International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
SJIF (2024): 6.623

Design and Implementation of an Automated Power Factor Correction System Using Capacitor Banks

Supriya Jamdar

[1]Department of Electrical Engineering, AISSMS Institute of Information Technology, Pune, India
Email: *s.jamdar911[at]gmail.com*

Abstract: ***In alternating current (AC) power systems, the effective utilization of electrical energy is directly dependent on the power factor of the system. Low power factor, normally due to inductive loads like motors, transformers, and lighting ballasts, causes high demand for current, which translates into high losses in transmission and distribution lines, voltage drops, low system capacity, and increased electricity bills. To overcome these challenges, the current paper discusses the design, development, and verification of an automatic power factor correction (APFC) system with a microcontroller-based controller unit and a step wise capacitor bank. The system detects real-time voltage and current waveforms via sensing circuits and calculates the phase angle difference to decide the power factor. According to the measured power factor, the microcontroller dynamically switches on or off capacitors to provide the necessary leading reactive power, thus compensating the lagging component caused by inductive loads. The system is implemented using low-cost, easily available components such as a current transformer (CT), potential transformer (PT), zero-crossing detectors, a relay module, and a bank of shunt capacitors. Simulation and experimental confirmation were carried out under different loading conditions to test system performance. The findings exhibit a notable increase in power factor-from levels as low as 0.72 to as high as 0.97-along with line current reduction and improved power quality. Economic assessment also shows substantial annual savings and a brief payback period on investment. The ease, scalability, and efficiency of the system render it appropriate for residential, commercial, and small-scale industrial applications, leading to more sustainable energy consumption habits.***

Keywords: Power Factor Correction, Capacitor Bank, Re active Power, Microcontroller, Power Quality, Energy Efficiency, Inductive Load Compensation, Automated Control

1. Introduction

The growing need for electrical power in industrial, commercial, and household sectors has brought about a sharper need for economical utilization of power. Of all the indicators of system performance, the power factor (PF) is an important one to judge how efficiently the electrical power is being converted to useful work. Low power factor results in a higher flow of current, high transmission losses, bad voltage regulation, and a higher cost of energy, especially in systems comprising mainly inductive loads [1]. Inductive devices like induction motors, transformers, air conditioners, and ballasts for lighting result in voltage and current waveforms lag, producing a lagging power factor. This inductive component, while necessary for establishing magnetic fields in inductive loads, delivers no real work and loads the distribution network [2]. To have energy efficiency and a sure system operation, keeping the power factor near unity is important. Power factor correction (PFC) is a popular solution to address these challenges. By providing leading reactive power from capacitor banks, the total reactive demand from the supply is decreased, thus reducing losses and enhancing voltage profiles. Conventional PFC systems employ fixed capacitors or manual switches, which are not adaptive to dynamic load changes [3]. Recent developments have resulted in the de sign of automated power factor correction (APFC) systems that dynamically track and control reactive compensation in real time. Microcontroller-based systems, such as those incorporating Arduino or PIC controllers, provide an effective and economical platform for such control strategies to be implemented [4], [5]. These systems determine the phase angle between current and voltage, compute the power factor, and energize capacitor banks as necessary to keep the desired PF level, usually above 0.95 [1], [6].

Additionally, intelligent APFC systems have been suggested for industrial use based on sensor inputs, zero-crossing detection, and relay modules to switch capacitors based on real-time needs [2], [4]. In certain advanced configurations, simulation software such as MATLAB/Simulink or ERACS is employed to simulate complex load profiles and optimize capacitor placement and switching [5]. This article describes the design and development of an automatic power factor correction system based on a microcontroller-driven capacitor bank. The developed system is able to monitor and compensate in real time, providing robust and efficient power factor correction under different load conditions. It uses low-cost hardware, easy-to-implement algorithmic control, and established compensation strategies to achieve scalable and efficient energy saving in power systems.

2. Theoretical Background

Power factor (PF) is an electrical engineering's essential parameter characterizing the efficiency with which electric power is being transformed into useful work output. Power factor is determined as a ratio of real power (P), in units of kilowatts (kW), to apparent power (S), in units of kilovolt amperes (kVA):

$$PF = \frac{P}{S} = \cos(\phi) \quad (1)$$

where ϕ is the angle of phase difference between the waveforms of current and voltage. In resistive loads, the current and voltage are in the same phase and the power factor is 1.0 (unity). In inductive and capacitive loads, the current lags and leads the voltage, respectively, decreasing the PF and thus enhancing the reactive power (Q) component.

The total apparent power (S) in an AC circuit is composed of real power (P) and reactive power (Q), represented by the power triangle:

$$S^2 = P^2 + Q^2 \quad (2)$$

Reactive power is essential for the operation of magnetic devices, but it does not perform any real work. Excessive reactive power leads to higher current flow in the distribution system, resulting in increased I2R losses, overheating of components, and reduced system capacity [2].

To correct a low power factor, reactive power compensation is introduced using capacitors, which supply leading reactive power. This counteracts the lagging reactive power of inductive loads and reduces the overall reactive demand from the source. The amount of reactive power (Qc) required from a capacitor to improve the PF from an initial value of cos(ϕ1) to a desired value of cos(ϕ2) is given by:

$$Qc = P.(\tan(\phi 1) - \tan(\phi 2)) \quad (3)$$

Once the required reactive power is known, the capacitance needed can be calculated using:

$$C = \frac{Qc}{2\pi f V^2} \quad (4)$$

where:
- C is the capacitance in farads (F),
- f is the supply frequency (typically 50 or 60 Hz),
- V is the RMS line voltage.

In real-world applications, capacitor banks are designed in discrete steps (e.g., 10kVAR, 20kVAR, etc.) and switched in or out of the circuit according to real-time power factor measurements. Automation of this switching is essential to maintaining an optimal PF under varying load conditions [3]. Current research indicates that microcontroller-based automatic systems can accurately monitor the phase difference between current and voltage and switch capacitors accordingly, providing a cost-effective and scalable method for real-time compensation [1], [4]. Further, industrial simulation packages like ERACS and MATLAB/Simulink have been utilized to simulate power systems and identify optimal capacitor placements and sizes [5]. The integration of dispersed energy sources such as solar PV with conventional capacitor banks has also been seen to have potential in further enhancing the power quality and minimizing reliance on the grid for reactive power support [6].

3. Methodology

The suggested power factor correction system utilizes a microcontroller-controlled capacitor bank to monitor and correct the power factor in real time. Sensing the electrical parameters, determining the power factor, and dynamic switching of capacitor banks to supply the necessary reactive power are steps involved in this methodology. This entire process is described in this section.

3.1 System Overview

The system is composed of the following key components:
- **Voltage and Current Sensing:** A potential transformer (PT) steps down the line voltage, while a current transformer (CT) samples the line current.
- **Zero-Crossing Detection:** Voltage and current signals are passed through zero-crossing detectors to determine the phase angle difference.
- **Microcontroller Unit:** An Arduino Uno is used to compute the power factor by analyzing the time delay between voltage and current zero crossings.
- **Capacitor Bank:** A multi-stage bank of shunt capacitors (e.g., 10 µF, 20 µF, 40 µF, 80 µF) is used to supply leading reactive power.
- **Relay Module:** A 4-channel relay driver enables or disables specific capacitor combinations based on real time PF measurements.
- **Display Unit:** A 20×4 I2C LCD displays the calculated power factor and status of the capacitor bank.

3.2 Operating Algorithm

Control algorithm of the system is as below:
1) Measure voltage and current waveforms with PT and CT.
2) Determine zero-crossing points of voltage and current signals.
3) Find phase angle ϕ between the signals.
4) Calculate power factor using PF = cos(ϕ).
5) Measure the power factor and compare with the reference threshold (usually 0.95).
6) Calculate the required reactive power by:

$$Qc = P.(\tan(\phi 1) - \tan(\phi 2)) \quad (5)$$

7) Operate the needed set of capacitor banks by means of relays.
8) Repeat the process continuously for dynamic compensation.

3.3 Capacitor Sizing

In order to provide proper correction under varying load conditions, the capacitors are chosen in binary-weighted steps (e.g., 10 µF, 20 µF, 40 µF, etc.). The controller can create multiple combinations to provide the desired kVAR compensation. The switching logic is programmed according to the range of the power factor:
- If PF ≥0.95, no compensation is applied.
- If 0.90 ≤ PF < 0.95, one or more capacitors are activated.
- If PF < 0.90, maximum available capacitance is engaged.

3.4 Block Diagram Description

The system block diagram is designed as follows:
1) Input AC power is provided to load and CT/PT sensors.
2) Current and voltage signals are directed to zero-crossing detector circuits.
3) XOR gate output pulse is transferred to Arduino to calculate the time difference.
4) The Arduino computes PF and switches the necessary relay(s).

5) The capacitor bank provides the necessary leading reactive power to the system.

This approach guarantees that the system automatically compensates for fluctuating load conditions, compensates in real time, and keeps the power factor near unity.

4. System Design and Implementation

The suggested power factor correction system is constructed from low-cost and readily available components. It is intended to monitor the power factor in real time, examine changes in the load, and engage suitable capacitor bank stages accordingly.

4.1 Hardware Components

The hardware implementation includes the following components:

- **Arduino Uno:** Serves as the central control unit to process input signals and manage the relay switching logic.
- **Current Transformer (CT):** Monitors the current consumed by the load and delivers a scaled output to the Arduino.
- **Potential Transformer (PT):** Reduces the line voltage to a measurable level for the microcontroller.
- **Zero-Crossing Detector Circuit:** Constructed from LM741 op-amps, 1N751A Zener diodes, and resistors to sense the zero crossing points of current and voltage signals.
- **XOR Gate (SN74HC86N):** Compares voltage and current square waves to generate a pulse width that is proportional to the phase difference.
- **Relay Module:** 4-channel relay module employed for switching various stages of capacitors based on the control signals provided by the Arduino.
- **Capacitor Bank:** 10 µF, 20 µF, 40 µF, and 80 µF capacitors for multi-staged compensation.
- **Display Unit:** A 20×4 LCD with I textsuperscript2C interface for showing the real-time power factor and system status.
- **Load Bank:** Made up of resistive loads (bulbs) and inductive loads (chokes or motors) in order to mimic real world fluctuations.

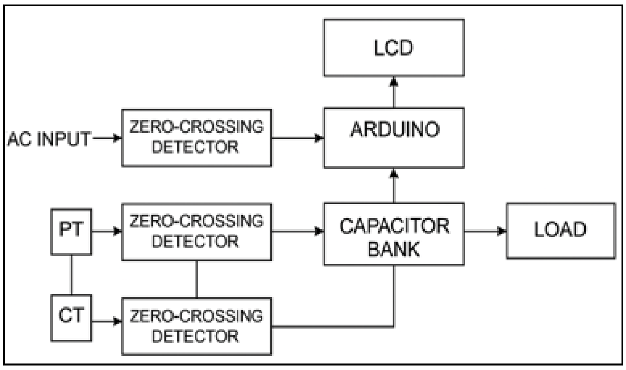

Figure 1: Block Diagram

4.2 Software and Control Logic

The Arduino Uno is coded using the Arduino IDE in embedded C. The microcontroller:

- Detects the time delay between voltage and current zero crossings through interrupt routines.
- Computes the phase angle ϕ and then computes the power factor by using the cosine function.
- Compares the computed power factor against the predefined threshold (e.g., 0.95).
- Depending on the deviation, trigger one or more capacitors through relay outputs.

4.3 Working Example

When the inductive load is applied, the voltage and current waveforms lag, and this is picked up by the system. Arduino gets square pulses from the XOR gate and checks the time lag. It calculates the power factor and phase angle. If PF falls below a certain level, the Arduino toggles the capacitor stages sequentially to improve the PF. For example, when power factor decreases to 0.72, the system will drive 40 µF and 10 µF capacitors. For light load and PF of about 0.

5. Results and Discussion

The operation of the automated power factor correction system was tested under different loading conditions on a laboratory-scale test bench using a prototype. The test configuration consisted of a variable inductive load, resistive lamps, a digital multimeter for verification, and the Arduino-based controller with a staged capacitor bank.

5.1 Experimental Observation

The system was subjected to the following test conditions:
1) Pure resistive load
2) Pure inductive load (e.g., choke coil)
3) Mixed load (resistive + inductive)

Table I provides a summary of the measured power factor and capacitor bank response for different load conditions.

Table 1: Experimental Results Under Different Load Condition

Load Type	Initial PF	Corrected PF	Capacitors Activated
Inductive Only	0.72	0.95	$10\,\mu F + 40\,\mu F$
Mixed Load	0.8	0.97	$20\,\mu F$
Light Load	0.88	0.98	$10\,\mu F$
Resistive Only	~1.00	~1.00	None

5.2 Performance Analysis

The findings verify that the system efficiently detects de graded power factor conditions and initiates correction measures automatically. Important performance indicators are:

- **Response Time:** The controller could check and correct the power factor in less than 1 second.
- **Accuracy:** Calculated values of power factor were consistent with the manual computation and the readings on the multimeter.

- **Efficiency:** Overcompensation was avoided by utilizing only the needed combination of capacitors.

The improvement in power factor substantially reduced line current, which means reduced transmission losses and a more efficient utilization of the installed electrical infrastructure.

5.3 Economic Implications

An economic analysis was also done to find out the cost saving impact of the system. Assuming a medium-sized installation with an average load of 10 kW having a low power factor of 0.75, penalties to the utility can cross INR 20,000 annually. Having installed the suggested system and keeping the PF more than 0.95, the penalty is wiped out, and electrical bills decrease. The cost of the prototype system was around INR 4,000 consisting of sensors, relays, microcontroller, and capacitors. This corresponds to a payback period of less than 3 months under normal industrial conditions.

5.4 Limitations and Considerations

Although the system worked fine under testing, the following were limitations seen:

- **Single-phase Operation:** The current system is restricted to single-phase systems; subsequent versions need to accommodate three-phase systems.
- **Harmonic Distortion:** The system does not remove harmonics. Overcompensation in nonlinear loads needs to be prevented.
- **Fixed Step Sizes:** The resolution of the correction de pends on the available capacitor values. Increasing the number of steps can increase precision.

6. Conclusion

The article described the design and implementation of an automated power factor correction system based on a microcontroller-control strategy and a multi-stage capacitor bank. The system continuously monitors power factor in real time, determines the phase difference between voltage and current, and dynamically switches capacitors to provide the required reactive power. Test outcomes reflected a wide power factor enhancement-0.72 to more than 0.95-increase, and thereby decreased the line current, transmission losses, and energy costs. The utilization of Arduino Uno, relay drivers, and capacitors in implementing hardware was low cost and withstanding. Economic analysis assures immediate return on investment, particularly in small and medium industrial establishments where power factor charges are routine. Modularity of the system also facilitates scalability to higher capacities for big installations. Though the present configuration is restricted to single-phase systems, it is possible to incorporate three-phase capability, harmonic filtering, and IoT based remote monitoring in future. As there is more focus on energy efficiency and reducing costs, such systems are a promising solution for sustainable power management.

References

[1] Md. Sajidur Rahman et al., “Automatic Power Factor Measurement and Improvement Using Capacitor Bank,” IEEE, 2022.
[2] Utpal et al., “Automatic Power Factor Correction Using Capacitor Banks,” IJIREEICE, vol. 4, no. 4, 2016.
[3] A. Kumar Tiwari et al., “Automatic Power Factor Correction Using Capacitive Bank,” IJERA, vol. 4, issue 2, 2014.
[4] M. Ayaz et al., “Dynamic Power Factor Correction in Industrial Systems: An Automated Capacitor Bank Control Approach,” IEEE, 2023.
[5] Ahmed R. Bakr et al., “A Study on Power Factor Correction with Capacitor Bank Using ERACS Software,” IJERA, vol. 11, 2021.
[6] M. Kalhari et al., “Power Factor Improvement of Industrial Loads using a Capacitor Bank and a Solar PV System,” ICATC, 2022.

Author Profile

Supriya Jamdar is currently pursuing a Bachelor of Technology (B.Tech) degree in Electrical Engineering from AISSMS Institute of Information Technology (IOIT), Pune, India. Presently in the third year of the program, she is actively engaged in academic projects and technical research. Her areas of interest include microcontroller-based system design, power systems, renewable energy. She is committed to exploring innovative solutions and contributing to the advancement of electrical engineering.