

## **Improving power factor by using Capacitor Bank**

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**Abstract** - The present research paper examines the design and application of Capacitor Banks as a major technique to enhance Power Factor (PF) of electrical systems. The introduction of inductive loads in the contemporary industrial environment (induction motors and transformers) causes lagging power factor, which causes higher transmission losses, voltage instability, and high utility penalties. The paper is about the use of fixed compensation to Automatic Power Factor Correction (APFC) systems, which use microcontroller-based logic to actively switch capacitor steps with regards to real-time changes in load. The proposed system is able to reduce source demand, minimise the heating losses of  $I^2R$ , as well as improve the overall distribution network efficiency by offering localised reactive power compensation. The process involves mathematical modelling of reactive power requirements, simulation and hardware testing. Experiments show that the power factor of optimized capacitor bank integration can be substantially increased compared to a typical lagging value (e.g., 0.75) to nearly unity (0.98-0.99). Moreover, the paper touches upon the critical operational aspects, such as harmonic resonance and switching transient, and gives a holistic framework of the attainment of a more stable and cost-effective electrical infrastructure.

**Keywords**- Power Factor correction (PFC), Capacitor Banks, Reactive Power, APFC, Electrical Efficiency, Energy Conservation.

### **1.INTRODUCTION**

Power Factor (PF) is of great importance in determining the efficiency of power transmission and distribution in modern electrical power systems. Inductive loads are mostly seen in industrial and commercial loads like induction motors, transformers and fluorescent lighting. Such loads need two kinds of power: Active Power (kW), which does the real work and Reactive Power (kVAR), which is needed to keep the electromagnetic fields needed to make the equipment run.

#### 1.1 The Concept of Power Factor

The ratio of the real power (P) to the total apparent power (S) flowing in the circuit is called the Power Factor.

The low power factor implies that a lot of reactive power is being taken off the grid. This causes various technical and economic inefficiencies such as the elevation of line currents, augmentation of the losses of the  $I^2R$  and substantial voltage drops across the distribution network.

#### 1.2 The Problem of Low Power Factor

A low power factor (usually less than 0.8 lagging) results in the utility provider having to deliver higher current in order to sustain the same real power load. This places an undue strain on the infrastructure resulting in:

- Transformers and Switchgear overloading: Increased current decreases the capacity of the existing equipment.
- Voltage Instability: Voltage drops are higher with increased current, and this could impact the operation of delicate industrial equipment.
- Economic Penalties: Utility companies commonly charge industrial consumers "Power Factor Penalties" to offset the inefficiency that they add to the grid.

#### 1.3 Capacitor Banks as a Solution

Shunt Capacitor Banks are installed to alleviate these problems. Capacitors provide a local reactive power (leading kVAR), which effectively cancels the inductive reactive power (lagging kVAR) that is needed by the load. This reactive power is locally available and therefore, the load on the source is minimized, the power factor is brought close to unity and the efficiency of the system in total is increased.

#### 1.4 Research Objectives

This study will focus on analyzing how capacitor banks are designed, implemented, and perform in enhancing power factor. This paper explores:

- The power factor correction mathematical modelling.

- Introduction of Automatic Power Factor Correction (APFC) systems to deal with variable loads.
- The effectiveness of capacitor banks on energy saving and voltage stability.
- The issues relating to switching capacitors, including inrush currents and possible harmonic resonance.

- Fuzzy Logic and AI: New studies discussed the application of Fuzzy Logic to manage nonlinear changes in loads more incrementally than traditional binary switching, which reduces mechanical wear of relays (Selvan et al., 2014).

## 2. LITERATURE REVIEW

The Literature Review gives you the academic and technical background of your research. It must show how the discipline has developed over time through manual process to the present state-of-the-art Automatic Power Factor Correction (APFC) systems.

Reactive power management has been the focus of research in electrical engineering many decades. This review classifies the development of Power Factor (PF) correction techniques and the issues that are tackled by the current researchers.

### 2.1 The development of Correction Manual to Correction Automatic.

Traditionally, improvement of power factor was accomplished by manually switching the banks of the static capacitors. Nevertheless, according to researchers, manual methods cannot be effectively used with fluctuating industrial loads due to the frequent occurrence of under-compensation (resulting in utility penalties) or over-compensation (leading to leading power factor and voltage swells) (ECCE, 2023).

A major step was to go to Automatic Power Factor Correction (APFC) systems. Early APFC systems used discrete logic gates, and modern systems have switched to microcontroller-based (e.g., 8051, PIC or Arduino) and PLC-based controllers (IRJIET, 2024). ZeroCrossing Detection (ZCD) is used in these systems to measure the phase difference between voltage and current in real-time, enabling a high level of precision when switching on the capacitor bank (IRJIET, 2024).

### 2.2 Control Algorithms and Efficiency.

- PI Controllers: Studies by Xue et al. (2019) and other modern researchers have shown that Proportional-Integral (PI) controllers in APFC units can greatly decrease the time spent adjusting the power factor, increasing the efficiency of inductive loads such as induction motors (ECCE, 2023).

### 2.3 Problems: Switching Transients and Harmonics.

- Transients: Transients are large spikes of voltages and currents caused by switching capacitor banks (JREE, 2025). Otherwise, these transients may cause damage to sensitive electronic equipment and deteriorate the insulation of motors (JREE, 2025).
- Harmonic Resonance: Capacitor banks can cause harmonic resonance in modern industrial settings full of Power Electronic equipment (VFDs, rectifiers) (IEEE Xplore, 2018). Studies indicate that detuned reactors or harmonic filters, together with capacitor banks are required to avoid amplification of harmonic currents, otherwise capacitors may fail (NEPSI, 2013).

### 2.4 Technical Feasibility and Accuracy

In 2024, Jayabarathi et al. confirmed the technical viability of capacitor banks as both a reactive power compensation and slight harmonic reduction tool (IJEC, 2026). Nevertheless, they observed that the performance of these systems significantly relies on the precision of the sizing, and the resolution of the capacitor steps in use (IJEC, 2026). Mis-sizing remains one of the most common reasons that cost facilities thousands of dollars in utility fines each year (Power Grid, 2025).

## 3. Simulation and Results

To assess the effects of shunt capacitance on a three-phase distribution system, the simulation was carried out with the help of MATLAB/Simulink (IURESMS, 2019). The model is composed of an 11kV source, which is stepped down to 415 V, providing an inductive load of 10kW and 5kVAR.

### 3.1 Simulation Scenarios

- Uncompensated Inductive Load: The initial simulation scenario involved only the 10kW + 5kVAR load connected. The reactive power was lagging, which resulted in a huge shift in phase between the voltage and current.

- **Compensated Load:** A Capacitive Load bank was paralleled with the existing inductive load. The capacitor supplies leading reactive power, part of which cancels the lagging reactive power of the inductor.

### 3.2 Before Connecting the Capacitor Bank

When the system is linked to only the 10kW and 5kVAR load, it is said to be an Inductive Load scenario.

- **Reactive Power Demand:** Inductive loads (such as motors or transformers) use reactive power to generate magnetic fields including inductive loads (motors, transformers, etc.). This power swings between the source and the load without being consumed
- **Phase Lag:** The voltage is in phase with the current. This forms an increased Apparent Power (S) of all the power that must be provided by the grid
- **Low Efficiency:** With such a power factor (0.8944 in your simulation) the system is drawing more current than is necessary to do the same amount of work (Active Power, P).

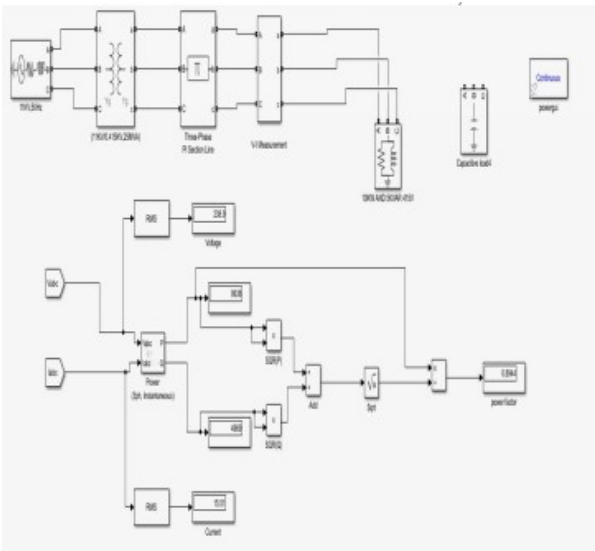


FIGURE 1. Before Connecting the Capacitor Bank

### 3.3 After Connecting the Capacitor Bank

When you introduce the Capacitive Load in parallel, you are performing Power Factor Correction (PFC).

**Reactive Power Compensation:** Capacitors provide "leading" reactive power. This effectively "supplies" the

reactive power that the inductor needs locally. Instead of the 5kVAR coming all the way from the 11kV source, the capacitor provides a portion of it.

- **Resultant Reactive Power:** The net reactive power seen by the source is reduced ( $Q_{new} = Q_{\{L\}} - Q_{\{C\}}$ ). In your simulation, this dropped the reactive power from 4969 VAR to 3501 VAR.

**Phase Alignment:** As the net reactive power decreases, the phase angle ( $\theta$ ) between the voltage and current decreases.

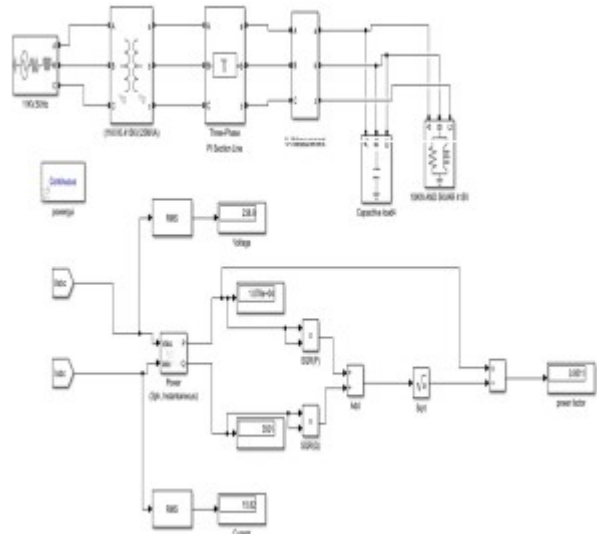


FIGURE 2. After Connecting the Capacitor Bank

### 3.4 Comparative Analysis

The following table summarizes the system parameters captured from the "Before" (uncompensated) and "After" (compensated) simulation displays.

Parameter	Before Compensation	After Compensation	Change / Impact
Power Factor (PF)	0.8944	0.9511	Improved by ~6.3%
Line Current (RMS)	15.51 A	15.82 A	Slight increase*
Active Power (P)	9938 W	10780 W	Increased
Reactive Power (Q)	4969 VAR	3501 VAR	Decreased by ~1468 VAR
Line Voltage (RMS)	238.9 V	238.9 V	Maintained constant

- inefficiency results in increased electricity bills because of kVA demand charges, and causes thermal stress of the 415 V distribution bus.

#### 4.1 The Practical Solution: Automatic Power Factor

##### Correction (APFC)

The solution to this is to install an APFC Panel (represented by the Capacitive load block in your model) connected in parallel to the main 415 V bus.

1. Implementation: The APFC panel is used to check the phase angle between the voltage and current. It activates certain steps of capacitor banks to generate leading reactive power, when it detects a lagging power factor.
2. Performance Results: By switching the capacitor bank, the system will accomplish the following observed in the simulation.
  - Reactive Power Offset: The reactive power requirement of the utility decreases by the difference between 4969 VAR and 3501 VAR since capacitors supply the difference locally.
  - Efficiency Gain: The overall system Power Factor is improved to 0.9511, which is above the typical utility penalty threshold (usually 0.90 or 0.92).
  - Voltage Regulation: The line voltage is maintained constant at 238.9 V and therefore the sensitive control electronics on the molding machines are not subjected to any voltage variations.

#### 4.2 Final Outcome

The solution is effective in optimizing the electrical network. The active power (P) raise to 10,780 W in this particular simulation, but the decrease in the reactive component (Q) means that the transformer will work much more efficiently to ensure that the go-round does not overheat and avoids the extra charge of Low Power Factor on the monthly utility bill.

## 5. Applications

The simulation model is an original electrical engineering solution to improving power quality. The system provides a solution to a number of critical industrial and commercial

requirements by incorporating a parallel capacitor bank with an inductive load.

### 5.1 Industrial Load Management

The main use of this model is in facilities where large inductive machines are used, including motors, pumps and compressors.

- Motor Control Centers: These systems are used in many industrial plants to counter the lagging power factor of induction motors.
- HVAC Systems: Capacitor banks are used in largescale commercial buildings to compensate the inductive reactance of chiller and fan motors.
- Pumping Stations: This model is used in municipal water treatment plants in /order to lower the reactive power requirement of high capacity water pumps.

### 5.2 Distribution Network Efficiency

Utility companies and electrical engineers use this model to optimize a distribution network, like the 11kV/415 V transformer configuration in your pictures.

- Transformer Stress Reduction: The transformer needs to provide less reactive current, which lowers internal heating and eliminates overloading.
- Line Loss Mitigation: When the power factor is improved, the total current flowing through the transmission lines (PI sections) is significantly reduced which also greatly reduces copper losses through the grid caused by the current flowing through the transmission lines (PI sections).
- Voltage Regulation: The model depicts the problem of reactive compensation that is used to maintain a constant line voltage (238.9 V) along

with avoiding voltage drops at the end of long distribution lines.

### 5.3 Economic and Regulatory Compliance

The practical applications of this model in the real world can be regarded as a direct instrument of cost management.

- Avoidance of Utility Penalties: Most electricity companies impose additional charges on a consumer whose power factor is under a specified level (typically 0.90 or 0.95).
- Energy Conservation: The industrial consumers can reduce their overall energy use and environmental impact by making the system more efficient.

#### 5.4 Smart Grid and APFC Panels

The reason behind this simulation is the main algorithm of Automatic Power Factor Correction (APFC) panels.

- **Dynamic Compensation:** Dynamic compensation is used in real-time applications where sensors detect the phase shift (as in your "power factor" display block) and automatically step capacitors in or out to achieve the desired efficiency.
- **Model-Based Design:** This particular MATLAB/Simulink setup is used by the engineers to test and verify the capacitor bank sizing before it is actually installed into a factory or a substation.

#### 6. Key Performance Observations

- **Power Factor Optimization:** The primary objective was achieved as the power factor shifted from 0.8944 to a much healthier 0.9511. This brings the system closer to unity, indicating more efficient power utilization
- **Reactive Power Compensation:** The reactive power demand on the source dropped significantly from 4969 VAR to 3501 VAR. This confirms that the "Capacitive load" block is successfully supplying the leading kVAR required to cancel out a portion of the inductive lagging Kvar.
- **System Stability:** The RMS Voltage remained perfectly constant at 238.9 V across both scenarios. This indicates that the 25MVA transformer and the distribution line maintained steady regulation despite the change in load characteristics.
- **Current Dynamics:** Interestingly, the line current increased slightly from 15.51 A to 15.82 A. This is attributed to the simultaneous rise in active power (SPS) in this specific model setup, which outweighed the reduction in reactive current component.

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