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Application of Advanced Soft Computing Techniques for Power Quality Improvement Using Active Power Filters in Radial Distribution System

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Abstract

This paper investigates the application of advanced soft computing techniques: northern goshawk optimization (NGO) and coati optimization algorithm (COA) for improving power quality (PQ) using active power filter (APF) in radial distribution systems (RDS). While beneficial, the growing adoption of solar photovoltaic (SPV) systems introduces power quality concerns like harmonic distortion due to their nonlinear nature. This distribution generator (DG) type is called nonlinear DG (NLDG). Harmonics is the leading cause of poor PQ. This study considers nonlinear loads (NLs) at two end nodes and nonlinear DG (NLDG) integrated into the RDS. APFs are optimally placed to reduce the harmonics and enhance PQ. The proposed approach utilizes soft computing techniques to minimize the APF current while adhering to inequality constraints. The NGO, inspired by natural processes, is employed for optimal APF sizing. This method prioritizes a balance between exploration and exploitation for efficient searching. The effectiveness of NGO is evaluated through simulations on the IEEE-69 bus RDS and compared with another recent soft computing technique, the COA. Here, four different cases are considered: a) only NL+NLDG, b) APF at bus 27, c) APF at bus 35, and d) APFs are at 27 and 35 buses. These cases are considered to analyze the effect of placement and sizing of APFs on PQ in RDS. The results validate the stability and efficacy of NGO in addressing this optimization problem for PQ improvement in RDS.

Keywords: Active Power Filter, Harmonics, Power Quality, Power System Optimization, Radial Distribution System, Soft Computing.

Introduction

Modern soft computing techniques and artificial intelligence (AI) are revolutionizing the field of electrical engineering. AI systems can forecast and improve power grid behavior, reducing energy losses and boosting stability. Machine learning is used to examine large-scale sensor data in order to identify equipment defects and prevent outages. AI - enabled control systems can efficiently integrate renewable energy sources and handle complex energy distribution networks. Performance prediction and design optimization are aided by computational technologies like finite element analysis, which models electrical systems and components. Electrical engineering is developing to become more clever, efficient, and sustainable as a result of these advancements (1-4). The ability of soft computing techniques to tolerate uncertainty and imprecision provides the theoretical basis for their application in power systems. By imitating nature, animal, bird, human learning and reasoning, techniques like fuzzy logic, neural networks, and evolutionary algorithms are skilled at resolving challenging optimization and control issues. With regard to improving power quality (PQ) in radial distribution systems (RDS), these methods offer real-time, adaptive control solutions that improve performance, dependability, and efficiency under a range of load scenarios.

Electronic devices have become increasingly necessary in today's environment, resulting in an increasing reliance on them. Light-emitting diodes, dimmers, inverters, variable speed drives, constant power supply,

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cell phones, and PCs are a few of these gadgets. They introduce harmonics into the distribution system, which leads to poor PQ (5). Sensitive electronics are susceptible to damage from PQ issues such as harmonics, surges, and voltage sags, which can result in malfunctions, data loss, and downtime. These problems also cause production disruption, higher energy costs, and decreased efficiency. Furthermore, issues with PQ can be dangerous because voltage variations can cause accidents and fires.

Moreover, distributed generation (DG) sources like wind farms and solar photovoltaic are the primary drivers of the smart grid's expansion. It is getting much attention because of its various benefits. An essential duty in the industry is integrating DG with the RDS (6). However, poor integration might lead to PQ problems because of the converter's harmonics (7). Nonlinear DG (NLDG) is a converter-based DG system that supplements the RDS with harmonics (8, 9).

However, the NLDG and nonlinear properties of these devices result in more harmonic pollution. As a result, concerns about harmonics in PQ among suppliers and users are growing. These harmonics have a detrimental effect on distribution system performance, which emphasizes how critical it is to resolve these problems (10-12). In an article (13), a number of harmonic mitigating strategies are covered. Harmonics are reduced by an active power filter (APF) (14). It injects nonlinear current in the opposite direction into the RDS at the same node as the NL load. Therefore, the harmonics are mitigated or reduced as per requirement. APFs' rating has a significant influence on their success. Therefore, they must be sized and placed exactly to guarantee cost-effectiveness (15). Furthermore, to attain the best possible performance, individual and total harmonic distortion in voltage (IHDv and THDv) must be met according to IEEE standards (16).

Careful examination of the exact placement and rating of APFs in RDS is necessary to ascertain whether contemporary power distribution networks continue to be dependable, efficient, and stable. Lowering harmonics and raising PQ becomes more and more important as NL and more renewable energy sources are added to RDS. The placement and rating of APFs can improve voltage stability, reduce power losses, and reduce harmonic distortions in RDS, all of which improve the RDS's overall performance. By highlighting the necessity for additional research, recent studies have emphasized the importance of optimizing APF location and sizing in boosting PQ and grid dependability (17-19).

To optimize the costs, APF's current should be as low as practical. For this, an optimization approach is required. As a result, numerous optimization techniques have been put forth. PSO has been used, and its variations are also used (20). Additionally, a genetic approach is used. Other methods, such as the harmony search (21), firefly algorithm (22), grey wolf optimizer (23) and, most recently, the JAYA algorithm (24), are applied to this problem.

For instance, various optimization algorithms were used for the optimal placement and sizing for a DG (25), the best location for an electric vehicle charging station, the best place to allocate UPFC (26), reactive power dispatch, balancing energy generation and peak demand in microgrid (27), identification of forged images (28), and real time object detection (29).

Furthermore, many research topics employ a range of optimization methodologies, including PQ enhancement using APF (17), solar irradiance forecasting, PV-wind-based microgrid implementation (30), UPQC using PSO based PI tuning (31), fault detection in AC motor, and harmonic mitigation of solar PV (32).

According to the No Free Lunch Theorem (NFL) (33), no optimization algorithm can provide the best answers to every optimization issue. Since the nature of the issue may have an impact on an algorithm's performance, researchers employ unique algorithms.

One of the most useful stochastic techniques for resolving optimization issues is the use of optimization algorithms. Soft computing solutions provide a more dynamic and intelligent way to regulate PQ. In comparison to conventional procedures, they may produce possibly better outcomes, manage complex circumstances, and adjust to changing conditions. Traditional PQ management techniques face challenges due to real-world complexity. Soft computing techniques like northern goshawk optimization (NGO) and coati optimization algorithm (COA) offer benefits like robust global search capabilities and balanced exploration and exploitation. Implementation procedures, convergence checks, and performance comparisons are discussed in this paper.

This study presents the NGO method, a new swarm-based algorithm that mimics the behavior of northern goshawks while they hunt prey. This hunting method consists of two stages: the tail and pursuit procedure and the identification of the prey. After outlining the several stages of the suggested NGO algorithm, its mathematical modeling is provided so that optimization issues can be resolved. The efficacy of NGO in resolving optimization issues is assessed using 68 distinct objective functions.

The outcomes of simulations and testing demonstrate that the suggested NGO algorithm performs effectively in solving optimization problems and is significantly more competitive than comparable algorithms by striking the right balance between exploration and exploitation.

It is recently proposed by Dehghani et al. (34). 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 (35). It is widely used in engineering fields like optimal placement of PV and DG (36), PV model parameters identification, smart home energy management (37), optimal allocation of DG (38), and optimal reconfiguration of RDS (39).

A cooperative technique that imitates the foraging behaviors of the South American mammal coatis is called the coati COA. COA efficiently looks for the best answers in complex contexts by letting participants explore and discuss what they find. This allows COA to adapt to different coati behaviors and produce outstanding results. Dehghani et al. have proposed it (40). Numerous technical fields have made extensive use of it, including big data optimization (41), emotion recognition, and optimal power flow (42).

Although traditional approaches to PQ control do exist, they are not well suited to the non-linearities of real-world systems and can be computationally costly. Because of their innate capacity for learning, adapting, and managing uncertainty, this study takes a fresh approach by utilizing sophisticated soft computing approaches, specifically NGO and COA. This provides a possibly better and more reliable way to use APFs in RDS to improve PQ.

The PQ enhancement through APFs in the presence of NL and NLDG is the subject of numerous significant contributions in this work. The following are the primary contributions:

• Integration of NGO with harmonic load flow (HLF): To determine the appropriate filter rating, the paper combines the NGO with HLF analysis. This method takes into account the system's reaction to harmonics brought about by the NL + NLDG.

• Two algorithms are compared: Two algorithms, NGO and COA, are compared and examined in this work for four different scenarios: NLs + NLDGs (without APF), APF at 27, APF at 35, and APFs at 27 and 35. The objective is to assess their effectiveness in determining the appropriate APF rating.

• NGO superiority over COA: The computational experiments show that, for all situations and data under consideration, the NGO performs better than the COA by producing the least APF current.

As far as the authors are aware, this is the first time the NGO has been utilized to solve this problem. Computational tests are used to assess the performance of the NGO, and the best value of the fitness function is compared with COA. In this case, the IEEE-69 RDS system is used to simulate and determine the most appropriate value of the APF current using NGO and COA for the NL + NLDG buses under consideration.

The format of this document is as follows: The problem formulation is given in the following section, followed by a written analysis and discussion of the findings, and a conclusion to the article in the last section.

Methodology

This section covers APF, RDS modeling, load flow with harmonics, and the use of NGO to create an objective function that lowers harmonics and raises PQ.

Modeling of RDS, HLF, and APF

Resistance, inductance, and impedance; the three RDS parameters are modeled in a harmonic environment in accordance with (43). As stated in (43), the APF is modeled as a harmonic generator. The HLF technique, which is based on network topology, is used for harmonic analysis (44). The two relationship matrices that form the basis of this method are the BIBC matrix and the BCBV matrix.

Objective Function

The objective function (OF) is an important part of the optimization process. Determining the appropriate APF rating to enhance PQ is a constrained 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 following three constraints have been considered: THDv, IHDv, and I_{apfmax} are the three variables. IEEE Standard 519 requires the first two standard constraints, whereas the third constraint is dependent on the NL
current. As an example, an objective function is shown as

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

H is the highest-order harmonic in this equation. *DP* indicates the dynamic punishment factor. Bus number *m* is represented by *n*, the total number of buses.

The following limitations apply to the objective function:

$$THD_V - 0.05 \le 0$$
$$IHD_V - 0.03 \le 0$$
$$I_{apf} \le I_{apf,MAX} \quad [2]$$

The flowchart in Figure 1 illustrates how to use NGO to lower harmonics and increase PQ in RDS.

This study uses an modified IEEE-69 bus RDS (45), as shown in Figure 2. The NLDGs are connected to the buses with NLs in the system. The harmonic spectrum of the NLs, spanning from the 5^{th} to the 49^{th}, is consistent with the characteristics of a six-pulse converter (5). The NLs are precisely purposely positioned at end nodes at busses 27 and 35 of RDS.

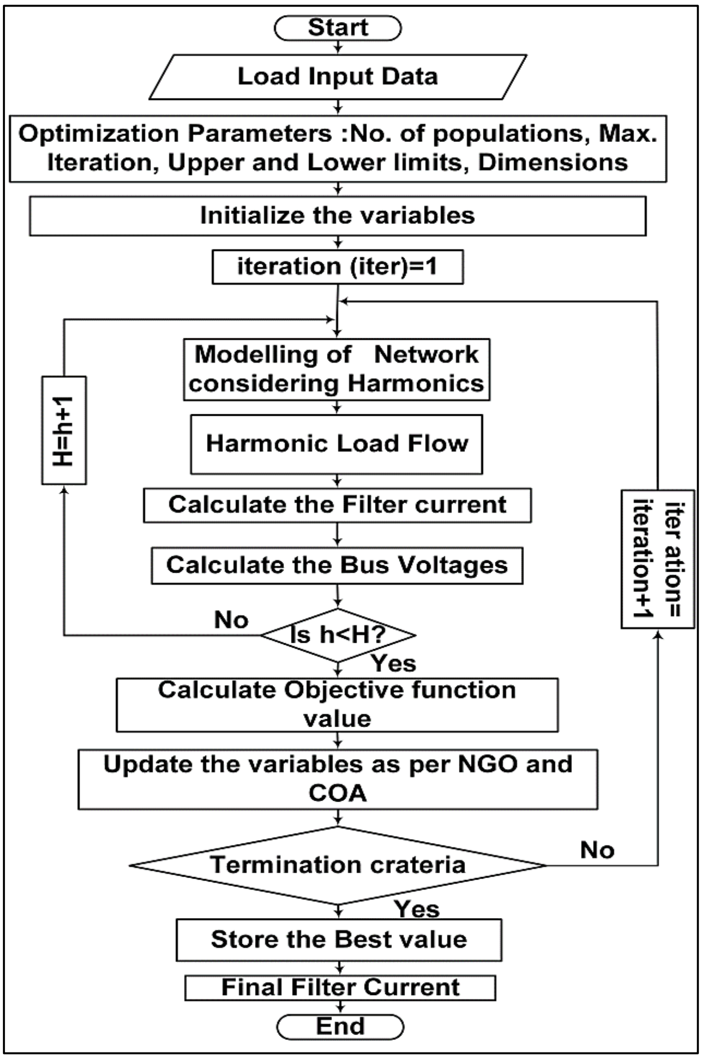

Figure 1: Flowchart

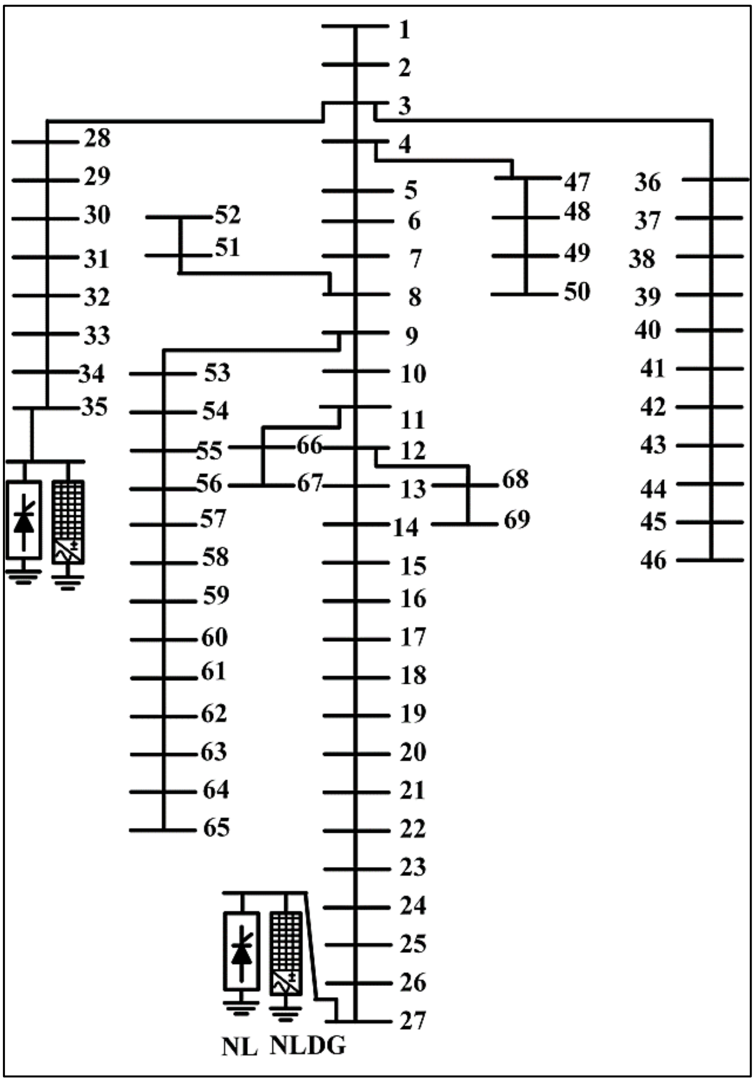

Figure 2: IEEE-69 bus RDS

Steps for Simulation

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 NGO, determine the lowest practical APF current in step eight. Step 9: Establish an algorithm's termination conditions. Likewise, repeat these steps for COA.

Results and Discussions

The analysis and discussion of the results are covered in this section.

As seen in Figure 2, the IEEE-69 bus system has two NLs + NLDGs at buses 27 and 35. In this case, the harmonic influence is amplified and impacts all 68 buses in the system, 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.

Harmonics significantly impact the RDS, as evidenced by the THDv values of twenty four of the sixty eight buses (excluding the first bus, which serves as a source bus); these readings are greater than 5%. Surprisingly, all buses display THDv, but only two have NLs + NLDGs. If a bus's THDv exceeds 5%, it cannot meet the IEEE standard limit. It shows the poor PQ of the RDS.

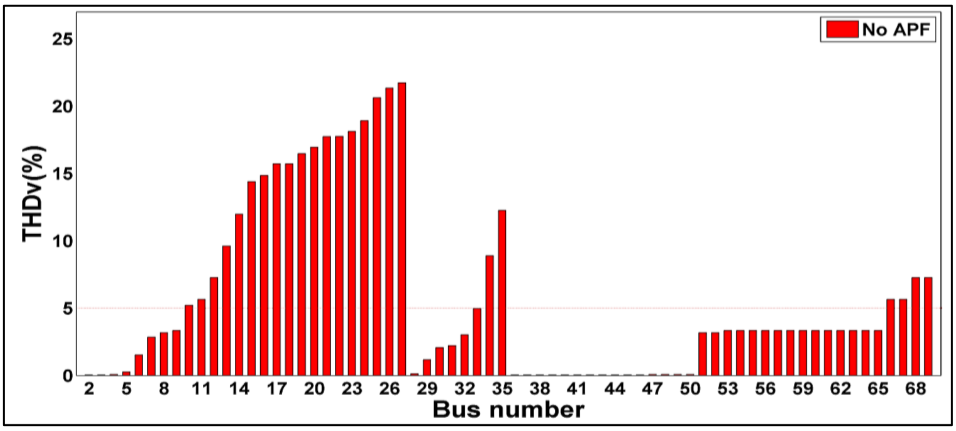

Figure 3: THDv at all buses without APF

Buses 27 and 35 have NLs + NLDGs on them. The corresponding THDv values for the two are 21.74% and 12.25%. In total, twenty four buses surpass the THDv 5% threshold.

Based on the data above, RDS appears to be a relatively polluted harmonic system. In order to comply with IEEE standard constraints, harmonic filter(s) must be utilized. With the NLs + NLDGs, busses 27 and 35 are assigned the APF concurrently. APFs at both buses, a single APF at bus 27, and a single APF at bus 35, make up the scenario. The APF's size is now another important consideration because it directly impacts the cost of the system. In this instance, the NGO optimization procedure calculates the necessary APF current. Thirty and sixty, respectively, are the maximum populations and iterations allowed. The steps in the corresponding flowchart (Figure 1) are followed to simulate this method for the selected test system.

Case 1

As shown in Figure 2, the NLs + NLDGs are connected at buses 27 and 35. These two nodes significantly harmonically distort the system. At bus 27 (21.74%), the THDv without APF is the highest. Bus 35 has a THDv of 12.25%.

Case 2

The APF is placed to bus 27 in an effort to lower the THDv as much as is practical. As can be shown in Figure 4, COA has converged at a value greater than NGO (49.23 p.u.), whereas NGO has dropped to a value of 40.76 p.u.. It has been noted that bus 27 is not the right place for APF.

Case 3

In this instance, no algorithm can satisfy the requirements and reach convergence. They do not even slightly converge. The values of COA and NGO are more due to penalty. There is no single algorithm can satisfy every condition. This suggests that bus 35 placement is improper for the APF to improve PQ.

Case 4

Buses 27 and 35 have the APFs installed. The outcome of HLF's soft computing techniques is displayed in Figure 5. For every algorithm, the convergence curve is shown in the specified circumstance.

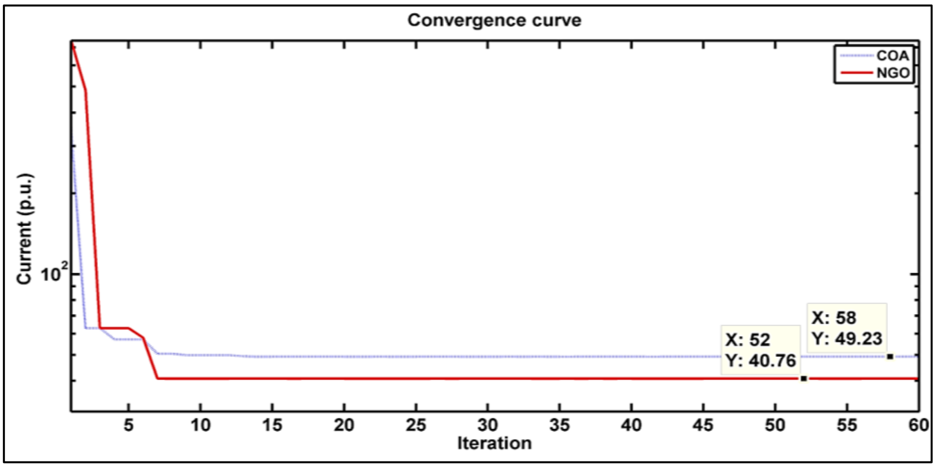

Figure 4: Algorithm convergence curves while APF is at bus 27

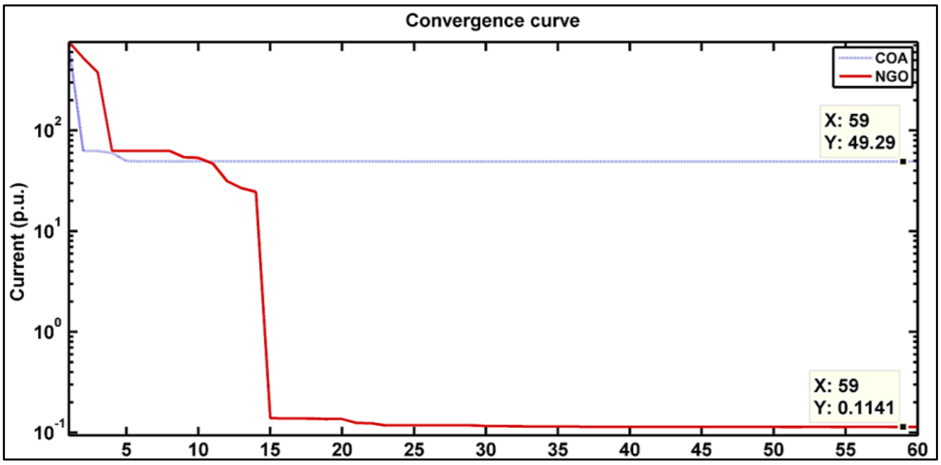

Figure 5: Algorithm convergence curves when APFs are present at buses 27 and 35

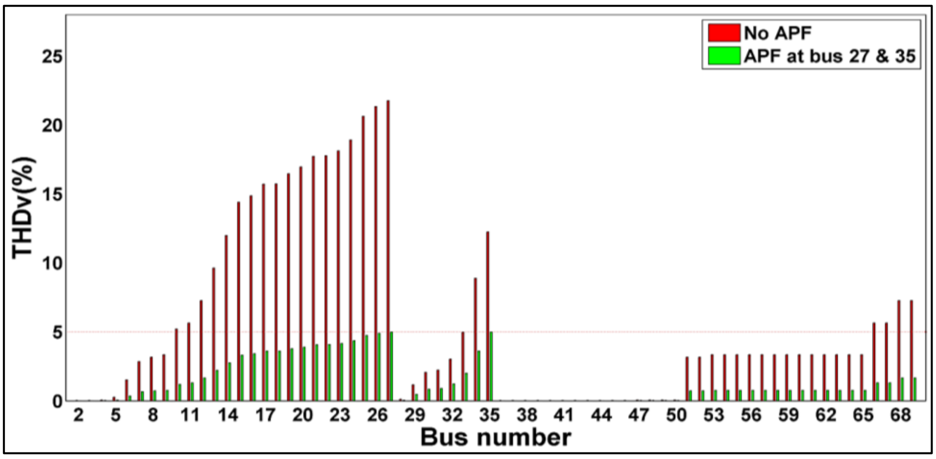

Figure 6: THDv at every bus, both with and without APFs after optimization

Figure 5 illustrates the NGO's methodology for calculating the minimum APF current. The COA does not converge to determine the lowest APF current. Conversely, as shown in Figure 5, the NGO technique converges effectively with a value of 0.1141 p.u. and offers the lowest APF current within the specified parameters. The NGO technique does converge well when the APFs are placed at buses 27 and 35; under these conditions, COA has determined the APF current to be 49.29 p.u. It is thought to be inappropriate.

After the APFs were placed at buses 27 and 35, Figure 6 shows that the THDv values of all the system's buses are now less than 5%. Notably, buses 27 and 35 now exhibit THDvs of 5%, respectively, compared to their prior THDvs of 21.74% and 12.25% without the APF and with the APFs established, respectively. Since all buses satisfy the standard limit of THDv is less than or equal to 5%, as shown in Figure 7, the APF's bus number and rating are crucial in improving PQ in the RDS.

Conclusion

This article investigates the application of NGO and COA to reduce harmonics through the APFs in RDS in order to improve PQ. Even with two NLS + NLDGs in the RDS illustrating the strong effects of harmonics. The IEEE-69 bus test system simulation successfully integrates NGO and COA with HLF. The measured THDv, which is more than 5% on 24 buses, emphasizes the detrimental effect of harmonics on PQ. At bus 27, THDv is 21.74%, which is the highest THDv. The fact that THDv was successfully reduced to 5% in all buses achievable only with two APFs installed at busses 27 and 35 highlights the critical role that APF placement plays (20). Remarkably, with just two APFs, THDv may be contained under the permitted limit on all RDS buses (16).

A minimum APF current of 0.1141 p.u. is found by the NGO algorithm, which satisfies the criterion and converges satisfactorily with busses 27 and 35. However, the COA cannot converge, suggesting that NGOs can do better in this situation. Conversely, NGO converges at 0.1141 p.u. as opposed to COA's 49.29 p.u..

Abbreviations

Nil.

Author Contributions

All the authors are equally contributed.

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethics Approval

This work does not need ethical approval.

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