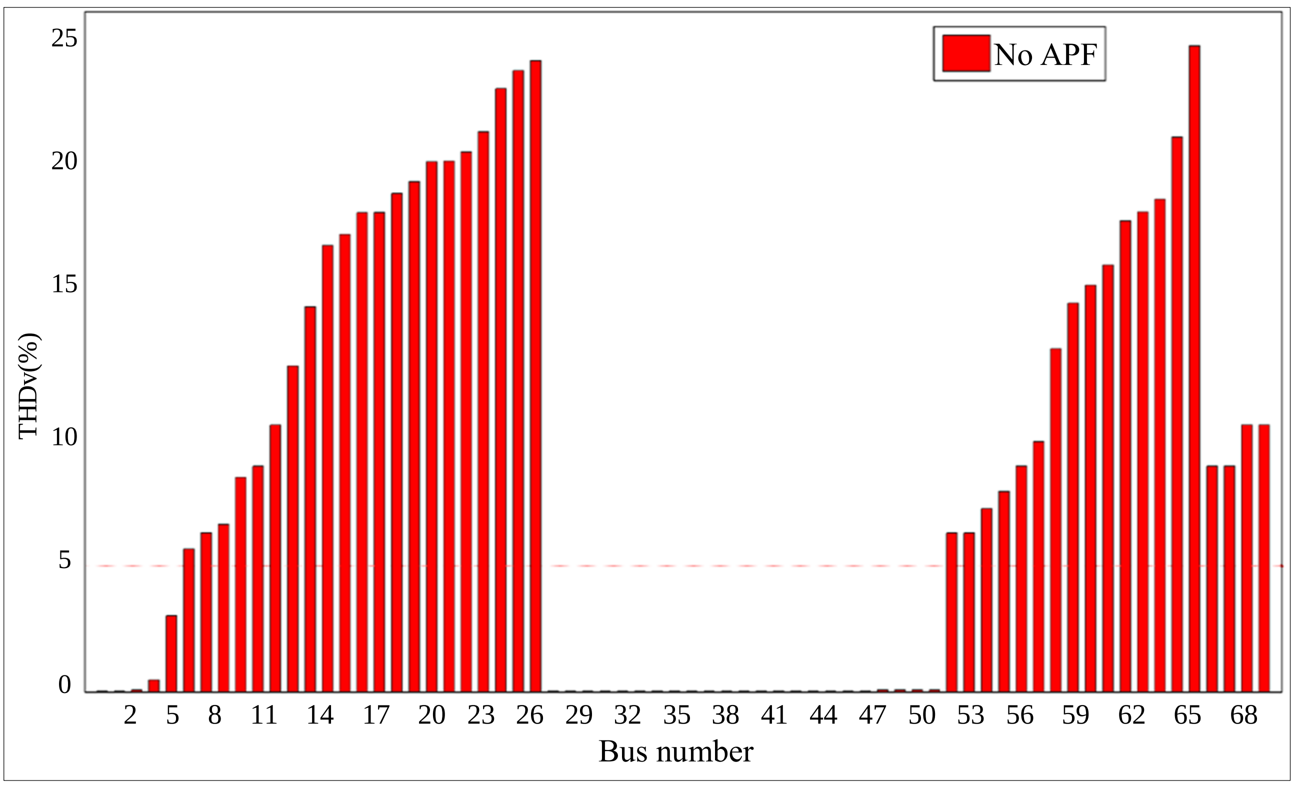

Fig. 4 THDv at all buses without APF

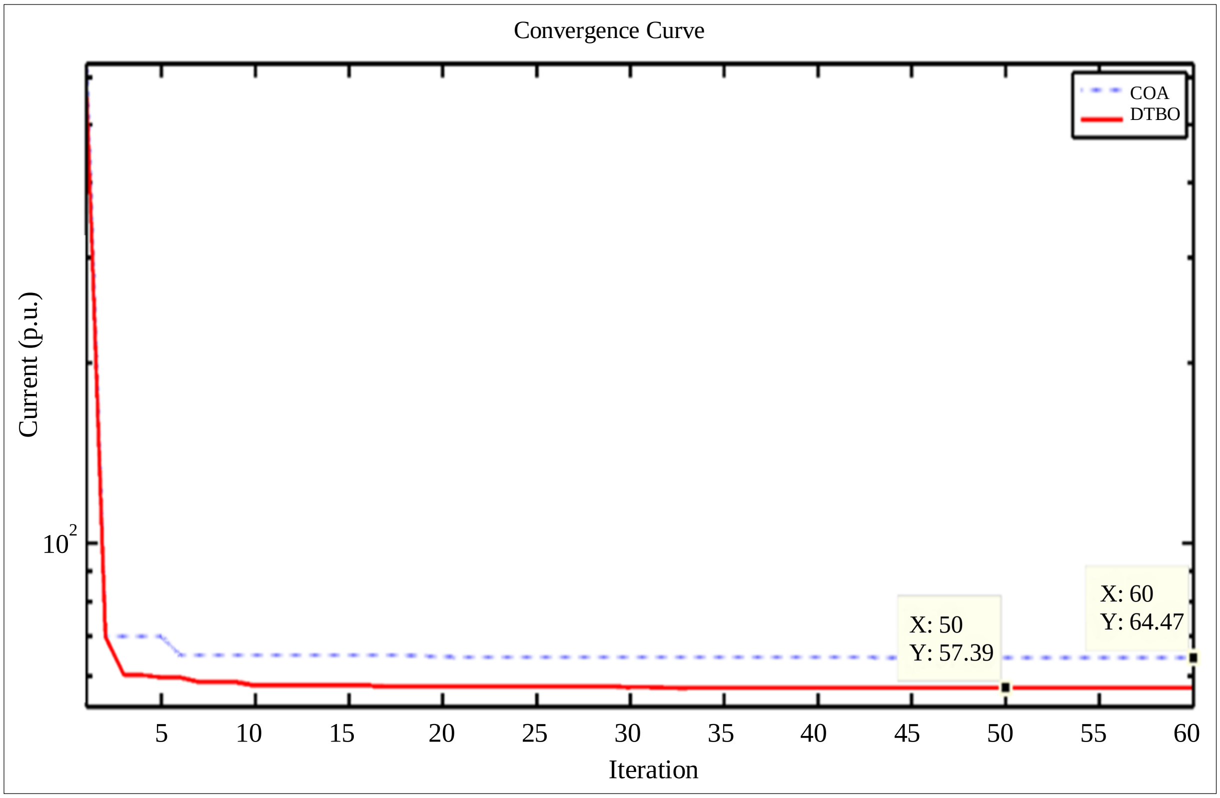

Fig. 5 Algorithm convergence curves while APF is at bus 27

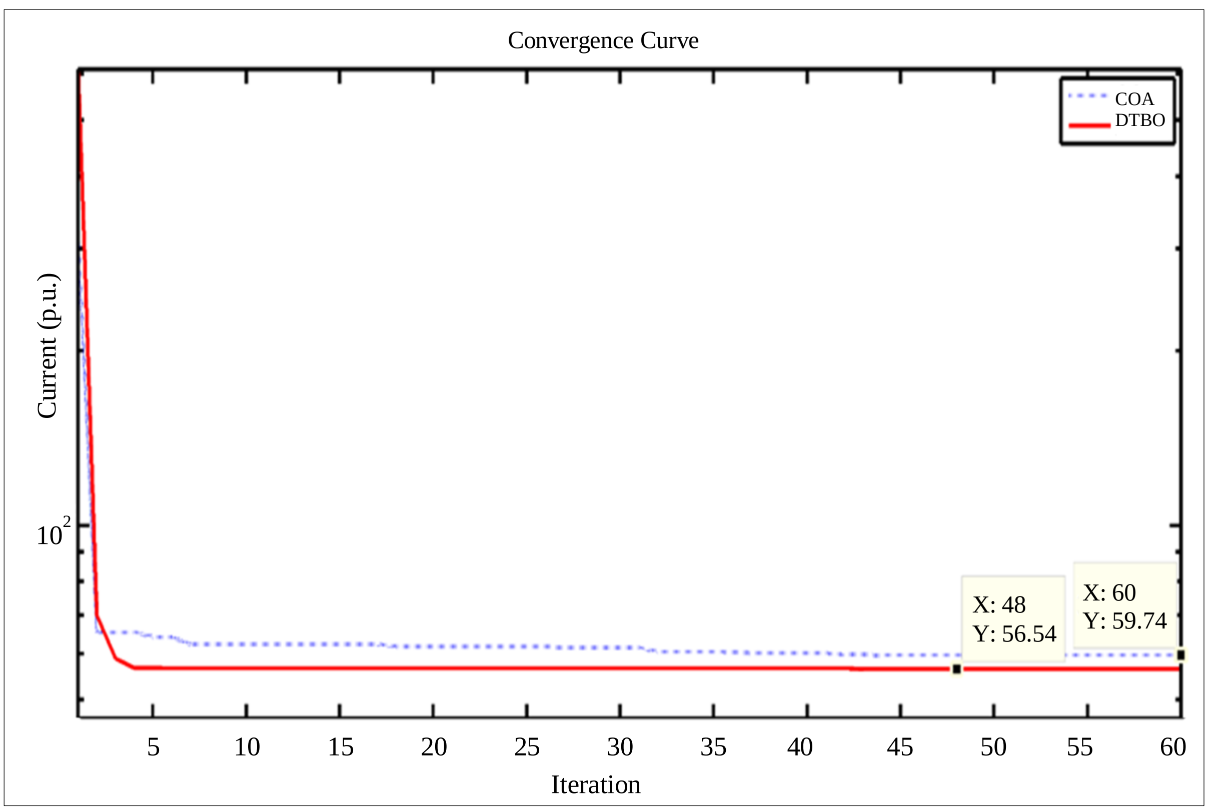

Fig. 6 Algorithm convergence curves while APF is at bus 65

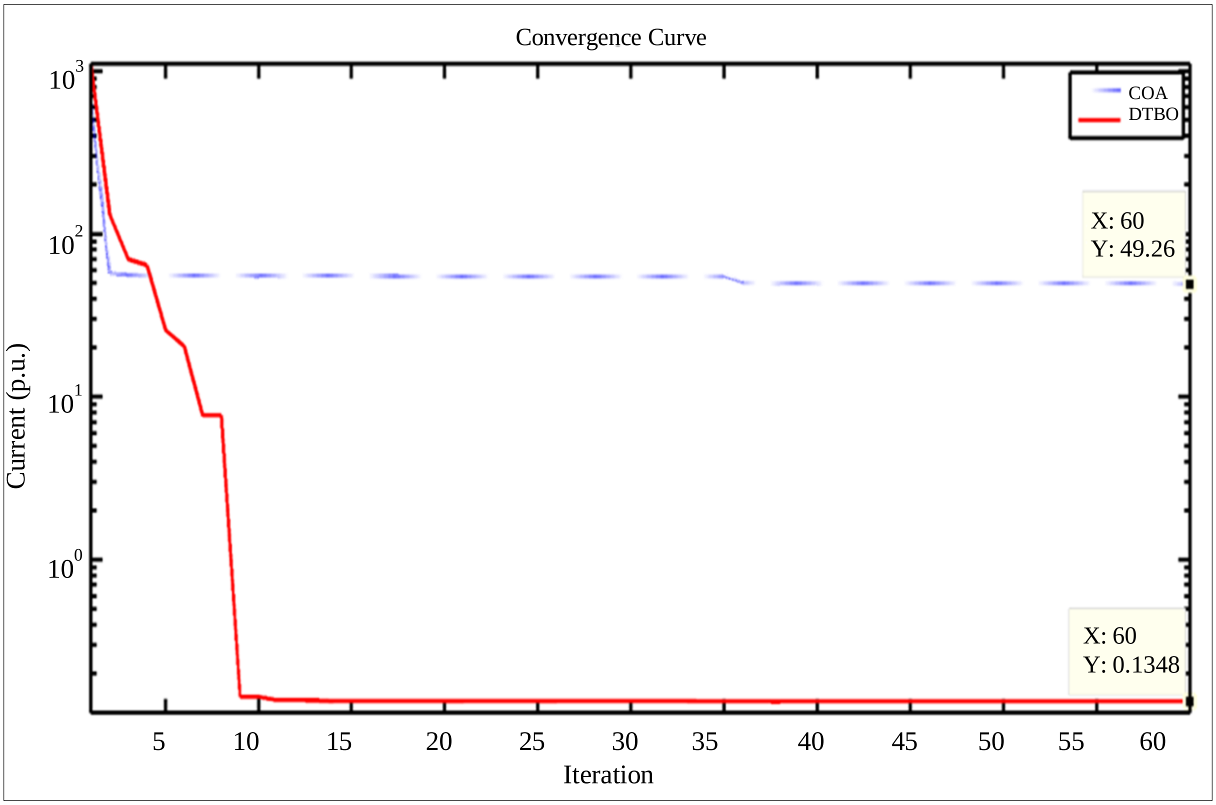

Fig. 7 Algorithm convergence curves while APF is at buses 27 and 65

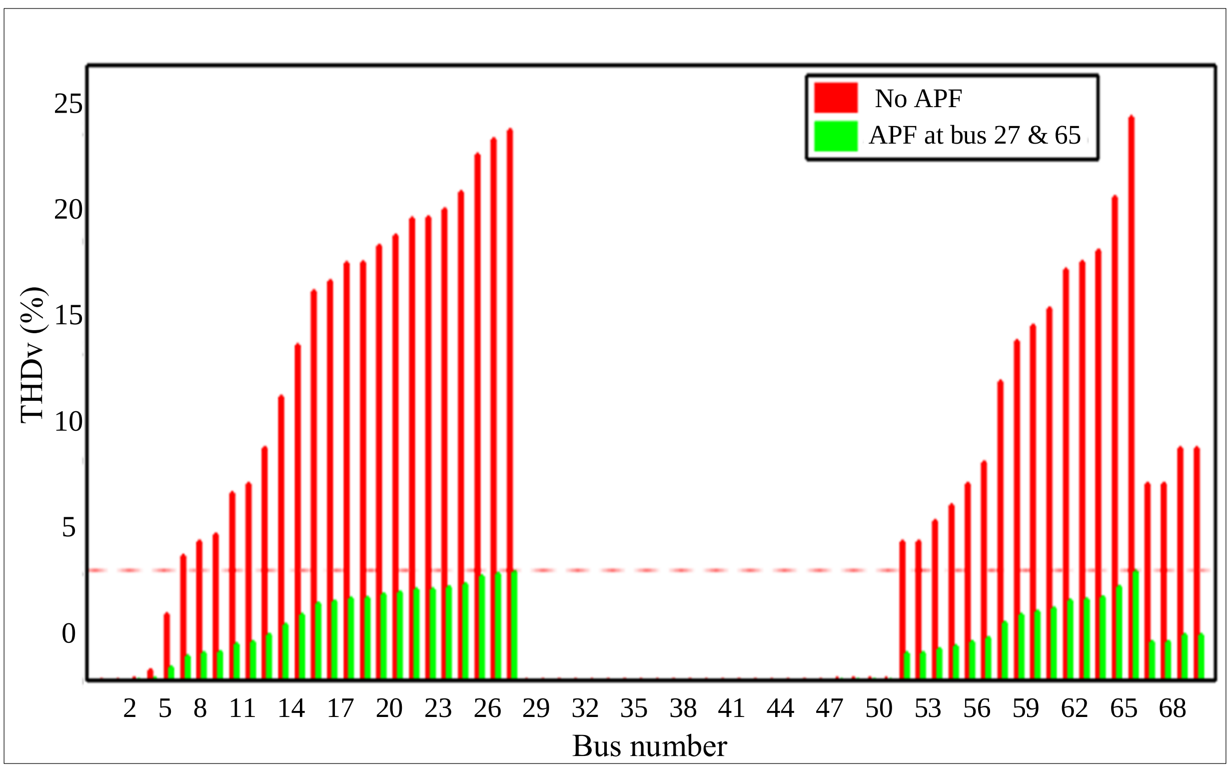

Fig. 8 THDv at every bus, both with and without APFs after optimization

According to the statistics above, RDS is a rather polluted harmonic system. Harmonic filter(s) must be used to meet IEEE standard limitations. The APF is concurrently allocated to buses 27 and 65, which have the NLs + NLDGs. The scenario is,

(i) Single APF at bus 27,
(ii) Single APF at bus 65, and
(iii) APFs at both buses.

Since the size of the APF directly affects its cost, it is now another crucial factor. The required APF current, in this case, is determined via the DTBO optimization process. The maximum number of populations and iterations are 30 and 60, respectively. Following the stages in the associated flowchart (Figure 2), this approach is fully replicated for the chosen test system.

3.1. Case 1

The NLs + NLDGs are connected at bus 27 and 65, as seen in Figure 3. These two nodes cause a significant harmonic distortion in the system. The highest THDv without APF is at bus 65 (25.63 %). The THDv of bus 27 is 25.03%.

3.2. Case 2

In order to reduce the THDv as much as feasible, the APF is connected to bus 27. As seen in Figure 5, DTBO has decreased to a value of 57.39 p.u., and COA has converged at a higher value than DTBO (64.47 p.u.). It is observed that bus 27 is not the appropriate location for APF.

3.3. Case 3

No algorithm can meet the criteria and achieve convergence in this case. They do not converge at all. DTBO and COA have values of 56.54 p.u. and 59.74 p.u., respectively. Figure 6 confirms that no single algorithm can meet all of the requirements. This indicates that the location of bus 65 is inappropriate for the APF to enhance PQ.

3.4. Case 4

The APFs are placed on buses 27 and 65. Figure 7 shows the result of HLF employing soft computing techniques. The convergence curve for each algorithm is displayed under the given condition.

The DTBO's method for determining the minimum APF current is shown in Figure 7. The COA does not converge to find the lowest APF current. On the other hand, the DTBO method, as illustrated in Figure 7, provides the lowest APF current within the given parameters and converges efficiently with a value of 0.1348 p.u.

When the APFs are positioned at buses 27 and 65, the DTBO approach does converge successfully; in these circumstances, COA has calculated the APF current of 49.26 p.u. It is considered to be improper. Figure 8 demonstrates that all of the system’s buses now have THDv values that are less than 5% after the APFs were installed at buses 27 and 65. Notably, buses 27 and 65, which have a THDv of 25.03 % and 25.63%, respectively, without the APF, now have a THDv of 4.95 % and 4.97 % with the APFs in place.

The APF’s bus number and rating play a critical role in enhancing PQ in the RDS, as evidenced by Figure 8, which shows that all buses meet the standard limit of THDv, which is less than or equal to 5%. Table 1 presents the comparison of results obtained by applying two soft computing techniques, DTBO and COA.

Figure 7 shows that the DTBO fared better than the other considered algorithm COA. The DTBO has the best value (0.1348 p.u.) and converges quickly compared to COA. The optimal value decreases as the number of iterations rises. With the fastest convergence rate, the DTBO has the lowest best value. It can be seen from the statistical test that the DTBO curve is smooth. It indicates that the DTBO is very steady and consistent. DTBO has discovered the minimum solution. The COA did not attain the minimum solution that DTBO was able to achieve. It displays noteworthy results in contrast to COA.

Table 1. Comparison of soft computing techniques

Bus	APF	I_{apf} by DTBO	I_{apf} by COA	Status
27	1	57.39	64.47	Both not Converged
65	1	56.54	59.74	Both not Converged
27,65	2	0.1348	49.26	Only DTBO Converged

4. Conclusion

This paper investigates how to improve PQ by reducing harmonics through the APFs in RDS utilizing the DTBO and COA. The IEEE-69 bus test system simulation effectively combines DTBO and COA with HLF, even with two NLS + NLDGs in the RDS, demonstrating the high influence of harmonics. The negative impact of harmonics on PQ is highlighted by the measured THDv, which is greater than 5% on 40 buses.

Bus number 65 has the highest THDv, 25.63 percent. The successful decrease of THDv in all buses to 5%, which is only possible when two APFs are installed at buses 27 and 65, emphasizes the crucial significance that APF placement plays. Amazingly, THDv can be contained under the allowed limit at all RDS buses with just two APFs. The DTBO algorithm satisfies the condition and converges satisfactorily with buses

27 and 65, yielding a minimum APF current of 0.1348 p.u. However, COA cannot converge, indicating that DTBO performs better in this scenario. In contrast, DTBO converges at 0.1348 p.u. Compared to the 49.26 p.u. that COA found.

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