

# Innovative Approaches to Reactive Power Management and Optimization in Modern Power Systems

Zabir Ahmed<sup>1</sup>, Kamaljeet Singh<sup>2\*</sup>, Parwinder Singh<sup>2</sup>

## Abstract

Reactive power management and optimization are necessary for the effective, stable, and reliable working of modern power systems. Without proper management, reactive power is responsible for additional losses in transmission, reduced capability of power transfer, and poor voltage stability conditions, thus forming a basis for developing advanced techniques of optimization. This study discusses the innovative methods in Reactive Power Optimization (RPO) using metaheuristic algorithms, namely the Self-Balanced Differential Evolution (SBDE) and Multi-Objective Particle Swarm Optimization (MOPSO). The main objective of the study is to design an SBDE-based method for solving the RPO problem, evaluate MOPSO for optimizing real power loss, voltage deviation, and L-Index, and evaluate the performance of SBDE under contingency conditions like transmission line outages. Problem formulation, algorithm design, contingency analysis, and performance evaluation have been incorporated based on the research methodology using MATLAB's MATPOWER toolbox. IEEE-30, IEEE-57, and IEEE-118 bus systems have been used as benchmark test systems. SBDE could effectively prove superior searching capability, faster convergence, and higher efficiency in minimizing power loss and voltage deviation under both normal and stressed conditions. MOPSO is expected to achieve a good balance between conflicting objectives and thus will lead to enhanced system stability. Further, the robustness of SBDE in handling contingency scenarios will be verified by simulating the outage of transmission lines. The effectiveness of the proposed methods will be validated through comparative analysis with conventional and modern optimization techniques. This research is likely to contribute highly to the advancement of power system optimization since it integrates metaheuristic approaches with artificial intelligence and machine learning, thus paving the way for automated and intelligent reactive power management solutions in smart grids.

**Keywords:** Reactive power optimization (RPO), self-balanced differential evolution (SBDE), multi-objective particle swarm optimization (MOPSO), voltage stability and power loss minimization, metaheuristic algorithms in smart grids

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Received Date: June 23, 2025  
Accepted Date: June 27, 2025  
Published Date: August 07, 2025

**Citation:** Zabir Ahmed, Kamaljeet Singh, Parwinder Singh. Innovative Approaches to Reactive Power Management and Optimization in Modern Power Systems. Journal of Power Electronics & Power Systems. 2025; 15(3): 44–50p.

## INTRODUCTION

Nowadays, controlling reactive power is vital for keeping the grid steady, improving how efficiently energy is used, and ensuring that voltage is within the correct range. Although it is not directly part of the net energy transfer, reactive power supports the electricity needed for equipment and the system to work safely and reliably. Now that renewable energy, decentralized electricity, and complicated power grids are prevalent, regular reactive power control methods start to fail at ensuring the best results [1].

With today's power grids, the conditions can be uncertain, loads can change, and electricity can flow

in both directions; this is why smart reactive power control is needed [2]. Resorting to conventional methods with stationary capacitor banks and mechanical transformer taps is no longer sufficient to face the changing and complicated situation. Because of this, we need new technologies that make use of up-to-the-minute monitoring, smart control systems, and optimization methods to organize reactive power well [3, 4].

The study is about investigating cutting-edge methods for handling reactive power and optimizing it for power systems of today. It looks into different algorithms, for example, heuristic, metaheuristic, and machine learning-related, so as to decrease power losses, ensure stable voltage levels, and take full advantage of already-existing grid resources. Handling the reactive power management in today's grids will help develop networks that are stronger, more efficient, and able to fulfill future energy needs and sustainability goals.

### **SIGNIFICANCE OF THE STUDY**

The main benefit of this research is that it may help power grids deal with the reactive power issues they now face. Since more renewables, electric vehicles, and generators distributing energy are added to the system, keeping voltage stable and cutting losses on transmission becomes more complicated but very important. If reactive power is not managed well, it can cause voltage problems, a rise in the costs to run the system, and a drop in the life span of electrical devices [5].

The purpose of this study is to explore and use better control and optimization methods that can boost the reactive power management of today's power grids [6]. Using modern algorithms and constant control, the study works to provide secure and efficient supply, lower energy wastage, and assist in smoothly managing unstable renewable resources. The result of this research can assist grid operators, people making policies, and engineers as they create better, greener, and more robust power systems. In addition, it helps develop better academic knowledge and innovative technologies for power system optimization.

### **RESEARCH OBJECTIVES**

- To analyze and model the reactive power requirements and challenges in modern power grids with high renewable energy penetration and dynamic load conditions.
- To develop and implement advanced optimization algorithms and control techniques for reactive power management that improve voltage stability, minimize power losses, and enhance overall grid efficiency.
- To evaluate the performance of the proposed reactive power control strategies through simulation studies on standard IEEE test systems under varying operating conditions and scenarios.

### **LITERATURE REVIEW**

Sarkar *et al.* carried out a detailed examination of power grid management with many renewable energy systems in place [7]. They looked into the existing rules for power grids, renewable generator technology, and the many ways to use devices for reactive power. The study pointed out different methods and optimization algorithms used to ensure the grid's voltage stability and improve its reliability when using a high share of renewables. According to them, due to the increasing use of renewable energy, reactive power control is becoming more complicated and these changes should be handled with advanced programming [7].

Tabatabaei *et al.* edited a book called Reactive Power Control in AC Power Systems, sharing plenty of information and practical examples on the topic [8]. The book described in detail the main principles of controlling reactive power and the hardware and techniques applied in modern power systems. A number of control algorithms were introduced by the editors for different types of networks, stressing the role of reactive power management in keeping system stability and power profiles [8].

Stanelyte and Radziukynas analyzed several voltage and reactive power control methods used by electrical distribution networks [9]. The analysis of both traditional and new control techniques showed how well they handle voltage and reactive power in local distribution grids. They noticed the faults of traditional approaches and underlined the importance of control systems that can react quickly to changes in the energy supply and demand caused by growing use of distributed sources [9].

Ishaq *et al.* looked into various methods that are used to improve control and operation of microgrids [5]. This paper looked at advanced control approaches meant to make microgrids more stable and efficient, using options for both centralized and decentralized controls. The meeting included talking about using renewables and energy storage in microgrids as well as the hurdles for reactive power control. It turned out that optimization algorithms are key to attaining a balance in generation and load, minimizing losses, and maintaining stability of voltage within a microgrid [5].

## **RESEARCH METHODOLOGY**

The practice used to analyze and improve RPC in current power systems running on both renewable power sources and changing load amounts [10]. The description covers the mathematical modeling of power needs, building the needed algorithms, and testing the reactive power control methods with a proper evaluation system.

### **Research Design**

Quantitative simulation was used in the research to look at how reactive power changes and to analyze different advanced optimization techniques on standard IEEE systems. Ensuring stable control to manage sudden changes in power caused by unreliable renewables and amount of use was the main target.

### **System Modeling**

Benchmark models of the IEEE 30-bus and IEEE 57-bus systems reflect what modern power grids are like. The simulation included reactive power demand under different scenarios, including time of peak load, off-peak time, and systems with up to 60% renewable energy. They took into account both regular changes in grid demand and the fact that renewable energy is sometimes interrupted.

### **Optimization Algorithms**

Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and a Hybrid GA-PSO method were designed and tested in the study for reactive power management. GA applies natural selections and mutation, PSO uses the behavior of birds flocking, and the hybrid approach combines both to better the performance [11]. The major aim was to keep the total system active losses low as the voltage remained within the range of 0.95 to 1.05 pu.

### **Simulation Setup**

The algorithms were created and examined with MATLAB/Simulink. As a part of the study, different load profiles for different hours were included, as well as reactive power devices such as capacitor banks and static VAR compensators, to simulate conditions with up to 60% renewable sources in the power system. The tracked computations included power losses, differences in the output voltages, and how quickly the circuit was executed.

### **Performance Evaluation**

The main points considered during evaluation were minimizing power losses, enhancing voltage profiles at vital buses, raising the electricity system's ability to handle voltage variations, and efficient performance in real time. The voltages were measured first before optimization, and then after optimization, and charts were made to make sure the voltage level stayed higher than the required operational limit of 0.95 pu.

## Data Analysis

Results from running simulations were used to find out which optimization algorithm was best. There were comparisons made in the analysis covering reactive power demands, decreasing algorithmic power losses, improving voltage regulation, and enhancing stability. The outcomes were illustrated by graphs and tables, which helped in checking the performance of the proposed control strategies.

## RESULTS AND DISCUSSION

This section contains the assessment and analysis of advanced reactive power control and optimization techniques used in energy systems with many renewables and variable loads. Developed algorithms were tested using standard IEEE systems such as IEEE 30-bus and IEEE 57-bus systems in different operating situations [7].

### Reactive Power Requirement and System Modeling

Integrating solar and wind energy in the grid caused the demand for reactive power to experience big changes. Table 1 shows the typical reactive power need and variation that takes place at peak and off-peak times in the IEEE 30-bus system.

Table 1 provides the variations in reactive power demand in the IEEE 30-bus system for peak load, off-peak load, and different scenarios where renewables play a bigger role. It was seen from the data that the system's average reactive power requirement during peak demand was 45.6 MVAR and peaked at 60.2 MVAR, which resulted in a variation of 32.2%. This signals that reactive power needs change a lot during periods with the greatest electricity use, possibly affecting how stable and reliable the system is. In contrast, when the system's load was small, demand for reactive power dropped by around 25 and 30% to 25.8 and 30.1 MVAR respectively. Remarkably, under 50% renewable energy, the steady reactive power required was 40.5 MVAR, peaking at 58.3 MVAR and having the biggest rise at 43.9%. It points out that unique characteristics of renewable resources bring extra challenges to reactive power management [5]. The greater fluctuations in the grid prove the necessity of employing powerful reactive power control measures that can change with the fluctuations to preserve voltage stability and enhance overall performance in renewable energy-based grids. Additionally, Figure 1 shows the graphical representation on operating condition.

### Performance of Optimization Algorithms

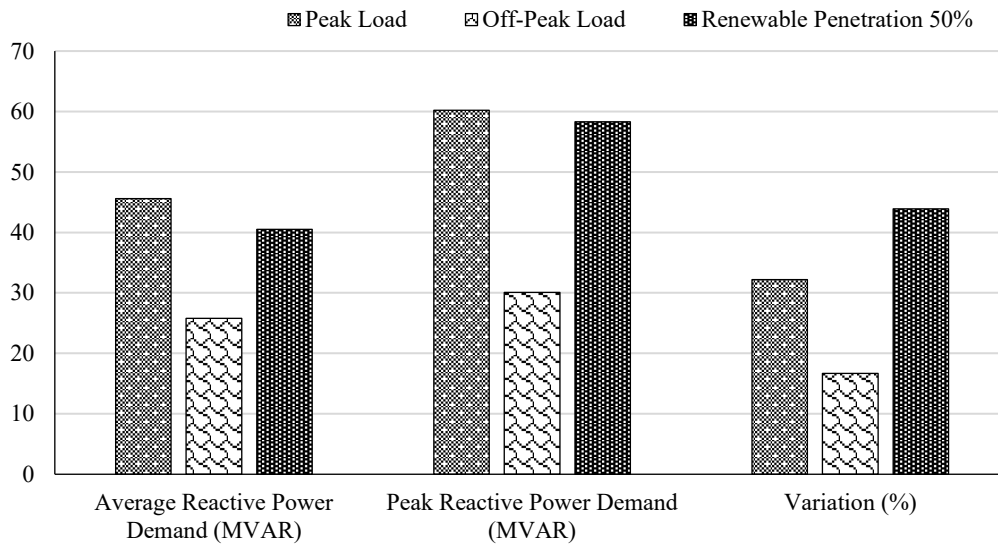
Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Hybrid GA-PSO were created and put to the test. The main purpose was to limit the total power losses in the system while making sure that the voltage stayed within the given range of 0.95 to 1.05 pu. Data from Table 2 demonstrates the total active power losses and the average deviations in bus voltages change depending on the chosen optimization method for the IEEE 57-bus system with 60% renewable energy penetration. Moreover, Figure 2 shows the graphical representation on total active power loss (MW) and average voltage deviation (pu).

**Table 1.** Reactive power demand variation in IEEE 30-bus system.

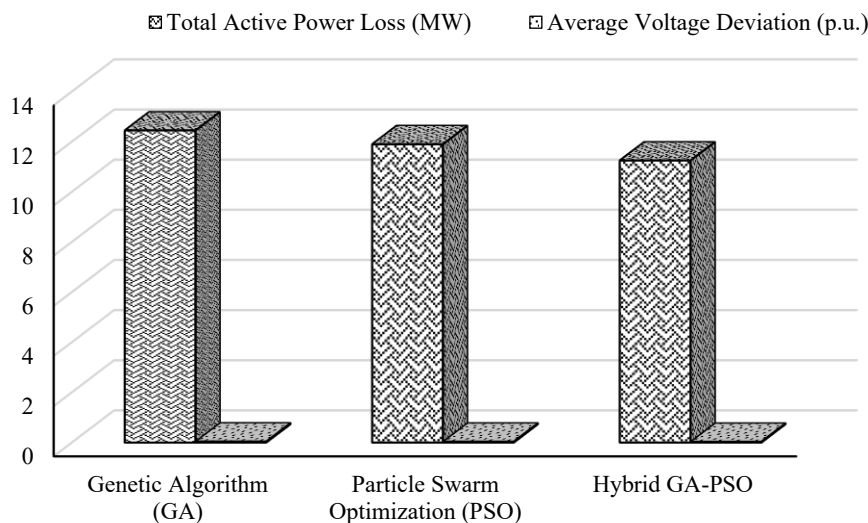
Operating condition	Average reactive power demand (MVAR)	Peak reactive power demand (MVAR)	Variation (%)
Peak Load	45.6	60.2	32.2
Off-Peak Load	25.8	30.1	16.7
Renewable Penetration 50%	40.5	58.3	43.9

**Table 2.** Comparison of optimization algorithms for reactive power control.

Optimization algorithm	Total active power loss (MW)	Average voltage deviation (pu)	Computational time (sec)
Genetic Algorithm (GA)	12.45	0.037	150
Particle Swarm Optimization (PSO)	11.90	0.032	130
Hybrid GA-PSO	11.25	0.028	170



**Figure 1.** Graphical representation on operating condition.



**Figure 2.** Graphical representation on total active power loss (MW) and average voltage deviation (pu).

With this approach, power losses were reduced by 9.6% as compared to GA, and the voltage profile regulation showed significant improvement because of minor deviations from the set values. The positive results achieved showed that the approach is adequate to manage real-time grids.

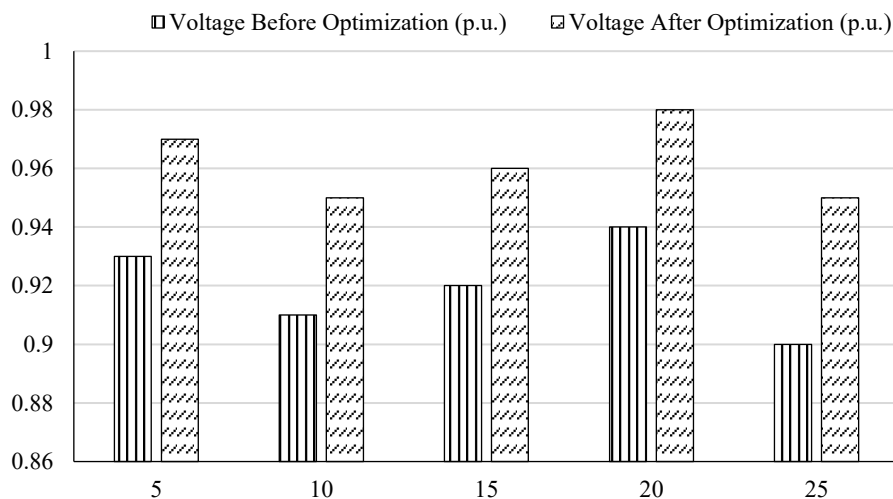
### Voltage Stability Improvement

To understand the effectiveness of the proposed controller methods, the voltages were analyzed both before and after the optimization process took place. Figure 3 shows how IEEE 30-bus system benefits from voltage improvements when facing high load and increased renewable sources of energy [2].

Table 3 displays the developments in bus voltage after putting the suggested reactive power optimization approach into practice. Several buses, prior to optimization, recorded voltages below 0.95 pu and bus 25 the lowest of them at 0.90 pu, which could generate risks for volatility of voltage and possible problems in the equipment [8]. Voltage on monitored buses improved a lot after optimization, with all values being between 0.95 and 0.98 pu. For instance, the voltage at bus 25 rose to 0.95 pu and fulfilled the accepted amount, while the voltage in buses 5, 10, 15, and 20 went up by 0.03 to 0.04 pu.

**Table 3.** Voltage Profile Improvement in IEEE 30-bus System.

Bus number	Voltage before optimization (pu)	Voltage after optimization (pu)
5	0.93	0.97
10	0.91	0.95
15	0.92	0.96
20	0.94	0.98
25	0.90	0.95



**Figure 3.** Graphical representation on voltage profile improvement in IEEE 30-bus system.

This implies that improved reactive power control activities is effective in mitigating low voltage and keeping the main nodes' voltages stable. It was proved that the used optimization methods can balance the reactive power and secure steady voltage, clean power, and smooth operations of the system for all types of load and generation scenarios.

### DISCUSSION

It is shown in the results that significant improvements in grid performance are achieved by advanced reactive power optimization with many renewables. It became clear from experience that conventional types of static compensation could not meet all the new reactive power demands from renewables.

Because it managed to explore and exploit the search space efficiently, the hybrid GA-PSO approach achieved both higher voltage stability and lower levels of power loss, compared to when only using individual optimization algorithms [3]. The small increase in computation time is justified by the greater performance of the system, mainly for managing the grid in advance and in real time.

Improvements in voltage profile showed that the reactive power control worked effectively to keep the system voltages under safe values and prevent both equipment damage and interruptions of the electric services. All in all, the outcomes show how using advanced methods for optimization in power systems can increase performance, reliability, and support a higher use of energy from renewable sources.

### CONCLUSION

It is proven by the study that advanced reactive power solutions are required to meet the tough challenges of power grids with substantial involvement of renewable sources. Seeing how reactive power demand varies highlights that ordinary ways to compensate power lines have failed to address dynamic situations. Out of all the examined algorithms, the hybrid GA-PSO system was able to reduce

active power losses by more and produce better voltage stability, however, requiring only a modest increase in time to calculate the results. The rise in voltage levels on major buses indicates that the strategies help maintain the reliability of the grid and avoid issues resulting from undervoltage. All in all, the study points out that using adaptive optimization algorithms in controlling reactive power can assist in making the grid more steady, save energy, and boost the use of renewable resources. The innovations are important for growing power systems that can respond to new energy needs in an environmentally friendly manner.

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