FOREX Publication
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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 12, Issue 4 | Pages 1222-1229 | e-ISSN: 2347-470X

Application of Walrus Optimizer for Power Quality Improvement in Radial Distribution System

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ABSTRACT- To increase power quality (PQ) in radial distribution systems (RDS) by utilizing active power filters (APFs), this research discusses the application of walrus optimization algorithms (WaOA). The main problem with the PQ is harmonics. The harmonics are added to the RDS by nonlinear loads (NLs). In this instance, together with NL at two end nodes, nonlinear distributed generation (NLDG) is additionally considered. APFs are used to decrease the harmonics to specified limits. In this instance, APFs are positioned correctly to reduce harmonics and improve PQ. WaOA is utilized to maximize the APF's size at the ideal bus location. The WaOA is inspired by natural processes and contains features that are well-balanced for both exploration and exploitation. Within limitations on inequality, optimization seeks to minimize APF's current. On the IEEE-69 bus RDS, a simulation is run to assess the WaOA's performance. Four distinct cases are examined here: a) NL+NLDG only (no APF); b) APF at bus 27; c) APF at bus 67, and d) APFs are located at busses 27 and 67. These examples are taken into consideration to examine the impact of APF sizing and location on PQ in RDS. Using the artificial bee colony (ABC) optimization method, a comparison analysis is performed. The simulation results confirm that the WaOA algorithm solves the optimization problem with stability and efficacy.

Keywords: Active power filter; Harmonics; power quality; Radial distribution system; Walrus optimization algorithm.

ARTICLE INFORMATION

Author(s): Ashokkumar Lakum, Hitesh Karkar, Shilpa Kaila and Shilpa Patel;

Received: 08/09/2024; **Accepted**: 22/10/2024; **Published**: 30/11/2024;
e-ISSN: 2347-470X;
Paper Id: IJEER 0809-06;
Citation: 10.37391/ijeer.120413
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-12/ijeer-120413.html

Crossref member
CROSSREF.ORG THE CITATION LINKING BACKBONE

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1. INTRODUCTION

Today's world requires more and more power electronic devices, which has led to an increased reliance on them. Several examples of these products are PCs, cell phones, dimmers, inverters, variable speed drives, constant power supply, and LEDs. Poor power quality (PQ) is the result of them adding harmonics to the distribution system [1, 2].

Furthermore, distributed generation (DG) is one of the primary drivers driving the expansion of the smart grid. It is garnering a lot of attention due to its numerous benefits. One of the key tasks in the field is integrating DG with the radial distribution system (RDS) [3, 4]. On the other hand, poor integration might result in PQ problems because to the converter's harmonics [5]. A DG system based on converters that introduced harmonics to the RDS is referred to as nonlinear DG (NLDG) [6, 7].

However, the nonlinear characteristics and NLDG of these devices lead to an increase in harmonic pollution. 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 [8–10]. A number of harmonic mitigation techniques are discussed in [11]. An active power filter (APF) is used to mitigate harmonics [12]. At the same node as the NL load, it feeds the RDS with nonlinear current in the opposite direction. The harmonics are therefore eliminated. To save money, it's crucial to size and position APFs correctly, as their efficacy is closely correlated with their rating [13]. Moreover, meeting of IEEE standards for individual and total harmonic distortion in voltage (IHDv and THDv) is necessary to achieve optimal performance [14].

The precise placement and rating of APFs in RDS require careful study if modern power distribution networks are to remain stable, dependable, and effective. It becomes increasingly important to increase PQ and decrease harmonics when non-linear loads and more sources of green energy are introduced to RDS. In RDS, the positioning and ratings of APFs can improve voltage stability, reduce power losses, and reduce harmonic distortions; all of which improve the RDS overall

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performance. Recent studies [15–17] have highlighted the significance maximizing PQ and grid reliability through the optimization of APF placement and size by emphasizing the need for more research in this area.

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. There has been use of PSO and its variations [18]. Moreover, a genetic method is employed [19]. For this problem, other algorithms are used, including a harmony search [20], firefly algorithm [21, 22], grey wolf optimizer [23], and most recently, JAYA algorithm [24].

For example, optimal DG location and sizing [25, 26], optimal capacitor integration [27], power system stabilizer [28], MPPT, electric automobiles, microgrid PQ enhancement, and APF-based PQ improvement [15] are just a few of the research topics that use a variety of optimization methodologies.

The No Free Lunch Theorem (NFL) [29] states that no method can offer the optimal solutions for every optimization problem. Since the type of challenge might affect an algorithm's performance, researchers use novel algorithms.

Based on how walruses forage for food, the walrus optimization algorithm (WaOA) is an optimization method inspired by nature. It was put forth in 2022 by Mohammad Dehghani and Pavel Trojovsky. It imitates the effective foraging and adjustment techniques walruses use in their native environment. WaOA strikes a balance in the pursuit of the best answers to challenging optimization issues by utilizing the ideas of exploration and exploitation. With the help of walruses' adaptive behavior and collective intelligence, WaOA seeks to explore solution areas and arrive at almost ideal solutions quickly [30]. This metaheuristic algorithm is a valuable tool for researchers and practitioners in various sectors because it has demonstrated promising outcomes in various optimization problems. It has been utilized widely in recent research like precise modeling of battery and solar cell [31, 32], optimal power flow [33], economic load dispatch, optimal allocation of FACTS devices [34], and optimal operation of distribution system [35]. Moreover, recent research has extensively documented WaOA's and its variants' efficiency in resolving challenging optimization issues. WaOA, for instance, has been successfully applied in the area of electrical power systems for memory in microgrid [36], optimal rating of microgrid [37], economic load dispatch centre [38], and optimal power flow [39]. These more recent applications demonstrate the WaOA algorithm's versatility and dependability in addressing a range of optimization problems.

Inspired by foraging habits of honey bees, the artificial bee colony (ABC) algorithm is a metaheuristic optimization method. It imitates how individual bees in a colony search for and utilize food sources. Bees as scouts, watchers, and workers are used by ABC to iteratively identify the optimal solutions to optimization problems. ABC's popularity has grown since D. Karaboga and B. Basturk introduced it in 2005, owing to its user-friendliness and effectiveness in addressing a range of numerical optimization issues [40]. It has applications in engineering, machine learning, and other domains searching for efficient optimization methods [41–44].

The PQ improvement caused by APFs when NL and NLDG are present is the subject of numerous significant contributions presented in this work. The following are the primary contributions:

- Integration of WaOA with harmonic load flow (HLF): In order to determine the appropriate filter rating, the article combines the WaOA with HLF analysis. This method takes into account the system's reaction to harmonics brought about by the NL + NLDG.
- Two algorithms are compared: In this work, four scenarios; NLs + NLDGs (without APF), APF at 27, APF at 67, and APFs at 27 and 67 are compared and analysed between two algorithms, WaOA and ABC. The objective is to assess their effectiveness in determining the appropriate APF rating.
- WaOA's superiority over ABC: The computational tests show that WaOA performs better than ABC by producing the least amount of APF current for all situations involving the data under consideration.

As far as the authors are aware, this is the first time the WaOA has been used to this situation. Computational tests are used to assess WaOA's performance, and the best value of the fitness function is compared with ABC. Here, WaOA and ABC are used to simulate the IEEE-69 RDS system and determine the ideal APF current value for the NL + NLDG buses under consideration.

The format of this document is as follows: The method part is the following one. The problem is formulated in a harmonic setting in this part. It entails modelling in a harmonic context for RDS, APF, NL, and NLDG. An optimization approach is combined with the harmonic load flow. The section that analyses and discusses the results is then written. Four distinct scenarios are presented in this section to highlight the significance of APF placement and sizing in RDS using graphs. The last section of the study presents the conclusion derived from the data in the four scenarios. It evaluates whether the optimization process successfully converged and establishes the optimal scenario for improving power quality.

2. PROBLEM FORMULATION

This section discusses RDS modelling, APF, and load flow with harmonics (HLF). An objective function with restrictions is created using WaOA to improve PQ by bringing harmonics, or THDv, into accepted bounds.

2.1. Modelling of RDS, APF and HLF

Resistance, inductance, and impedance the three RDS parameters are modelled in a harmonic environment in accordance with [45]. According to [45], the APF is represented as a harmonic generator. The HLF technique, which is based on network topology, is used for harmonic analysis [46]. The two relationship matrices that form the basis of this method are the BIBC matrix and the BCBV matrix.

2.2. Objective function

The objective function (OF) is a crucial part of the optimization process. Determining the appropriate APF rating to enhance PQ is a limited nonlinear problem. In this instance, the variable of decision is the APF current. It is essential to lower APF's current because its cost rises with its current rating. To improve the PQ in RDS with APF, the subsequent three constraints have been considered: *THDv*, *IHDv*, and *Iapf max* are the three variables. IEEE Standard 519 requires the first two standard constraints, whereas the third constraint is contingent to the NL current [14]. An objective function is shown as

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

Here, *H* is the highest-order harmonic of the considered harmonic spectrum; *h* is the order of harmonic, the bus number is denoted by *m*, *n* represents the total number of buses, I_{apf} is the filter current, and the dynamic penalty is denoted by *DP*. The goal of optimization, particularly when working with confined issues, is to add a penalty term to the objective function to change a limited problem into an unconstrained one. *DP* is the one of the strategies for handling constraints in optimization problems. Throughout the optimization process, these techniques modify the penalty values to enhance convergence toward feasible solutions. The working of DP is initially started with a relatively small penalty for constraint violations and gradually increases it as the optimization progresses.

Moreover, to make the optimization more realistic and impactful the cost is considered in the optimization function and it is represented by (2). There are two components to the overall cost of APF: fixed costs and incremental costs. The incremental cost is determined by the current compensated by the APF and is $ 7,20,000 per unit current [13]. The fixed cost is determined by the number of APF units and is $90,000 per unit. The following is the APF incremental cost:

$$C_{INC} = 7{,}20{,}000 \times I_{apf} \tag{2}$$

The total cost is given as,

$$Cost_{apf} = (No.\,of APF_S \times 90{,}000) + C_{INC} \tag{3}$$

The objective function is a function of current of APF, fixed and incremental cost of APF. It is illustrated as,

$$OF_{TC} = \min Cost_{apf} + DP \tag{4}$$

The following limitations apply to the objective function:

$$THD_V - 0.05 \le 0$$

$$IHD_V - 0.03 \le 0$$

$$I_{apf} \le I_{apf,MAX} \tag{5}$$

Here, *THDv* is the total harmonic distortion in terms of voltage, IHD_V is the individual harmonic distortion in terms of voltage, and $I_{apf,\ MAX}$ is the maximum limit for APF current. IEEE standards limits for *THDv* and IHD_V are 5% and 3% respectively [14].

The flowchart in *figure 1* illustrates how WaOA can be used to raise PQ in RDS.

2.3. Simulation step

First, load the pertinent data from the test system, including the harmonic spectrum. Define the optimization settings in the next step. Continue to *step 3*, where a model of the harmonic environment is generated using the inputs. In *step 4*, the HLF analysis should be performed. The THDv should be calculated using NLs + NLDGs in *step 5*. Integrate the APF into the system prior to going to *step 6*. Include the APF in the load flow harmonics in *step 7*. Using the WaOA, *step 8* entails determining the lowest practical APF current. *Step 9*: Establish an algorithm's termination conditions. Likewise, repeat these steps for ABC.

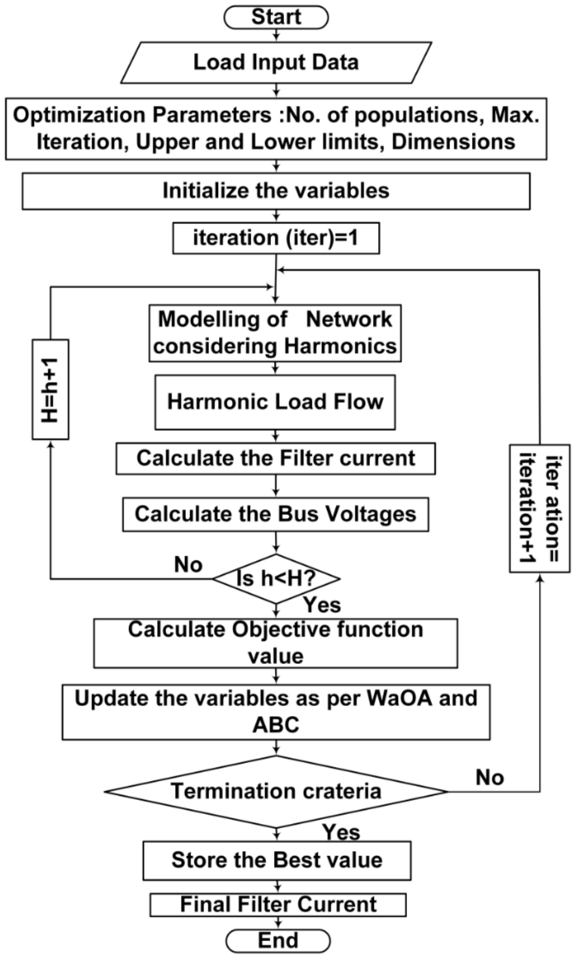

Figure 1. Flowchart

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International Journal of
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Research Article | Volume 12, Issue 4 | Pages 1222-1229 | e-ISSN: 2347-470X

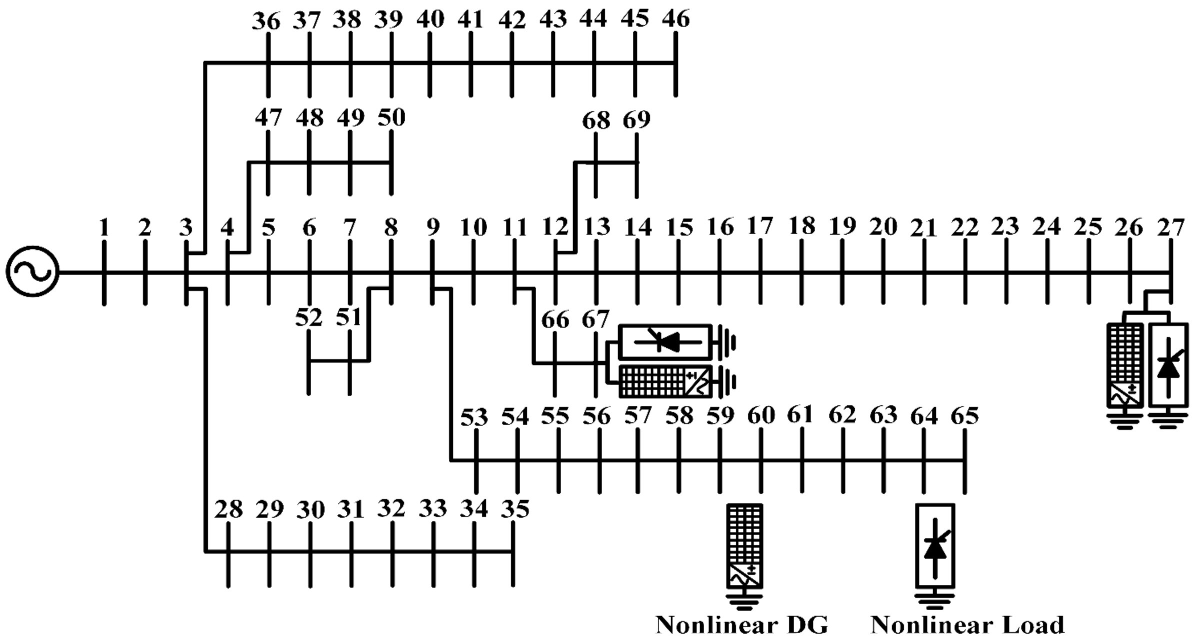

Figure 2. IEEE-69-bus RDS

3. RESULTS AND DISCUSSION

The analysis and discussion of the results are covered in this section. As seen in *figure 2*, the IEEE-69 bus system features two NLs + NLDGs at buses 27 and 67. In this case, the harmonic impact is amplified and impacts all 67 buses in the RDS even if only two nodes have NLs + NLDGs. When there is no APF, HLF calculates the THDv% for every bus; the results are displayed in *figure 3*.

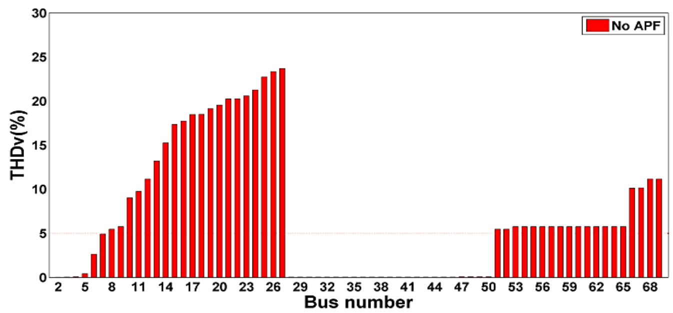

Figure 3. THDv at all buses without APF

The THDv values of 39 buses of the total 68 buses (excluding the first bus, which serves as a source bus) show that harmonics have a pervasive influence over the RDS; these readings are greater than 5%. Remarkably, all buses display THDv, but only two have NLs + NLDGs. Thirty-nine buses cannot fulfill the IEEE standard limit if their THDv is larger than 5%. It displays the RDS's low PQ. There are NLs + NLDGs on busses 27 and 67. THDv values for both are 23.70% and 11.16%, respectively. According to the statistics above, RDS is a rather dirty harmonic system. Harmonic filter(s) must be used in order to meet IEEE standard limitations. The APF is concurrently allocated to busses 27 and 67, which are the NLs + NLDGs. APFs at both buses, a single APF at bus 27, and a single APF at bus 67 make up the scenario. Since the size of the APF directly affects its cost, it is now another crucial factor. Here, the required APF current is determined by the WaOA optimization process.

A key factor in the optimization process is the relationship between the number of search agents and the maximum iterations. High iterations and a huge population boost the possibility of discovering a global solution and improve exploration, but they also dramatically increase computational time and resource requirements. A less population with less iteration, on the other hand, is quick and effective but runs the risk of early convergence and lower-quality results from constrained exploration. While a large population and few iterations speed up exploration, they may also prevent the algorithm from having enough time to fine-tune the optimal solution. High iterations and a limited population, on the other hand, allow for a comprehensive search of the solution space, but may also limit exploration and diversity.

In optimization problems, the number of populations (search agents) and maximum iterations has a major effect on the computational cost. The computational cost rises with the number of search agents deployed since more calculations must be made at each iteration, which results in more resource usage and longer runtimes. On the other hand, employing fewer search agents lowers the computational load and increases process efficiency by reducing memory usage and calculation time. This is especially useful for large-scale problems or situations with limited resources. In a similar vein, longer run times arise from more iteration, which may not be appropriate in situations when quick results are needed. Conversely, less iteration can save computing effort; for low-dimensional or straightforward situations, this is sometimes adequate, preventing the need for pointless calculations. Here, the maximum number of populations, iterations, and general optimization parameters are 30 and 70, respectively.

By following the stages in the associated flowchart *(figure 1)*, this approach is fully replicated for the chosen test system.

3.1 NLs + NLDGs (excluding APF) at 27 and 67:

As shown in *figure 2*, at bus 27 and 67, the NLs and NLDGs are connected. The system is significantly harmonically distorted by these two nodes. At bus 27, the THDv without APF is highest (23.70%). Bus 67's THDv is 11.16 percent.

3.2 APF located on bus 27

To diminish the THDv as much as feasible, the APF is connected at bus 27. Conversely, less than 5% of all buses for THDv have a single APF, which is adequate if positioned correctly. WaOA has decreased to a minimum value of 0.0763 p.u., as seen in *figure 4*. As opposed to WaOA, ABC has converged at a higher value (0.1054 p.u.). WaOA has therefore converged and is able to determine the least APF current value in this situation. It is observed that bus 27 is the appropriate location for APF. Put otherwise, the THDv on all buses can be lowered by less than 5% using just one APF on bus 27. In this case, WaOA outperforms ABC in terms of the present APF. It is clear from the Figure 4 that, WaOA converged in 6 iterations while, ABC took 45 iterations for convergence. It shows that the performance of WaOA is better compared to ABC.

3.3 APF placed on bus 67:

No algorithm can meet the criteria and achieve convergence in this case. They do not converge at all. With 29.08 p.u., WaOA converged while ABC converged at 29.29 p.u. *figure 5* confirms that no single algorithm can meet all of the requirements. This indicates that the location of bus 67 is inappropriate for the placement of APF to enhance PQ.

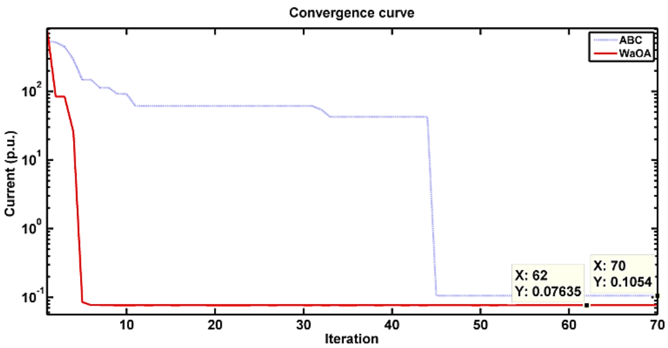

Figure 4. Convergence curves for algorithms while APF is at bus 27

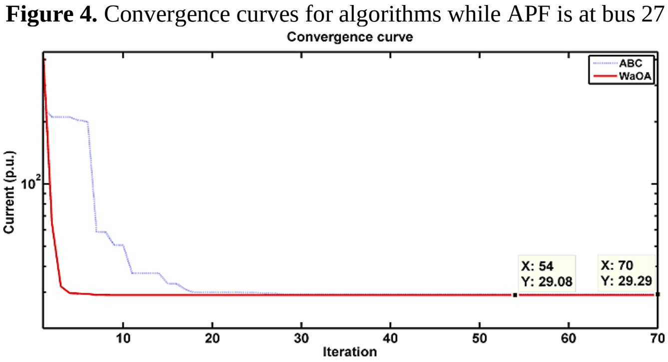

Figure 4. Convergence curves for algorithms while APF is at bus 69

3.4 APFs located on buses 27 and 67

There currently, busses 27 and 67 have APF. *Figure 6* shows the result of HLF employing optimization techniques. The convergence curve for each algorithm is displayed under the given condition. The WaOA's method for determining the minimal APF current is shown in Fig. 6. This example shows that ABC fails to converge to find APF current at its minimum. On the other hand, the WaOA method, as illustrated in Fig. 6, provides the lowest APF current within given parameters efficiently. At 0.0759 (p.u.), the computed APF current is reached. However, when the APFs are positioned at buses 27 and 67, the WaOA approach does converge successfully; in these circumstances, ABC (102.4000 p.u.) calculated the APF current. It is thought to be improper.

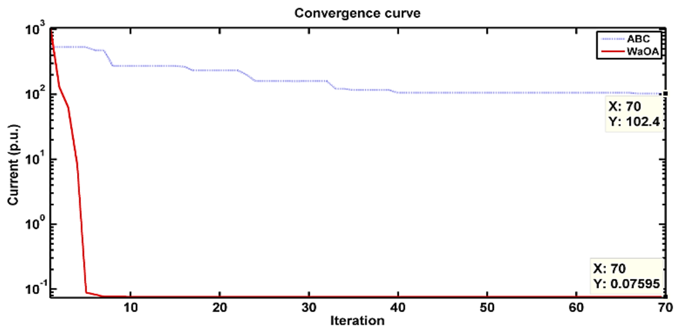

Figure 5. Convergence curves for algorithms while APF is at buses 27 and 67

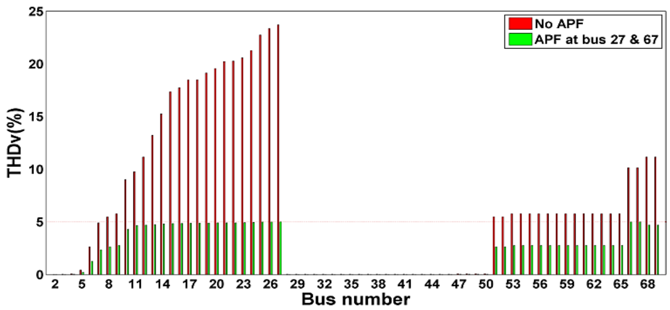

Figure 6. THDv at each bus, following optimization, with and without APFs

Table 1. Comparison of Optimization algorithms

Bus	APF	Iapf by WaOA	Iapf by ABC	Status
27	1	**0.0763**	**0.1054**	**Both converged**
67	1	29.08	29.29	Both not converged
27, 67	2	**0.0759**	102.4	**Only WaOA converged**

According to *figure 6*, the WaOA converged in 8 iterations while, ABC took 66 iterations for convergence. It shows that again the performance of WaOA is better compared to ABC.

After the APFs were placed at buses 27 and 67, *figure 7* shows that the THDv values of all the system's buses are now less than 5%. Notably, the figure shows that busses 27 and 67, which had THDv of 23.70% and 11.16%, respectively, before the APFs were installed, now have THDv of 5.00%. Since every bus complies with the THDv standard limit of less than or equal to 5%, as shown in Fig. 7, the APF's bus number and rating are crucial in improving PQ in the RDS.

In above discussion, the objective function is only I_{apf} *i.e. equation (2).* To make the optimization more realistic and impactful the cost is considered in objective function as expressed in *equation (4).* According to this objective function when APF is placed at 27 the cost is calculated by both optimization algorithms are: $145008 and $ 165960 by WaOA and ABC respectively. Here, also WaOA is found lower cost compared to ABC. While APFs are placed at 27 and 67 buses the cost of the APFs are increased due to increment in number of APFs. In this case, the WaOA is converged and the cost found is $ 234720, while ABC is not converged. The cost found by ABC is very high due to penalty factor.

4. CONCLUSIONS

To sum up, this paper investigates how to improve PQ in RDS utilizing the WaOA and ABC. WaOA and ABC are successfully paired with HLF in the IEEE-69 bus test system simulation. Even with two NLS + NLDGs in the RDS, the simulation demonstrating broad influence of harmonics. The detrimental effects of harmonics on PQ are shown by the measured THDv, which is greater than 5% on thirty-nine busses. 27 is the bus with the greatest THDv, 23.70%. The successful decrease of THDv in all buses to 5%, which is only possible when a single APF is installed at bus 27, emphasizes the crucial significance that APF placement plays. Two APFs at busses 27 and 67 are also used to do it. It is amazing that THDv can be contained under the allowed limit at all RDS busses with just one APF or two APFs.

The WaOA algorithm satisfies the condition and converges successfully with buses 27 and 67, yielding a lowest APF current of 0.0759 p.u. However, ABC is unable to converge, indicating WaOA's superior performance in this particular instance. WaOA converges at 0.0763 p.u. in comparison to ABC's 0.1054 p.u. On bus 27, one APF was investigated concurrently. It's interesting to note that both buses have the optimum location, despite the fact that bus 27 alone has a higher total APF current (0.0763 p.u.) than bus 67 together (0.0759 p.u.). The current of APF alone is the primary goal here. The objective function does not account for the cost. APF at buses 27 and 67 is therefore an option, but it is not the best one. The cost of APF will be the primary goal of this ongoing development. Due to the quantity of APFs, bus 27 (0.0763 p.u.) is currently the optimum location rather than busses 27 and 67 (0.0759 p.u.). A single APF is less expensive than two APFs. Thus, the practical solution is obtained by taking the cost into account in the objective function. The lowest cost for considered case is $145008 found by WaOA compared to $ 165960 found by ABC. For two APFs obtained cost ($ 234720) is too high compared to the cost ($145008) of one APF. Therefore, it is finally concluded that, the optimal placement is at bus 27 and cost is $145008.

Author Contributions: Author Contributions: "Conceptualization, Ashokkumar Lakum; methodology, Ashokkumar Lakum and Hitesh Karkar; software, Ashokkumar Lakum and Shilpa Patel; validation, Ashokkumar Lakum and Shilpa Kaila; formal analysis, Ashokkumar Lakum and Hitesh Karkar; investigation, Ashokkumar Lakum and Hitesh Karkar; resources, Ashokkumar Lakum; data curation, Ashokkumar and Shilpa Patel; writing—original draft preparation, all authors; writing—review and editing, all authors; visualization, Shilpa Patel; supervision, Ashokkumar Lakum. All authors have read and agreed to the published version of the manuscript"

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest."

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Research Article | Volume 12, Issue 4 | Pages 1222-1229 | e-ISSN: 2347-470X

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