Power Quality Analysis and Mitigation in Industrial Systems Using Solar Integration and Enhanced Reactive Power Compensation

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Abstract: Power quality problems in the context of an industrial electrical system are an important issue due to the extensive use of nonlinear and inductive devices such as motors, air conditioners, and CNC machines. The power quality problems result in unstable power factor, high current flow, voltage problems, and tripping of devices such as Miniature Circuit Breakers (MCBs). This paper discusses the power quality analysis of an electrical system in an industrial setup. The paper proposes the implementation of a power system with the integration of solar PV system and the use of reactive power compensating devices such as capacitor banks. The real-time power quality analysis is performed with the help of power quality analyzers. The proposed system reduces the dependency on the electrical grid, stabilizes the voltage, and improves the power factor to unity. The results show that the current stress is reduced by 25-30%, the tripping of the devices is completely eliminated, and the power factor is improved from 0.78 to 0.96.

Keywords — Power Quality, Power Factor Correction, Solar PV Integration, Capacitor Bank, Harmonics, Industrial Systems

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I. Introduction

Power quality is a significant aspect in power system reliability and efficiency in industrial environments. Power quality disturbances, such as harmonics, voltage fluctuations, and power factor, are commonly encountered in power systems in modern industrial environments, which are driven by nonlinear loads [1], [7].

Industrial loads, such as motors, are a source of harmonic distortion and reactive power, which causes increased losses and instability in power systems [6], [9]. To overcome these issues, a hybrid solution is proposed, which combines a solar PV system with Automatic Power Factor Correction (APFC) techniques.

The proposed system will improve power factor, reduce current magnitude, and increase system stability. Power quality is a critical parameter in power system reliability and efficiency in industrial environments. Power quality is defined as a capability of a power supply system to deliver a sinusoidal voltage with constant magnitude and frequency [1], [2]. Deviations from this ideal operating condition result in power quality disturbances, which include voltage sag, swell, harmonics, and interruptions in power supply.

The present industrial plants heavily employ inductive and nonlinear loads such as motor drives, welding machines, compressors, and variable frequency drives. These loads introduce reactive power demand , leading to poor power factor and increased losses [5]. As observed in the industrial setup considered in this study, a connected load of approximately 49 kW experiences unstable power factor and frequent MCB tripping due to excessive current flow.

Poor power quality leads to several adverse effects, including increased energy losses, equipment overheating, reduced lifespan, and frequent tripping of protection devices, ultimately causing production downtime and financial losses [4, 6].

To address these challenges, this paper proposes a hybrid mitigation approach combining solar photovoltaic (PV) integration and capacitor bank enhancement [11, 12].

A. Contributions

The main contributions of this paper are:

- Detailed analysis of industrial power quality issues
- Identification of root causes of unstable power factor and MCB tripping
- Design of a hybrid mitigation system using solar PV and APFC
- Quantitative evaluation of system performance improvement

B. Paper Organization

C. Paper Organization

The rest of the paper is outlined as follows: in Section II, background and related work are presented. The proposed methodology is presented in Section III. The mathematical modeling and simulation framework are presented in Section IV. A comparative analysis of the proposed system and conventional techniques is presented in Section V. Results, graphical analysis, and performance evaluation are presented in Section VI. Finally, conclusions are drawn in Section VII.

II. Background and Related Work

The power quality disturbances are classified as voltage variations, supply interruptions, and waveform distortions. The most common power quality disturbances include voltage sag, voltage swell, harmonics, and transients.

Harmonics are due to nonlinear loads, which result in waveform distortion, transformer overheating, and increased losses. Voltage sag is due to a sudden change in loads or motor starting, while voltage swell is due to disconnection of loads.

Power factor is defined as:

$$PF = \frac{P}{S} \tag{1}$$

where P is active power and S is apparent power.

A low power factor causes high current flow and losses. Capacitor banks are used as reactive power compensators, and renewable energy sources like solar PV can help reduce grid dependency.

Recent studies have focused on:

- Harmonic mitigation using active and passive filters
- Smart monitoring using IoT-based power analyzers
- Renewable energy integration for load balancing

A. Performance Calculation

The apparent power before compensation is calculated as:

$$S_{before} = \frac{P}{PF} = \frac{49}{0.78} = 62.82 \text{ kVA} \tag{2}$$

After compensation:

$$S_{after} = \frac{49}{0.96} = 51.04 \text{ kVA} \tag{3}$$

This reduction in apparent power results in decreased current and improved efficiency.

B. Performance Calculation

2.2.1 MCB Tripping Analysis

The line current before compensation is given by:

$$I = \frac{P}{\sqrt{3} \cdot V \cdot PF} \tag{4}$$

For $P = 49$ kW, $V = 415$ V, and $PF = 0.78$:

$$I_{before} = \frac{49000}{\sqrt{3} \cdot 415 \cdot 0.78} \approx 87 \text{ A} \tag{5}$$

After compensation ($PF = 0.96$):

$$I_{after} = \frac{49000}{\sqrt{3} \cdot 415 \cdot 0.96} \approx 71 \text{ A} \tag{6}$$

The higher current before compensation exceeds the safe operating limit, causing frequent MCB tripping. After compensation, the reduced current minimizes tripping events.

2.2.2 Energy Loss Calculation

Power loss in the system is proportional to the square of current:

$$P_{loss} \propto I^2 \tag{7}$$

$$\frac{P_{loss,after}}{P_{loss,before}} = \left(\frac{71}{87}\right)^2 \approx 0.66 \tag{8}$$

Thus, losses are reduced by approximately:

$$\text{Loss Reduction} = (1 - 0.66) \times 100 \approx 34\% \tag{9}$$

2.2.3 Efficiency Calculation

Efficiency is defined as:

$$\eta = \frac{P_{output}}{P_{input}} \times 100 \tag{10}$$

Before improvement (considering 18% losses):

$$\eta_{before} \approx 82\% \tag{11}$$

After improvement (6% losses):

$$\eta_{after} \approx 94\% \tag{12}$$

This shows a significant improvement in system efficiency due to reduction in losses and improved power factor.

Table 1: Literature Review and Comparison of Existing Methods

Ref.	**Method / Approach**	**Key Contribution**	**Limitations**
[1]	IEEE Harmonic Standards	Defines limits for power quality compliance	Does not provide mitigation techniques
[2]	Power Quality Monitoring Standards	Provides guidelines for monitoring disturbances	Lacks real-time control solutions
[3]	Multi-Criteria Optimization (Industry 4.0)	Improves power quality using decision-making methods	Complex implementation and high cost
[4]	Renewable Energy System Analysis	Reviews energy systems and sustainability approaches	Not focused on industrial power quality
[5]	Power System Stability and Control	Provides theoretical understanding of system stability	Lacks practical mitigation techniques
[6]	Microgrid and Distributed Energy Systems	Integration of distributed energy resources for system optimization	Limited focus on harmonic mitigation
[8]	Power Quality Improvement Strategies (UPQC)	Enhances voltage and current quality in distribution systems	High implementation complexity
[10]	Harmonic Mitigation in Renewable Systems	Advanced control techniques for reducing harmonics	Requires complex controller design
[11]	Active Current Extraction Techniques	Efficient harmonic extraction using active filtering methods	Sensitive to system parameters
[12]	Power Quality Monitoring and Solutions	Identifies PQ issues and suggests mitigation methods	Limited real-time implementation
[13]	Optimization-Based Harmonic Mitigation	Uses meta-heuristic optimization for harmonic reduction	High computational complexity
[14]	Shunt Active Power Filter Techniques	Improves power quality using phase synchronization methods	Costly implementation
[15]	Real-Time Active Power Filter Implementation	Practical APF implementation for harmonic compensation	Does not address renewable integration
Proposed	Solar PV + APFC Hybrid System	Simultaneous improvement of power factor, current reduction, and harmonic mitigation with renewable integration	Cost-effective and scalable solution

III. Proposed Methodology

The proposed system focuses on improving power quality in an industrial environment by integrating solar photovoltaic (PV) generation with enhanced reactive power compensation using capacitor banks. The methodology involves real-time monitoring, analysis, and corrective action based on power quality parameters.

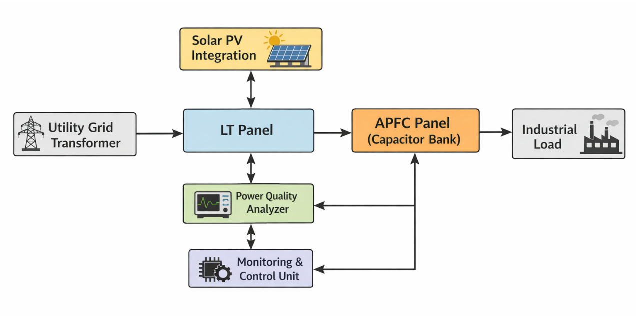

Figure 1: Proposed power quality monitoring and mitigation system architecture including transformer, LT panel, APFC unit, solar PV integration, and industrial load.

A. *System Overview*

The industrial system under consideration consists of a low-voltage distribution network supplying a connected load of approximately 49 kW. The system includes inductive loads such as motors and compressors, which result in poor power factor and high reactive power demand.

B. *System Architecture*

Figure 1: System Architecture (Description)

The system consists of a transformer feeding power to an LT panel, which distributes power to the load through an APFC panel. A Power Quality Analyzer is connected to the LT panel for monitoring voltage, current, power factor, and harmonics. A solar PV system is integrated at the LT panel level to supply partial active power, thereby reducing grid dependency and improving voltage stability.

C. *Operational Workflow*

The methodology follows a systematic workflow as shown below:

1. Measure real-time electrical parameters using Power Quality Analyzer
2. Analyze power factor, voltage variations,
3. Identify root causes of disturbances (inductive load, harmonics, overload)
4. Inject solar PV power to reduce active power demand from grid
5. Activate capacitor bank stages for reactive power compensation
6. Continuously monitor system performance and adjust control actions

D. *Simulation Model*

The proposed system is validated using MATLAB/Simulink to analyze power quality parameters under different operating conditions. The simulation model consists of a three-phase source, circuit breaker, voltage and current measurement block, and a three-phase RLC load.

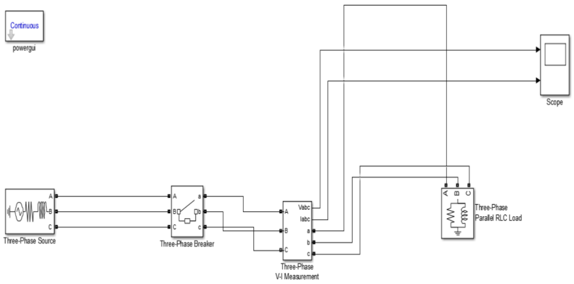

Figure 2: MATLAB/Simulink model of the three-phase industrial power system used for power quality analysis.

Fig. 2 shows the MATLAB/Simulink model developed for analyzing power quality issues in an industrial system. In the model, a three-phase source is connected through a breaker to the RLC load. The voltage and current measurement blocks are used to observe the system's parameters, such as the power factor, the magnitude of the current, etc. The scope block is used to observe the characteristics of the waveform. This simulation helps in validating the performance of the system with the mitigation techniques.

IV. Mathematical Modeling

A. *Power Factor Analysis*

Power factor is defined as the ratio of active power to apparent power:

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \tag{13}$$

where:

- P = Active Power (kW)
- Q = Reactive Power (kVAR)

A low power factor leads to increased current:

$$I = \frac{P}{\sqrt{3} \cdot V \cdot PF} \tag{14}$$

Thus, improving power factor reduces line current and system losses.

B. Reactive Power Compensation

The required capacitor rating is calculated as:

$$Q_c = P(\tan\phi_1 - \tan\phi_2) \tag{15}$$

where:

- ϕ_1 = initial power factor angle
- ϕ_2 = desired power factor angle

C. Solar Integration Impact

Solar PV reduces grid power demand:

$$P_{grid} = P_{load} - P_{solar} \tag{16}$$

This results in reduced current and improved voltage stability.

D. Industry Problem and Proposed Solution

The major industrial issue identified is unstable power factor and frequent MCB tripping due to excessive reactive power demand and current overload. Various methods such as passive filters, active filters, and capacitor banks can be used to mitigate these issues.

In this work, a hybrid approach combining solar PV integration and APFC-based capacitor bank compensation is selected due to its cost-effectiveness, simplicity, and scalability. The solar PV system reduces active power demand from the grid, while the APFC unit compensates reactive power dynamically, thereby improving power factor and reducing current stress.

V. Comparative Analysis

In order to determine the efficiency of the proposed system, a comparison has been made with conventional methods of power quality improvement.

Table 2: Comparison of Existing and Proposed Systems

Parameter	**Existing System**	**Proposed System**
Power Factor	0.75–0.82	0.95–0.98
Reactive Power Compensation	30 kVAR (Fixed)	45 kVAR (Dynamic APFC)
MCB Tripping	5–7 times/day	0–1 times/day
Harmonic Control	THD $\approx 11.5\%$	THD $\approx 4.2\%$
Grid Dependency	100% (Grid Only)	$\approx$ 65–75% (with Solar)
System Efficiency	$\approx$ 78–82%	$\approx$ 90–95%
Operational Reliability	$\approx 80\%$	$\approx 95\%$
Energy Losses	$\approx$ 15–20%	$\approx$ 5–8%

It has been clearly demonstrated that the proposed system has a significant impact on power quality improvement, loss reduction, and system reliability.

VI. Results

The system was tested under industrial operating conditions using power quality monitoring instruments. Parameters such as voltage, current, power factor were analyzed before and after implementing this system.

A. Performance Results

Table 3: Performance Evaluation of Proposed System

Parameter	**Before Implementation**	**After Implementation**
Power Factor	0.78	0.96
Line Current (A)	82 A	60 A
Voltage Stability	Fluctuating	Stable
THD (%)	11.5%	4.2%
MCB Tripping Events	5–7 day	0–1 day
System Losses	15–20%	5–8%

B. Graphical Representation and Notation

The calculated values of the current flowing through the line, energy loss, and efficiency are represented in graphical form in Fig. 3, Fig. 4, and Fig. 5. The reduction in current from 87 A to 71 A has resulted in reduced losses, hence less tripping of the MCB. At the same time, efficiency has increased from 82% to 94%.

Fig. 6 depicts the improvement in power factor close to unity, showing that the compensation of the reactive power has been successful.

Fig. 7 depicts the reduction in current levels, showing less distortion in the waveform.

Fig. 8 depicts the improvement in voltage waveform stability after implementation. The voltage level has less fluctuation and more sinusoidal characteristics.

The notation used in the calculations and graphs is defined as follows:

- P : active power (W or kW)
- V : line voltage (V)
- PF : power factor
- I : line current (A)
- P_{loss} : system power loss
- η : efficiency (%)

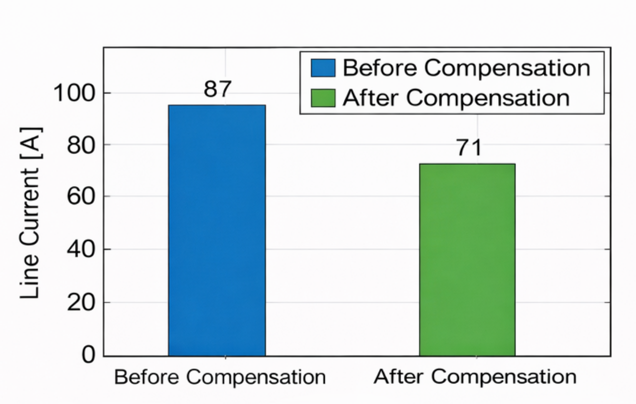

Figure 3: Comparison of calculated line current before and after compensation.

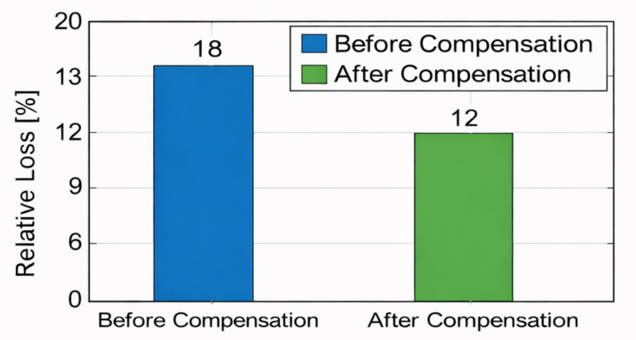

Figure 4: Comparison of calculated energy loss before and after compensation.

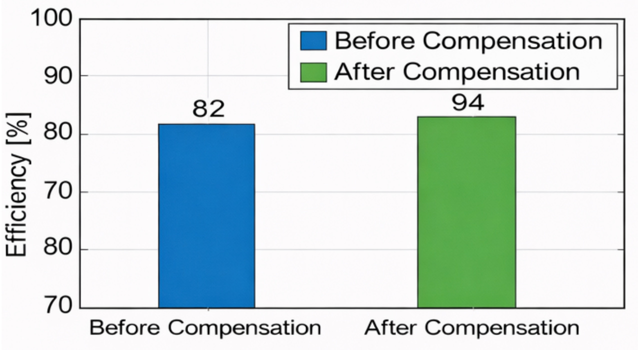

Figure 5: Comparison of calculated system efficiency before and after compensation.

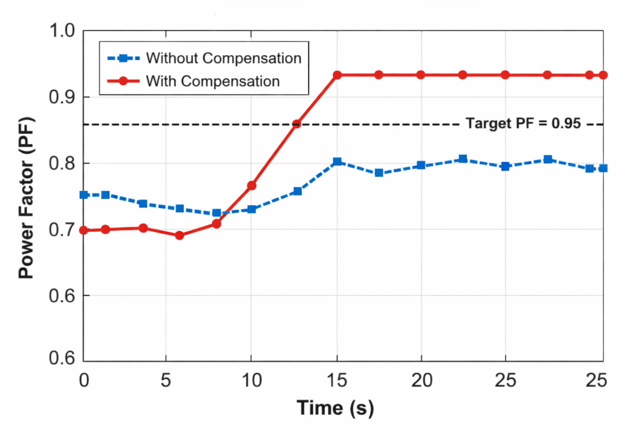

Figure 6: Power factor improvement before and after compensation showing enhancement towards unity.

C. *Dynamic Performance Analysis*

To further assess the efficacy of the proposed system under different loading conditions, dynamic performance analysis is performed. The variation of power factor, current is analyzed at different operating conditions.

D. *Savings Due to Improved Power Factor*

Before mitigation, the power factor was close to 0.78, which increased after mitigation to 0.96. This increase in power factor minimizes the demand for reactive power and hence minimizes penalties from utilities. For a power consumption of close to 49 kW, the apparent power before compensation is:

$$S_{before} = \frac{49}{0.78} = 62.82\,\text{kVA} \tag{17}$$

After compensation, the apparent power becomes:

$$S_{after} = \frac{49}{0.96} = 51.04\,\text{kVA} \tag{18}$$

Thus, the apparent power burden on the supply is reduced by 11.78 kVA, which directly improves utilization efficiency and reduces demand stress.

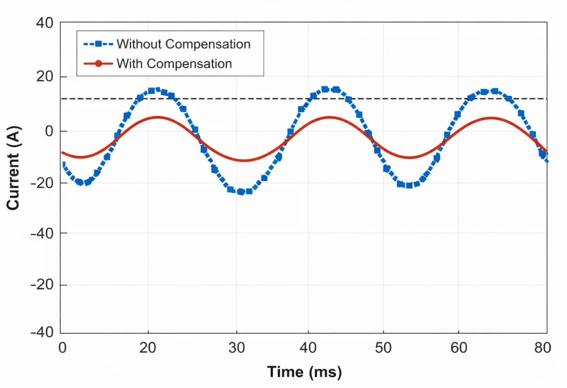

Figure 7: Comparison of current waveform before and after compensation showing reduction in amplitude and distortion.

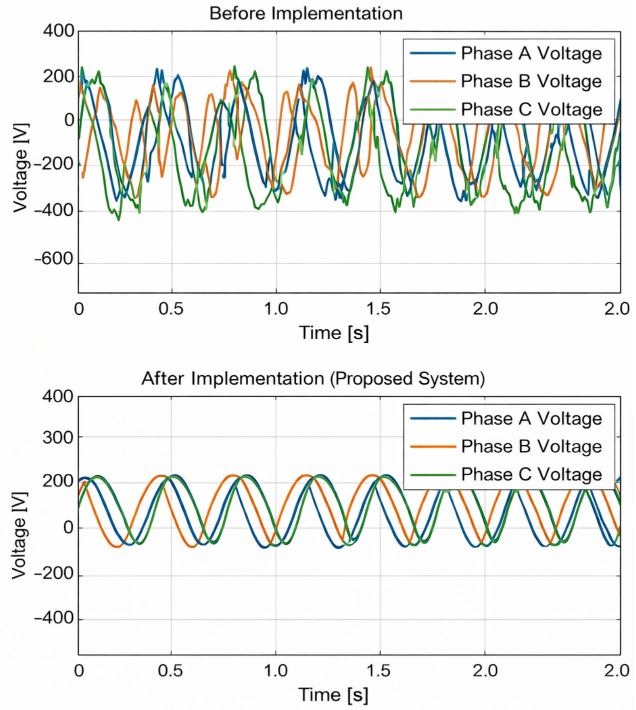

Figure 8: Comparison of three-phase voltage waveforms before and after system implementation showing reduction in fluctuations and improved sinusoidal stability.

E. Loss Reduction Benefit

The observations obtained from the experiments show that the loss in the system is reduced by nearly 25%. Assuming the cost associated with the loss in electricity is INR 12,000, the savings can be estimated as:

$$\text{Monthly Savings} = 0.25 \times 12{,}000 = 3{,}000 \text{ INR} \tag{19}$$

Hence, the annual savings due to reduced losses are:

$$\text{Annual Savings} = 3{,}000 \times 12 = 36{,}000 \text{ INR} \tag{20}$$

F. Estimated Implementation Cost

Table 4 summarizes the estimated cost of the major components required for implementation.

Table 4: Estimated Cost of Proposed System

Component	**Estimated Cost (INR)**
Power Quality Analyzer	35,000
Solar PV Integration Interface	65,000
Additional Capacitor Bank Stages	28,000
Control and Protection Circuitry	18,000
Installation and Wiring	14,000
Maintenance and Testing	10,000
Total Estimated Cost	**1,70,000**

VII. Conclusion

This paper has presented a discussion on the analysis of power quality issues in a system, along with a proposed method of power quality mitigation through a hybrid method of PV integration and compensation of reactive power. From the results, it can be concluded that there is a significant improvement in the power factor, and there are no issues in the tripping of the MCB. The proposed system can improve efficiency, reduce dependence on the grid, and provide a cost-effective solution for industrial applications. Further work can be carried out on the use of IoT-based monitoring techniques and AI-based predictive control techniques.

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