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A Systematic Review of Single-Tuned Passive Filters for Harmonic Mitigation in Distribution Networks

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Abstract

This paper is a systematic literature review on the relevance of passive filtering on eliminating harmonic distortion in distribution networks by optimal use and sizing of single-tuned passive filters (STPFs). The review explains how competing goals of power quality augmentation, loss reduction and cost minimization are balanced in the multi-objective optimization models through a critical analysis of the models. The key findings indicate that properly selected and designed STPFs are important to minimize the Total Harmonic Distortion (THD) and Current Harmonic Distortion (CHD) and at the same time enhance the voltage profiles and minimize power losses. These conclusions can be supported by simulations on IEEE standard test feeders, specifically the IEEE 33-bus system, and by empirical research of real distribution networks. The results have verified that the optimization-oriented filter allocation planning is much better than the traditional methods with significant power quality improvement under operating conditions.

Introduction

Harmonic distortion due to nonlinear loads, power electronic converters, and intermittently connected sources of generation are causing more and more challenges to distribution networks [1,2]. This distortion is in form of voltage anomalies, equipment overheating, augmented losses and malfunction of control systems [2]. The spread of renewable sources, variable frequency drives as well as power electric equipment has contributed to harmonic pollution in the distribution systems, which requires proper mitigation plans to ensure power quality and stability of the systems.

The IEEE Standard 519 is a detailed guideline on the maximum acceptable level of Total Harmonic Distortion (THD) in power systems [3]. Lack of compliance may cause reliability problems, equipment breakdowns and inefficiency. Economic effects of bad quality of power go further than the replacement of equipment to losses in production and shortening of equipment life and higher energy use.

Problem Statement

Conventional harmonic mitigation techniques do not take into account the most appropriate placing and size of filtering device hence poor operation and high implementation costs. Key issues are: (1) where filters should be installed in radial distribution feeders; (2) how filters can be sized to reduce harmonic in as cost-efficient manner as possible; (3) how to trade off between several goals, including reduction of power loss, improvement of the voltage profile, and cost constraints; and (4) how to have good performance under different load conditions and system designs.

Research Objectives

The following are the key objectives that this study will seek to address:

1. Investigation and study, the existing techniques of maximum distribution of passive tuned filters in the distribution systems.
2. Evaluate the multi-objective optimization methods of single-tuned passive filter (STPF) planning.
3. Assess filter topology and filter configuration performance.
4. Determine gaps in the current research and suggest the direction of the future research.
5. Support results with comparative case study of standard test systems and actual distribution networks.

Research Questions

1. What are the best optimization algorithms to use in STPF allocation in radial distribution feeders?
2. What are the effects of various objective functions such as optimal filter placement and sizing?
3. What is the impact of the variation in loads and distributed generation on the performance of STPF?
4. How effective are hybrid filter structures as compared to pure passive systems?

Literature Review

Generation, Impact and Standards of Harmonics.

The major contributors of harmonic generation in the distribution networks are nonlinear loads; such as rectifiers, inverters, arc furnaces, and electronic lighting systems [1,2]. Modern distribution systems have been getting more complicated in their harmonic spectrum because of increasing penetration of inverter-based distributed generation [2]. The voltages distort across the network, and affect sensitive equipment, and may lead to resonances where some harmonic orders are increased.

IEEE 519 provides a maximum voltage and current distortion limits to provide acceptable levels of power quality [3]. Single voltage harmonic components are typically restricted to 3% of the fundamental and the total harmonic distortion (THD) is restricted to 5% at the common coupling point. Short circuit ratio and harmonic order determine the limits of current distortion with the harmonic order of lower order being more restricted.

Filter Technologies and Reduction Measures.

Passive filters, active filters, and hybrid solutions are among mitigation strategies, and each set of filters has its own pros and cons [1,4]. Passive filters are economical and may be very successful when optimally sited and optimized. They are low impedance filters at certain frequencies and are commonly placed in shunt form with feeders to carry off harmonic currents [5].

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The most widespread passive solution is single-tuned passive filters (STPFs) and is the easiest to implement, reliable, and cost-effective [9,14]. The STPF performance is, however, susceptible to the characteristic of system impedance and can be impaired by the effect of detuning as component ages or as temperature varies [12]. The double-tuned filters have wider attenuation bandwidths but were more complex to design [8].

Active filters have better flexibility and are better performing because they apply the power electronic converters to produce compensating currents which counteract the harmonic distortion [13]. Nevertheless, they are still expensive and must have complex control mechanisms. Hybrid designs which integrate passive and active designs are also used to find a balance between cost and performance benefits [13,18].

Theoretical Framework

Design principles of passive tuned filters

Passive filters Passive filters are tuned LC circuits, devised to offer low impedance at certain harmonic frequencies, and thus to divert harmonic currents off critical circuits and utility supplies [5,14]. Basic design equations express inductance (L), capacitance (C) as well as quality factor (Q) to resonate at the required harmonic frequency. The design should take into consideration system impedance, harmonic current magnitude and any detuning effects that might occur [11-12].

The sharpness of the filter response is set by the quality factor Q, and it has a direct impact on filtering effectiveness and improving reactive power compensation [16]. Greater quality elements are more harmonic to attenuation but more sensitive to frequency variations. In real world, a Q value of 30-100 is a tradeoff between the ability to filter and the sensitivity to system parameter changes.

Multi-Objective Optimization Framework.

Optimal passive filter allocation (or single-tuned passive filters (STPFs)) is a multi-objective problem that is complex and must consider opposing objectives at the same time [2,5]. Examples of representative objective functions are:

1. Reduction of total installation and operating expenses such as filter equipment, installation cost, and operation expenses over the long run.
2. Power losses are minimized by reducing fundamental and harmonic losses.
3. Reduction of overall harmonic distortion (THD) to make IEEE 519 compliant at all network buses.
4. Elimination of existing harmonic distortion (CHD) by damping harmonic currents by means of distribution apparatus.
5. Enhancement of voltage profiles through keeping voltages within acceptable limits.
6. Filter reactive power injection frequency reaction to fundamental frequency reactive power injection [16].

The optimization problem is limited by the voltage constraints, power balance equations, equipment thermal constraints and power factor requirements [5,19]. This multi-objective characteristic typically provides the Pareto-optimal frontier and enables the decision-makers to choose the solutions according to the priorities and budget requirements [2].

Gaps in Literature

Although much has been done in the area of harmonic mitigation of distribution networks, there are still a number of important gaps:

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1. Integration of distributed generation: Few studies cover the interaction of passive filters and the inverter-based renewable energy source especially during fluctuating generation conditions [2,10].
2. Consideration of uncertainty: Not many studies utilize robust optimization or stochastic programming to deal with uncertainties in load patterns, generation profiles and system parameters [10].
3. Dynamic harmonic sources: The sources of harmonic are commonly assumed to be static in most studies, but the dynamic character of these sources is not considered [12].
4. Mass implementation: Mass implementation There has been little validation on large actual distribution networks, most of which have been limited to small systems [17,19].
5. Hybrid optimization methods: Compared to the integration of analytical techniques and meta-heuristics, computational efficiency should be further studied as to which methods of hybridization are the most effective [24,26].

Methodology

The systematic qualitative synthesis methodology of peer-reviewed literature is utilized in this review, though seminal publications published in 2014-2019 were included as well, whereas publications published after 2020 were prioritized. The strategy will be inclusive literature searches according to defined inclusion and exclusion criteria. Research that covered the passive harmonic filter design and optimization, single or double tune filter usage, multi-objective power system optimization, or improvement of power quality in distribution systems were not excluded. Duplicated case studies and unspecified methodology in articles were avoided. The literature that was found was critically analyzed in terms of optimization methods and comparative analysis was carried out between the standard test systems and the real distribution networks implementations.

Population and Sample

The search strategy was focused on articles dealing with:

- Passive harmful harmonic filter optimization and design.
- Single tuned and double tuned filters.
- Multi-objective power system optimization.
- Improvement in the quality of power in the distribution system.

Quality and methodological rigor were maintained by means of the selection of 28 relevant publications on the IEEE Xplore and Google Scholar databases.

Data Collection Methods

The systematic search of the keywords also used words such as: harmonic mitigation, passive filters, distribution systems, optimization, STPF allocation and power quality. The sources retrieved were rated in terms of relevance, quality of the publication venue and methodological transparency.

Data Analysis Methods

Literature collected was analyzed based on:

1. Classification of optimization techniques (genetic algorithms, particle swarm, immune algorithms, jellyfish algorithms, and so on)
2. Single-tuned, as well as double-tuned and hybrid filter topology.
3. Assessment of objective functions and limitations.
4. Comparison systems and methodologies.
5. Research gap and future identification.

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Results

The fourth step involves Multi-Objective Optimization of the STPF Planning.

Several studies use multi-objective methods to strike trade-offs between the cost of filters, reduction of losses and harmonic mitigation [2,5]. These methods employ evolutionary algorithms and hybrid heuristics to come up with Pareto-optimal solutions to filter sizing and location. The multi-objective paradigm allows the decision-makers to trade-off conflicting goals according to priorities and constraints of the system.

Abbas et al. [2] have shown that the multi-objective optimization is efficient in balancing conflicting objectives of cost minimization and harmonic mitigation in systems that integrate inverter-based distributed generation. Their non-dominated sorting technique gave the best filter settings in different investment situations.

Table 1: Comparison of Optimization Algorithms in STPF Allocation.

Algorithm	Advantages	Disadvantages	Best Application	Reference
Genetic Algorithm	Robust handles multi-objective problems effectively	Computationally intensive	Large-scale networks	[2,5]
Particle Swarm Optimization	Fast convergence, simple implementation	May trap in local optima	Medium-sized networks	[3]
Jellyfish Search	Good exploration-exploitation balance	Relatively new, limited validation	Complex multi-modal problems	[7,24]
Immune Algorithm	Adaptive, maintains solution diversity	Complex parameter tuning	Networks with varying topologies	[24]
Grey Wolf-Lévy	Effective for voltage control integration	Specialized application	Integrated planning problems	[3]

Swarm-Based and Evolutionary Swarm.

Genetic algorithms (GAs) and particle swarm optimization (PSO) are still popular in filter sizes and locations and coming up with near optimal placements in radial networks [1,2]. These meta-heuristics of population-based searching are useful in investigating the non-convexity and multi-modality of optimization landscape of filter planning issues. GA-based strategies prove to be solid in a wide variety of network structures, but as network size grows computational expenses rise significantly [5]. PSO variants are generally effective in the moderate-size problems and need to be carefully tuned on the parameters to prevent premature convergence [3].

Innovative Meta-heuristics and Immune Based Methods.

Fine-tuning of filters and sizing has been achieved by using immune algorithms and hybrid methods especially in complicated network topologies [24,26]. Jellyfish search optimization is a relatively new meta-heuristic to the meta-heuristic arsenal, which has shown good performance in STPF allocation problems [7,24]. This bio-inspired method is used to replicate jellyfish movement patterns in ocean currents and the results have been similar to the established optimization schemes.

An additional power system optimization has been applied using the concept of Archimedes optimization which is a buoyancy-based methodology, offering desirable exploration-exploitation trade-off [6]. Nevertheless, it needs a closer investigation as to whether it can be directly applied to STPF planning.

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Analytical and Heuristic Design Strategies.

A number of researches are available with decision-support systems of filter sizing and harmonic filter selection that offer theoretical basis to practical use [4,16]. In the case of single-tuned passive filters, curve-fitting processes are suggested to be optimal in reactive power selection, which will simplify the process of creating a filter, but will not reduce its effectiveness. These methods are tradeoffs of computational efficiency compared to meta-heuristic but with reduced optimality. The future studies ought to pursue hybrid approaches which integrate analytical insights along with the computational optimization [26].

Design and Analysis of Filters.

When correctly positioned and designed single-tuned passive filters can be used to very large extent to reduce the THD [9,14]. STPFs have shown the potential of 60-80% reduction in THD of moderately polluted systems [15,21]. Implementation should be done with an accurate system impedance characterization and a limited choice of filters [12]. Tolerances of components, and effects of component temperature and aging must be taken into account during the design process [12]. The analysis of the sensitivity shows that filters that have been designed to address both the 5 th and the 7 th harmonics would give the most benefits within the normal industrial and commercial distribution networks [9,14].

Table 2: THD Reduction using the various configurations of filters.

Filter Type	Network Type	Initial THD (%)	Final THD (%)	Reduction (%)	Reference
Single-tuned	IEEE 33-bus	15.2	4.8	68.4	[19-20]
Single-tuned	Basra distribution	12.5	4.2	66.4	[17]
Single-tuned	Industrial network	18.3	6.1	66.7	[14]
Double-tuned	Test system	16.8	3.2	81.0	[8]
Hybrid active	Industrial system	22.1	2.1	90.5	[18]

Hybrid and Double-Tuned arrangements.

Single-tuned filters cannot match a damped resistor design of power filters that are damped because they filter multiple harmonic orders at once [8]. The optimization algorithm based on the artificial hummingbird has been proven to be an effective and efficient host in situations with high penetration of renewable energy [8].

There are also hybrid active-passive filters that combine both active and passive filters.

Passive filtering in combination with active compensation is better configured to provide better performance at a higher cost [13,15,18]. The active component corrects any residual distortion and adjusts to different operating conditions, and the passive component gives a high level of harmonic attenuation. Experiments show that hybrid designs can realize reduction of more than 90 percent of THD in the worst polluted settings [18].

Factors that affect the performance of the filters.

Factor analyses revealed system impedance variation, load variation, and variation in component parameters as the determinants of LC passive filter performance [12]. In worst case situations temperature variations can cause capacitor and inductor values to be off by 2030 percent [12].

The reconfigurations of networks and the variations in distributed generation add more complexity that may deteriorate the performance of the filters or amplify the harmonic based on the circumstances [2,10]. Probabilistic planning algorithms solve these uncertainties by making sure that the filter designs should work reasonably over the anticipated operating conditions [10].

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Standard Networks and Real System validation.

IEEE Test Systems

IEEE 33-bus test feeders are routinely used to test the performance of STPF allocation schemes allowing cross-study comparison, as well as practical understanding of performance [5,19]. IEEE 33-bus radial distribution system is a de facto standard to test algorithms and baseline performance. The IEEE test system results prove that optimum STPF placement can decrease system THD by 15-20 percent and also enhance the voltage profiles and minimize losses [5,19]. Consistency in the performance of the algorithm implies that there are fairly fixed optimal solutions, but there can be local optima with respect to the formulation of the problem.

Table 3: Marks of Test Systems of validation.

System	Buses	Branches	Load (MW)	Load (MVAr)	Base Voltage (kV)	Primary Harmonic Sources	Reference
IEEE 33-bus	33	32	3.715	2.300	12.66	Nonlinear loads at buses 5, 14, 25	[5,19]
Tala city feeder	48	47	5.2	3.1	11	Industrial loads, VFDs	[19]
Basra distribution	41	40	4.8	2.9	11	Arc furnaces, rectifiers	[17]
Industrial network with PV	28	27	2.4	1.6	13.8	Inverters, motor drives	[10]

Real Distribution Network Implementations.

The practical relevance of the optimization-based methodology is supported by real-life implementations [5,17,19]. Experiments involving the application of STPF planning to Tala City distribution system and Basra distribution system confirm the applicability of the test system optimization strategies to the operation networks [17,19]. Case studies show that non-conforming levels of THD (> 8 percent) are capable of being brought down to less than IEEE levels (less than 5 percent) with careful filter spacing [17,21].

The Basra City distribution network case study shows how economically significant optimization-based planning can be: three well-placed STPFs had the same harmonic reduction to five randomly placed filters [17]. Passive filtering has been shown to be sustained by long-term performance in actual power quality improvements over several years of operation [21-23].

Table 4: Cost-Benefit Analysis between Optimization Strategies.

Planning Method	Filter Quantity	Installation Cost (relative)	THD Compliance	Payback Period	Reference
Rule-of-thumb	7-10	1.00	Partial	4-5 years	[17]
Single-objective optimization	5-7	0.75	Yes	3-4 years	[5]
Multi-objective optimization	3-5	0.60	Yes	2-3 years	[2,19]
Probabilistic planning	4-6	0.70	Yes (robust)	2.5-3.5 years	[10]

Comparative Appraisal of Objective Functions.

The choice of objective functions plays a significant role in determining the results of the planning [2,5]. Those that optimize just the cost, and those that reduce the THD without emphasis on cost, can give solutions with only a small power quality advantage, and solutions that are not economically feasible,

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respectively. Formulation's Multi-objective Multi-objective formulations are usually formulated with three to five objectives, and typically include combinations such as:

- Cost + THD + Power Loss [2,5,19]
- Cost + THD + Voltage Deviation [10]

V [3,4] = Cost + Power Loss + Voltage Profile.

Pareto-frontier and weighted methods give a comprehensive insight on objective trade-offs [2].

Discussion

The literature review shows that the multi-objective optimization strategies in choosing the optimum distributions of tuned passive filters in a distribution network are effective in minimizing harmonic distortion, and blocking tuning of voltage profiles. The findings directly answer the key research questions about the optimization algorithm efficiency to STPF placement and the influence of different objective functions on the system performance. Literature shows that mitigation of harmonics conducted through STPF necessitates appropriate power system modeling, strong optimization algorithms, and multi-objective functions that would balance quality improvement of power, economic feasibility, and operation limits [2,5,19].

The findings always indicate that 3-5 strategically placed filters are more effective in reducing harmonic than 7-10 randomly placed filters of the same total capacity [17,19]. This observation highlights the importance of optimization-oriented planning over rule-of-thumb in planning. The economic effects are also high as the optimized designs may save up to 30-40 percent in comparison to the non-optimized designs but still provide high performance [19].

The popularity of-computational intelligence is a sign of the nonlinear nature of the STPF allocation problem [24-28]. Although older optimization techniques can have local optima, and are sensitive to dimensionality, meta-heuristics have been shown to be highly flexible when evaluated on a wide variety of problem formulations and network structures.

Comparison with Existing Literature.

El-Ela et al. [19] make useful contributions in terms of the multi-objective functions and the use of optimization methods in the determination of the optimal STPF locations and sizes in both actual distribution networks and typical IEEE test feeders. The dual-validation method improves the self-confidence in practical applicability.

The focus on power loss, voltage deviation, and CHD are consistent with the major goals found in the literature and realistic needs of voltage and reactive control of power approach and strategies [4,19]. The realistic approach to load variations makes the proposed STPF plans stronger compared to the works that presuppose constant loading conditions [10,19].

The uncertainty of changes in the photovoltaic resources, which were overlooked by the previous probabilistic planning techniques, is now being considered by new probabilistic planning techniques [10], a major surpassment of deterministic optimization models to more realistic operating conditions.

Implications

The reviewed literature provides a number of theoretical conclusions:

1. The formulation of problems has significant influence over the quality of solutions, multi-objective formulations will always perform better than single-objective ones when the requirements are in conflict [2,5].
2. The choice of algorithm is not significant compared to the way problems are represented; well-structured problems will give similar results among meta-heuristics, and the nature of solution space determines the eventual gains [5,24].
3. Strong uncertainty management is necessary; deterministic algorithms do not work well in the real operation conditions and must be supplemented with uncertainty-sensitive algorithms [10].

Practical Implications

The paper presents real life advice to the engineers and planners of power systems:

1. Prioritization of investments: The phased implementation of the optimization-based planning can be performed with identification of the maximum-impact locating filters and their implementation depending on the budget limitations.
2. Predictability of performance: Predictable performance of a system can be done with validated predictive models, which are used to predict the post-installation harmonic conditions and verify compliance.
3. Adaptive planning: Mult objective-based sensitivity analysis and situation planning make adaptation to system expansion or reconfiguration easier.

Policy Implications

There should be regulatory systems and utility planning standards that include:

1. Optimization incentives: Economical considerations Cost-benefit analyses do show economic justification to deploy systematically filters.
2. Harmonic limit revision: Current standards could be needing revision to indicate the rising renewable energy penetration.
3. Planning integration: The process of the allocation of filters to the distributed generation interconnection approval should be included.

Limitations

Constraints and Weaknesses

The critical evaluation of the studies reviewed demonstrates that a number of substantive limitations to both generalizability and interpretation are present:

1. Limitations of test system: The IEEE 33-bus system is commonly used, but its features could be inadequate to reflect the features of distribution networks with high distributed generation penetration.
2. Simplified harmonic models' Simple frequency-domain models are too simple to time-varying harmonic behavior.
3. Lack of coordination in protection: The installation of filters may have an impact on the fault current level and protection device coordination.
4. Inadequate cost information: Economic analyses make use of cost estimates that have great regional and contextual differences.

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Impact on Results

These limitations suggest:

1. Bright performance forecasts: The actual performances can be different than the forecasts.
2. Scalability uncertainty: Solutions that have been tested on a limited-scale system need to be tested on a large network before being rolled out to large scale.
3. Long-term behavior: Long-term optimization studies generally do not take into account the effects of component aging and evolution of the system.

Future Research Directions

The gaps and limitations that need to be filled in future research are as follows:

1. Generation integration Inverter-based Inverters are devices that convert DC to AC and are typically connected to a grid. The paper is an exploration of tuned filter interactions between grid-connected inverters operating in different operating modes [2].
2. Hybrid filter designs Active- passive designs with wider harmonic spectrum content [13,18].
3. Strong and stochastic optimization: Algorithms that allow probabilistic uncertainty in load, generation and system parameters [10].
4. State-of-the-art meta-heuristics: Recent improvement of algorithmic technology to achieve a better exploration-exploitation gradient in STPF sizing problems [24,26].
5. Real-time adaptive control Schemes adapt dynamically to changing harmonic conditions by dynamically changing filter settings [13].
6. Life-cycle cost analysis: A detailed analysis of the economy that includes the maintenance costs, replacement costs, and decommissioning costs.
7. Resonance analysis: Characteristic examination into possible resonance conduct in a wide variety of system setups.
8. Smart grid integration: Methodical research on coordinated harmonic reducing in coincidence with distribution automation and smart grid technologies.

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Table 5: Research Gaps and solutions.

Research Gap	Current State	Proposed Solution	Expected Impact	Priority	Reference
DG integration	Limited studies	Co-optimization framework	High	Critical	[2,10]
Uncertainty modeling	Few probabilistic approaches	Stochastic programming	Medium-High	High	[10]
Real-time adaptation	Mostly static designs	Adaptive filter control	High	Medium	[13]
Large-scale validation	Limited real network data	Utility partnerships	Medium	High	[17,19]
Hybrid configurations	Emerging research	Cost-benefit analysis	Medium-High	Medium	[13,18]
Resonance analysis	Basic treatment	Comprehensive modal analysis	Medium	Medium	[12,27]
Life-cycle assessment	Economic focus only	Environmental impact study	Low-Medium	Low	[19]

Conclusion

The literature reviewed reveals that tuned passive filters are a feasible and cost-effective way of reducing harmonic in distribution systems. Key findings include:

1. Multi-objective optimization models are well-known to compromise competing objectives such as cost reduction, minimization of power loss, and removal of harmonic distortion [2,5,19].
2. Approximately optimal solutions to the problem of filter placement and sizing are generated by meta-heuristic algorithms (genetic algorithms, particle swarm optimization, jellyfish optimization) [1,2,7,24].
3. Practicability and efficiency can be proved by validation on IEEE test systems and actual distribution systems [5,17,19].
4. Single-tuned passive filters can also reduce total harmonic distortion by as much as 60-80 with optimal placing and can be brought to IEEE 519 compliance [9,14,21-23].
5. Probabilistic and robust optimization strategies ensure reliability of the solution in real world operating condition [10].

Recommendations

For Researchers

1. Focus on creating comprehensive frameworks of optimization that can handle mitigation of harmonic effects, distributed generation optimization and reconfigurability of networks.
2. Widely validate Utility alliances that permit testing of algorithms on operating distribution systems.
3. Find machine learning methods to do rapid filter sizing and location rather than doing optimization which is computationally expensive.
4. Define standard benchmark problems on which direct comparisons can be made on the performance of the algorithm.

For Practitioners

1. Use optimization-based planning tools in filter allocation decision instead of an empirical or rule of thumb approach.
2. Carry out detailed harmonic audits in the pre-filter location to appropriately define issues.
3. Introduce performance monitoring systems in order to determine performance of filters and identify de-tuning or degradation.
4. Create a step-by-step implementation strategy based on capital budgets and system evolution strategies.

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For Policymakers

1. Modify interconnection standards to make distribution generation installations harmonically assessed.
2. Install rewards schemes that promote active mitigation of harmonica in distribution systems.
3. Standardize technical procedures used in small and medium utilities in filter planning.
4. Assistive research to deal with emerging power quality management issues.

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