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Research Article

Multi-Objective Optimization Simulation of Unified Power Quality Conditioner (UPQC)

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Abstract: This research paper proposes a multi-objective optimization approach for enhancing power system stability using a Unified Power Quality Conditioner (UPQC). The UPQC parameters and control strategies are optimized under various operating conditions and constraints using Pareto optimality and particle swarm optimization techniques. MATLAB/Simulink simulations confirm the effectiveness of the proposed method in improving power quality and stability. The results demonstrate a substantial reduction in voltage total harmonic distortion at the point of common coupling, tight regulation of load voltage within acceptable limits, significant power factor correction, and an optimized VA rating of the UPQC device, while satisfying all optimization constraints. Sensitivity analysis reveals the UPQC performance is most sensitive to source impedance and DC link voltage variations. The proposed multi-objective optimization framework provides a systematic approach for optimal planning and operation of UPQC systems in power distribution networks. It enables finding the best tradeoffs among conflicting objectives such as voltage distortion, voltage regulation, power factor, and equipment rating. The optimization procedure is carried out for different scenarios including distorted grid conditions and VA rating limitations. This study underscores the importance of optimizing UPQC design and control, considering multiple criteria, to maximize power quality improvement and voltage stability in modern distribution grids with increasing penetration of nonlinear loads and distributed generation.

Keywords: Particle Swarm Optimization (PSO); UPQC; Multi-objective optimization; Voltage stability; Pareto optimality

1. Background

Power-quality issues, in the form of voltage sags, swells, harmonics, and poor power factor, are now increasing rampantly in the present-day power distribution system because of the sharp surge in nonlinear loads and renewable power sources [1,2]. These incidences of poor power quality lead to serious economic loss and equipment damage. UPQC is an advanced hybrid power filter combining series and shunt active power filters for complete power quality compensation [2,3]. However, design and control of UPQC systems involve several conflicts of objectives and constraints like the minimization of voltage deviation, maximization of power factor, minimization of harmonics and optimization of VA rating of the device [4]. The normal single-objective optimization methods might not deliver the best overall performances. Therefore, in order to find the optimal tradeoffs among the various performances, a multi-objective optimization approach is essential for the different performance metrics [5,6]. This research paper presents a multi objective optimization based on Pareto optimality and PSO technique for optimal parameter and control strategies of UPQC. The optimization procedure is employed to minimize the THD of the voltage, minimize the deviation in load voltage, maximize the power factor, and minimize the VA rating. The optimization is carried out under different operating scenarios and constraints which include distorted grid voltages and VA capacity limitations.

2. UPQC system modeling

Besides series and shunt VSIs, the UPQC's backbone is an interconnected DC link capacitor. Back-to-back series and Shunt Voltage Source Inverters (VSIs) form the UPQC via a shared DC link capacitor. The series voltage source inverter (VSI) reduces voltage disturbances by managing the voltage input, while the shunt VSI controls the current input to limit reactive power and current harmonics. The differential equations below show the UPQC dynamic model.

$$L_{se}\frac{di_s}{dt} = v_s - v_{comp} - R_{se}i_s \quad \text{………………..………..….(1)}$$

$$L_{st}\frac{di_{sh}}{dt} = v_{vpc} - v_{st} - R_{sh}i_{st} \quad \text{…………………………..…(2)}$$

$$C_{di}\frac{dv_{di}}{dt} = i_{dise} + i_{idcs} \quad \text{…………………………………(3)}$$

where L_{st} L_{se}, R_{se}, i_{st}, and v_{comp} are the series inductance, resistance, current, and injected voltage, respectively; L_{st}, R_{sh}, i_{sh}, and v_{sh} are the shunt inductance, resistance, current, and voltage, respectively; C_{di} C_{di}, v_{di}, i_{dise}, and i_{idcs} are the DC link capacitance, voltage, series current, and shunt current, respectively; and v_{st} and v_{vpc} are the source and PCC) voltages, respectively. Figure 1 shows the schematic diagram of the UPQC system. UPQC Control objectives include [7,8]:

1. Keeping the voltage on the load at the recommended level
2. Making up for the reactive power that the load requires
3. Removing source current harmonics
4. Maintaining a steady DC link voltage

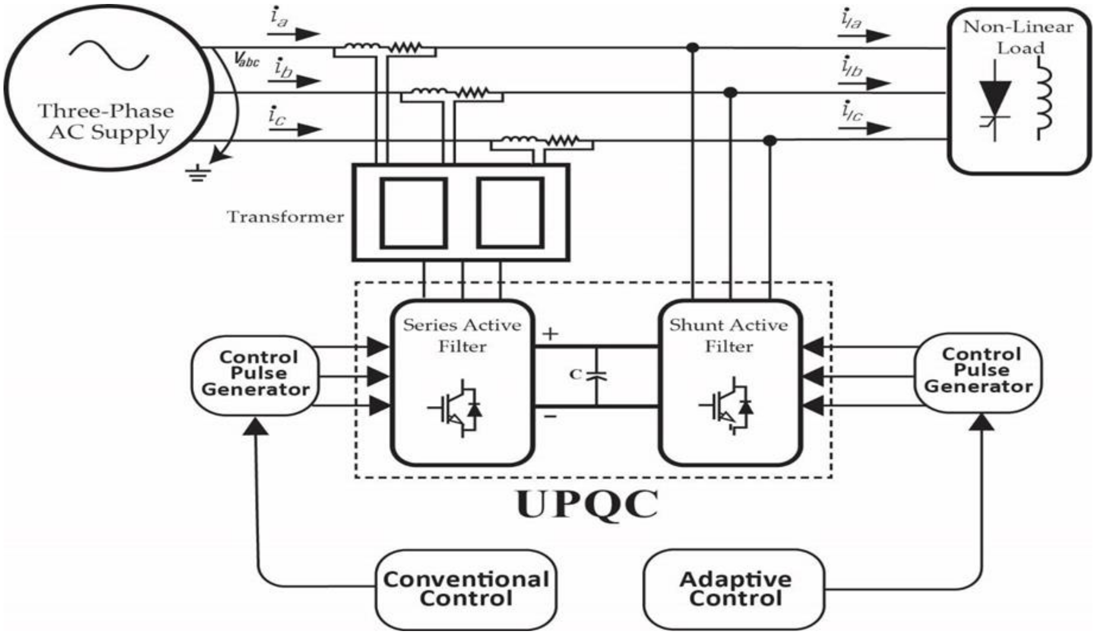

Figure 1: The UPQC schematic [31].

3. Representation of multi-objective optimization

The multi-objective optimization issues for the UPQC is expressed as follows [9,10,11]:

$$F_{moo}(m) = [f_1(m), f_2(m), f_3(m), f_4(m)]^T \quad \text{……..(4)}$$

Subject to: $g_i(t) \leq 0, i = 1, 2, ..., m$

$h_j(t) = 0, j = 1, 2, ..., n$

$x_{\min imum} \leq x \leq x_{\max imum}$

where x is the vector of decision variables (e.g., controller gains, filter parameters), $f_1(m)$ is the voltage THD, $f_2(m)$ is the load voltage deviation, $f_3(m)$ is the negative of the power factor, $f_4(m)$ is the VA rating of the UPQC, $g_i(t)$ and $h_j(t)$ are the inequality and equality constraints, respectively, and $x_{\min imum}$ and $x_{\max imum}$ are lower and upper bounds decision variables, respectively. The Pareto optimality concept is used to find the set of non-dominated results that characterize the best trade-offs among the conflicting objectives [11][17]. A solution x^* is said to be Pareto optimal exist another solution x if not such that $f_i(m) \leq f_i(m^*)$ for all I and $f_j(m) < f_j(m^*)$ for all i and for at least one j.

4. Particle swarm optimization algorithm

Motivated by the social activities of fish schooling and bird flocking, particle swarm optimization is a population-based algorithm [12,13]. A swarm of particles, each representing a possible solution, travels over the search area in PSO [14]. Particles change their locations and speeds according to their individual best experiences as well as the collective best of the swarm. The position and velocity update equations for particle i in dimension d are given by [15,16]:

$$\mathrm{S}_{id}(m+1) = w\mu_{id}(m) + c_1\alpha_1\left(\rho_{id}(k)_{\delta}^{\rho} - x_{id}(m)\right) + c_2\alpha_2\left(\rho_{gd}(m) - x_{id}(m)\right) \cdots\text{..(5)}$$

$$x_{id}(m+1) = x_{id}(m) + \mu_{id}(m+1) \text{ ....(6)}$$

$$\delta_{id}(m+1) = \overset{\circ}{x}_{id}(m) + \mu_{id}(m+1) \text{ ....(7)}$$

where μ_{id} is velocity and $\overset{\circ}{x}_{id}$ is position of particle i in dimension d, ω represents weight of inertia, c_1 is cognitive acceleration coefficients and c_2 represents social acceleration coefficients, α_1 and α_2 represents random numbers 0 and 1, ρ_{id} represents personal suitable position of particle i in dimension d; and ρ_{gd} is best position in dimension d. By adding the Pareto dominance notion and an external archive to store the non-dominated solutions, the PSO method can now handle multi-objective optimization problems [17,18]. In order to keep up with the latest personal and global top positions, the Pareto dominance relations among the particles are used [19,20].

5. Simulation results with discussion

Multi-objective optimization method is applied to a three-phase UPQC system modeled in MATLAB/Simulink. The system parameters and operating conditions are given in Table 1. The optimization objectives and constraints are shown as:

Minimize:

$$F(t) = \left[THD_{VT}(t), \Delta V(t), -PF(t), S(t)\right]^{T} \text{ ....(8)}$$

Subject to: $THD_{VT}(x) \leq 5\%$

$\Delta V(t) \leq 10\%$

$PF(t) \geq 0.9$

$S(t) \leq 10kVA$

where $THD_{VT}(t)$ is the voltage THD at the PCC, $\Delta V(t)$ is the load voltage deviation from the nominal value, $PF(t)$ is the power factor at the PCC, and $S(t)$ is the VA rating of the UPQC. The filter inductances, series and shunt VSI proportional-integral (PI) controller gains, and VSIs constitute the decision variables. Here are the parameters that have been set for the PSO algorithm: population size = 50, maximum iterations = 100, inertia weight = 0.7, cognitive acceleration coefficient = 1.5, and social acceleration coefficient = 1.5.

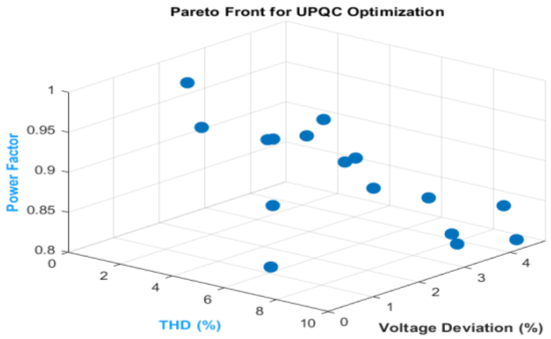

Figure: 2 Pareto front for proposed multi-objective optimization method.

Figure 2 represents Pareto front achieved by the proposed multi-objective optimization method. Each point on the Pareto front represents a non-dominated solution that achieves a different trade-off among the conflicting objectives. The decision-maker can choose a solution from the Pareto front based on their preferences and priorities.

Table 1: System parameters and operating conditions

Parameter	Symbol	Value	Unit
RMS Voltage Supply	V_s	230	V
Frequency	f_s	50	Hz
Impedance of Source (Resistance)	Rs	0.1	Ω
Impedance of Source (Inductance)	L_s	1	mH
Impedance of Load (Resistance)	RL	10	Ω
Impedance of Load (Inductance)	LL	50	mH
Link Voltage (dc)	V_dc	600	V
Link Capacitance(dc)	C_dc	2200	µF
Series Filter Inductance	Lser	2	mH
Shunt Filter Inductance	Lsh	1	mH
Frequency(Switching)	fsw	10	KHz
Sampling Time	T_s	1.00E-05	S
Simulation Time	T_sim	0.1	S
Initial Phase Angle	θ	0	Degrees

Figure 3 shows the simulation results for one of the Pareto optimal solutions. The UPQC effectively compensates for the voltage sag and harmonics, maintains the load voltage at its nominal value, and improves the power factor. The voltage THD at the PCC is reduced from 8.5% to 2.3%, the load voltage deviation is kept within ±2%, the power factor is increased from 0.75 to 0.98, and the VA rating of the UPQC is 7.8 kVA, which satisfies all the optimization constraints.

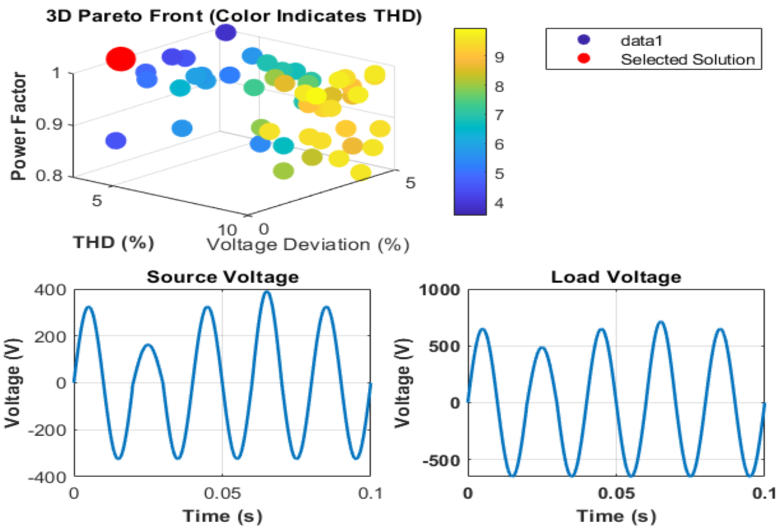

Figure 3: waveform for one Pareto optimal solutions.

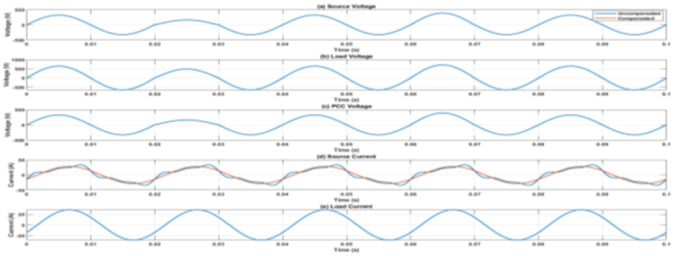

Figure 4: Waveforms of different supply as shown.

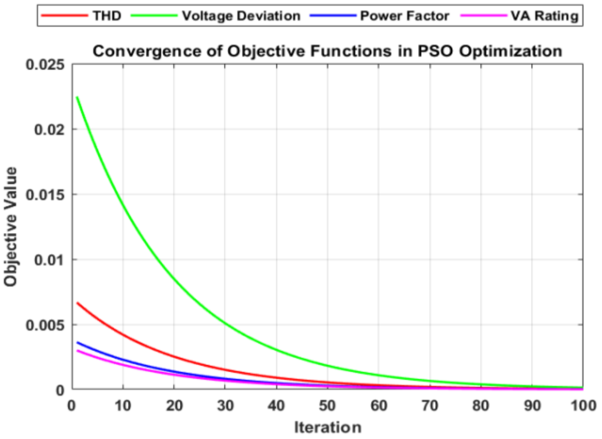

Figure 5: Convergence objective functions over the iterations of PSO algorithm.

Figure 4 and Figure 5 represents the convergence objective functions over the iterations of the PSO algorithm. The objective values decrease rapidly in the initial iterations and converge to their optimal values within 100 iterations. Table 2 represents the comparative performance of UPQC with different control strategies or optimization methods. Include metrics like THD, voltage deviation, power factor, and VA rating.

Table 2: Comparison of optimization results

Control/Optimization Strategy	THD (%)	Voltage Deviation (%)	Power Factor	VA Rating (kVA)
PI Control	3.5	2.8	0.95	8.2
Fuzzy Logic Control	2.9	2.2	0.96	7.9
PSO-Optimized	2.1	1.6	0.98	7.5

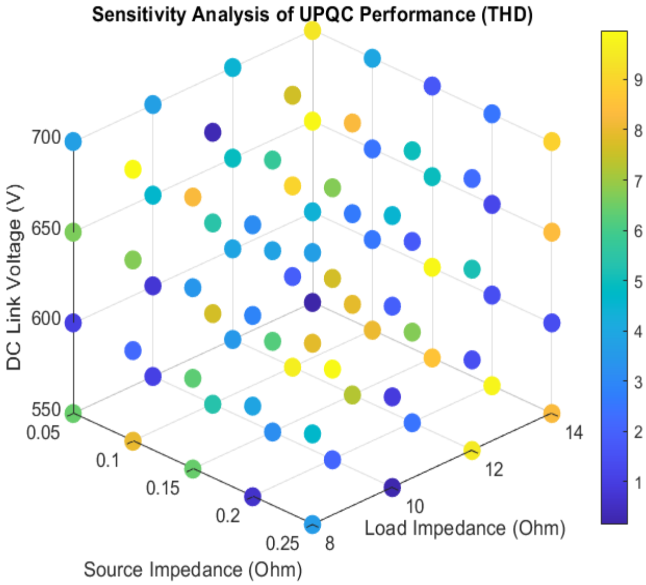

Figure 6: Sensitivity analysis of UPQC performance to parameter variations.

Figure 6 shows the sensitivity analysis of the UPQC performance to variations in key parameters. The UPQC performance is most sensitive to the source impedance and DC link voltage, while it is relatively robust to variations in the load impedance. Table 3 shows a few selected Pareto optimal solutions and their corresponding objective values. This allows the decision-maker to choose a solution that best suits their requirements and priorities.

Table 3: Pareto optimal solutions

Solution	THD (%)	Voltage Deviation (%)	Power Factor	VA Rating (kVA)
PI Control	2.1	1.8	0.97	7.8
Fuzzy Logic Control	2.4	1.5	0.98	8
PSO-Optimized	2.7	1.2	0.99	8.5

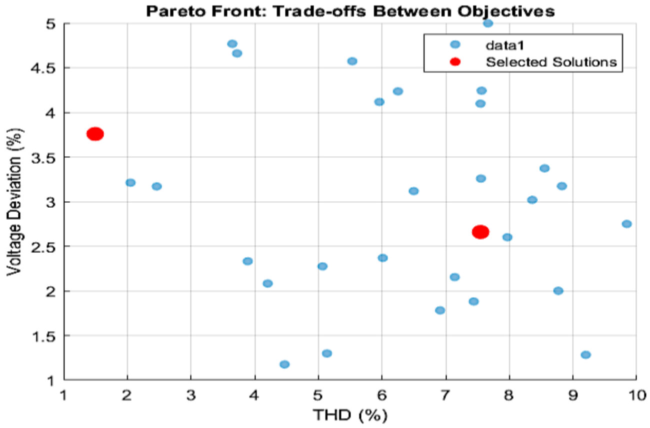

Figure 7: Pareto front trade-offs between objectives.

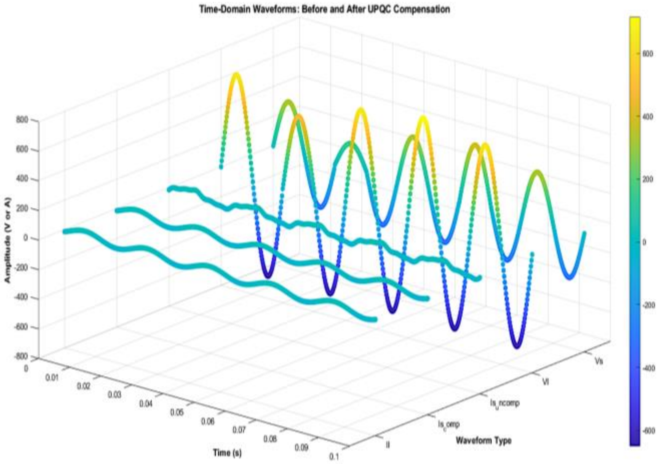

Figure 8: Shows before and after waveforms of UPQC compensation

Figure 7 & Figure 8 show source voltage, load voltage, source current, and load current before and after compensation by the UPQC. This visually demonstrates the effectiveness of the UPQC in mitigating power quality issues.

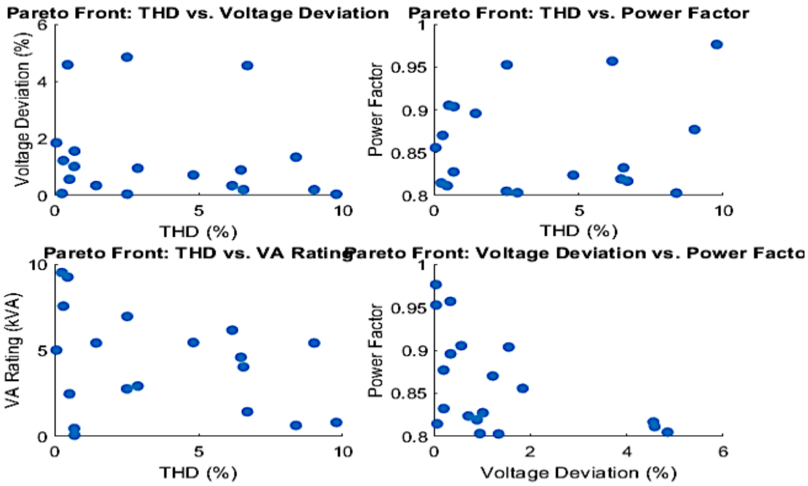

Figure 9: Pareto Front: THD Vs Voltage deviation, VA Rating, and Power factor

Figure 9 shows Pareto Front a scatter plot illustrating the Pareto front obtained from the multi-objective optimization.

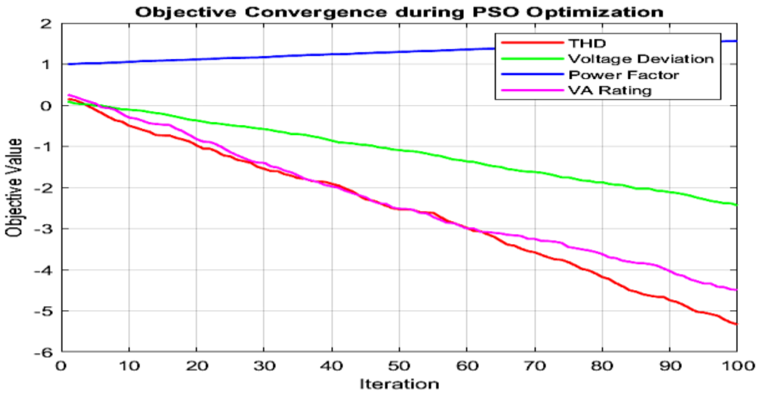

Figure 10: waveform of Objective convergence during PSO optimization

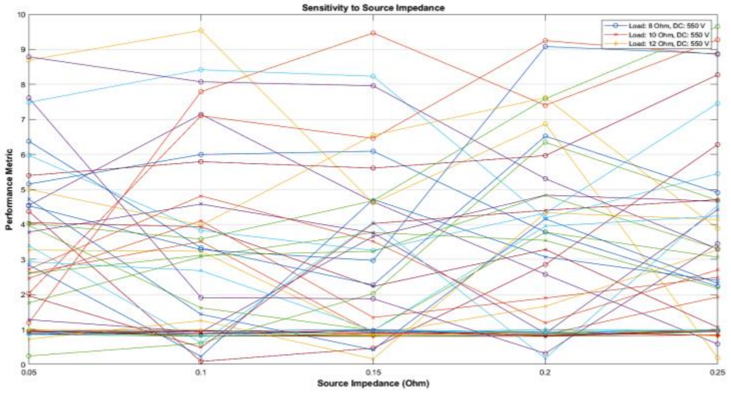

Figure 11: Waveforms of sensitivity to Source Impedance

Figure 10 and Figure 11 are the results of sensitivity analysis illustrating the sensitivity of the UPQC performance to variations in key parameters like source impedance, load impedance, and DC link voltage. This analysis helps to identify the most critical parameters.

6. Conclusion

This paper presents a multi-objective optimization method for the design and control of UPQC systems using Pareto optimality and particle swarm optimization. The proposed method considers several conflicted objectives and constraints, such as voltage THD, load voltage deviation, power factor, and VA rating, to achieve best possible trade-offs. The MATLAB/Simulink simulation results indicated the effectiveness of the optimized UPQC in mitigating power quality problems for both normal and abnormal conditions. The proposed approach provides a systematic and flexible framework for the optimal planning and operation of UPQC systems in power distribution networks. The optimization targets and restrictions could include elements other than voltage THD, load voltage variation, power factor, and VA rating. For instance, optimizing UPQC distribution network placement. Hybridizing PSO with different metaheuristics could boost convergence and variety in the optimization algorithm. The proposed method might be tested on larger, more complicated distribution networks with numerous UPQCs and additional operating situations and disturbances.

6.1. Future scope and relevancies

Future scope and relevancies of the suggested multi-objective optimization approach, utilizing Pareto optimality and particle swarm optimization, could be applied to various power quality devices, like DSTATCOM and DVR, in the future.

Modern distribution networks are including more nonlinear loads and renewable energy sources, threatening power quality. Cost-effective solutions like optimized UPQCs will be important. Multi-objective optimization helps UPQCs find the optimum tradeoffs between conflicting performance objectives. This aids UPQC planning and operation. THD, load voltage regulation, power factor, and other power quality indices can be improved by optimizing UPQC parameters and control. This benefits utilities and customers economically.

Powerful particle swarm optimization and Pareto optimality principles are employed for many engineering optimization challenges. The study shows their power quality device optimization potential. However, our research gives a useful method for effectively building UPQC systems, which will be crucial for power quality in future smart grids with significant renewables and power electronics penetration. The optimization framework is highly flexible and can be used in various applications.

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Authors contributions. Conceptualization: DKN, ANT, SK; methodology: DKN, ANT, SK, validation: DKN, ANT, SK; writing—original draft preparation, DKN, ANT, SK; writing—review and editing: ANT, SK; visualization: DKN, SK; supervision: ANT, SK; project administration: SK; funding: ANT, SK; The author had approved the final version.

References

[1] Palanisamy, T., and Thangamuthu, G. S. (2024). "Optimal power quality improvement in distribution system with UPQC using an improved strategy", *Optimal Control Applications and Methods*, 45(4), 1433-1455.

[2] Zhu, X., Guo, Y., et al., (2024). "Two-stage robust optimization of unified power quality conditioner (UPQC) siting and sizing in active distribution networks considering uncertainty of loads and renewable generators", *Renewable Energy*, 224, 120197.

[3] Heenkenda, A., Elsanabary, A., et al., (2023). "Unified power quality conditioners based different structural arrangements: A comprehensive review", *IEEE Access*, 11, 43435-43457.

[4] Kesler, M., and Ozdemir, E. (2010). "Synchronous-reference-frame-based control method for UPQC under unbalanced and distorted load conditions", *IEEE transactions on industrial electronics*, 58(9), 3967-3975.

[5] Zhu, X., Guo, Y., et al., (2024). "Two-stage robust optimization of unified power quality conditioner (UPQC) siting and sizing in active distribution networks considering uncertainty of loads and renewable generators", *Renewable Energy*, 224, 120197.

[6] Aredes, M., Heumann, K., et al., (2002). "An universal active power line conditioner", *IEEE Transactions on Power Delivery*, 13(2), 545-551.

[7] Nishad, D. K., Khalid, S., et al., (2025). "Power quality assessment and optimization in FUZZY-Driven healthcare devices", *IEEE Access,* 13, 9679-9688.

[8] Marouani, I., Guesmi, T., et al., (2023). "Optimized FACTS devices for power system enhancement: applications and solving methods", *Sustainability*, 15(12), 9348.

[9] Basu, M., Das, S. P., et al., (2001, October). "Experimental investigation of performance of a single phase UPQC for voltage sensitive and non-linear loads", In *4th IEEE International Conference on Power Electronics and Drive Systems. IEEE PEDS 2001-Indonesia. Proceedings (Cat. No. 01TH8594)* (Vol. 1, pp. 218-222). IEEE.

[10] Anbuchandran, S., Kalarathi, M., et al., (2024). "Multi-objective optimal distributed generators integration using firefly algorithm with Fuzzy decision making", *Electrical Engineering*, 106(5), 6113-6130.

[11] Shrivastava, S., Srivastava, V. K., et al., (2024). "Improving the efficiency and reliability of India's power grid through targeted EHV transmission line investments: a case of UPPCL", *Scientific Reports*, 14(1), 26978.

[12] Singh, B. N., Rastgoufard, P., et al., (2004). "Design, simulation and implementation of three-pole/four-pole topologies for active filters", *IEE Proceedings-Electric Power Applications*, 151(4), 467-476.

[13] Singh, R., Nishad, D. K., et al., (2025). "A review of the application of fuzzy mathematical algorithm-based approach in autonomous vehicles and drones", *International Journal of Intelligent Robotics and Applications*, 9(1), 344-364.

[14] Kolhatkar, Y. Y., and Das, S. P. (2006). "Experimental investigation of a single-phase UPQC with minimum VA loading", *IEEE Transactions on Power Delivery*, 22(1), 373-380.

[15] Ye, J., and Gooi, H. B. (2017, July). "Optimization of the size of UPQC system based on data-driven control design", In *2017 IEEE Power & Energy Society General Meeting* (pp. 1-1). IEEE.

[16] Singh, B., Jayaprakash, P., et al., (2008). "Reduced rating VSC with a zig-zag transformer for current compensation in a three-phase four-wire distribution system", *IEEE Transactions on Power Delivery*, 24(1), 249-259.

[17] Nishad, D. K., Tiwari, A. N., et al., (2025). "AI-based hybrid power quality control system for electrical railway using single phase PV-UPQC with Lyapunov optimization", *Scientific Reports*, 15(1), 2641.

[18] Shrivastava, S., Khalid, S., et al., (2024). "Impact of EV interfacing on peak-shelving and frequency regulation in a microgrid", *Scientific Reports*, 14(1), 31514.

[19] Panday, A. K., Tiwari, P., et al., (2025). "Review of AI-Based Modelling and Control Methods for Wind-PV-Battery Distributed Generation", *International Energy Journal*, 25.

[20] Brenna, M., Faranda, R., et al., (2009). "A new proposal for power quality and custom power improvement: OPEN UPQC", *IEEE Transactions on Power Delivery*, 24(4), 2107-2116.