Design and Analysis of an Adaptive Automatic Power Factor Correction System for Loss Reduction in Electrical Installations

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***Abstract*—Low power factor in electrical power systems caused by inductive and nonlinear loads leads to increased losses, poor voltage regulation, and economic penalties. Conventional power factor correction methods offer limited adaptability, while advanced solutions are costly and complex. This paper proposes an adaptive digital Automatic Power Factor Correction system using a binary-weighted switched capacitor bank. The system continuously measures voltage and current, computes the power factor in real time, and dynamically estimates the required compensating capacitance. Fine-grained capacitor switching enables accurate correction close to unity power factor under varying load conditions, improving efficiency, reducing losses, and enhancing overall system performance.**

***Index Terms*—APFC, power factor, power compensation, capacitor bank, digital control, power quality.**

I. Introduction

Electrical power systems are designed for the efficient, reliable and economical distribution of electrical power. The power factor is one of the parameters that significantly affect the efficiency of the power distribution process. The power factor is expressed as the ratio of the real power to the apparent power. The higher the value of the power factor, the better the use of electrical power. The low power factor shows inefficient working.

Reduced power factor is prevalent in contemporary power systems and this is mainly attributed to the increasing adoption of inductive and nonlinear loads such as induction motors, transformers, fluorescent lighting, welding machines, and power electronic converters. This is due to their high demand for reactive power in creating magnetic and electric fields, leading to a lag in the current flow with respect to voltage. This therefore leads to a reduction in power factor.

The power factor is low in the case where the current flow is not in phase with the voltage. As a result, the power factor has a significant impact on the electrical system in that it increases the current flowing into the system to provide the same amount of real power. As a result, there are increased losses in the transmission and distribution of the current. Further, increased current flow can lead to increased voltage drop and overheating of the equipment. Additionally, the life span of the electric equipment can be reduced. On the other hand, the capacity of the power generators and the transformers is affected due to low power factor. They are only rated in terms of apparent power(kVA).

Apart from the potential technical limitations, another reason that causes drawbacks to the system is the low power factor. Financial penalties or higher rates of tariffs are also charged by many power companies for operations below a certain limit of power factor, which is normally around 0.9. This further emphasizes the need for proper power factor correction in the power system.

With the rise in the penetration of inductive and nonlinear loads, the issue of power loss, which is linked with the low power factor, has made power factor improvement an essential technical challenge. The improvement of the power factor near unity will lead to a reduction in the current requirement, which will assist in decreasing the system power loss, along with the improvement of the voltage stability of the system. Thus, the analysis of the current power factor correction methods is required for the improvement of these solutions.

II. Problem Analysis

Poor power factor introduces several technical and economic challenges that degrade the performance of electrical power systems. These issues mainly arise due to excessive reactive power demand, increased current flow, and inefficient utilization of system capacity.

*A. **High Reactive Power Demand***

Reactive power is required for the operation of inductive and capacitive loads; however, excessive reactive power demand is a key characteristic of poor power factor operation. Reactive power is given by

$$Q = VI \sin\theta \tag{1}$$

where V is the RMS voltage, I is the RMS current, and θ is the phase angle between them. As the phase angle increases, a larger portion of apparent power is consumed as reactive power, reducing the efficiency of power delivery.

B. *Excessive Current Draw*

The relationship between apparent power S, real power P, and power factor PF is given by

$$S = \frac{P}{\text{PF}} \tag{2}$$

For a constant real power demand, a reduction in power factor increases apparent power and consequently the line current:

$$I = \frac{S}{V} \tag{3}$$

Higher current levels result in increased loading of conductors and electrical equipment, reducing system efficiency and available capacity.

C. *Increased I^2R Losses*

Copper losses in conductors are proportional to the square of the current and are expressed as

$$P_{\text{loss}} = I^2 R \tag{4}$$

Even a small increase in current due to poor power factor can cause a significant rise in losses, leading to wasted energy and increased operating temperatures.

D. *Poor Voltage Regulation*

Increased current flow caused by low power factor results in larger voltage drops across line impedance. The reactive component of current significantly contributes to voltage drop, particularly under inductive loading conditions, leading to poor voltage regulation and unstable voltage levels at the load end.

E. *Reduced System Capacity and Economic Penalties*

Since generators, transformers, and cables are rated in kVA, poor power factor reduces the usable real power capacity of existing infrastructure. Additionally, utilities often impose financial penalties on consumers operating below acceptable power factor limits, increasing operational costs.

III. Literature Review

There have been various methods developed to reduce the negative impact of low power factor in an electrical power system. The methods include very elementary passive solutions to highly sophisticated power electronic solutions for power factor correction. This section discusses existing literature, standards, commercial solutions, and patents with respect to power factor correction methods and their limitations and advantages.

A. *Passive Capacitor Banks*

The most popular method for power factor improvement in power systems is using passive shunt capacitor banks. The installation of capacitors to supply reactive power will compensate for the reactive power demand of inductive loads. Several studies have been done to establish the effectiveness of capacitor banks in decreasing reactive power transfer, reducing current demand, as well as reducing transmission losses.

However, as discussed in the reviews of reactive power compensation, the compensation offered by passive capacitors is stepwise and cannot be continuously varied based on the changing load. In light-load situations, the compensation offered by the capacitor can be excessive, thereby leading to a leading power factor and increasing the chances of over voltage. Moreover, the compensation offered by the capacitors fails to mitigate the harmonic distortion problems and even leads to harmonic resonances [1].

B. *Automatic Power Factor Correction Panels*

To overcome the shortcomings associated with fixed compensation, components called APFC(Automatic Power Factor Correction) panels have been developed. APFC uses controllers to switch the capacitor banks automatically, based on either the measured power factor values or the reactive power requirement.

From various literature and field observations, there is an improvement in power factor and reduction in penalties due to APFC panels. In reality, power factor correction systems function in steps, which are based upon capacitance values, thereby causing fluctuations in power factor values rather than achieving unity values. The correction time of power factor correction systems also has limitations in dynamic systems [2].

C. *Active Power Filters and Hybrid Systems*

Active Power Filters (APFs) are more advanced methods of power factor correction, which use power converters for realizing the compensation currents in real-time. The APFs can compensate for the reactive power and the harmonics present in the current. The application of APFs is possible for those power systems that use nonlinear loads, for instance, rectifiers and variable frequency drives. The studies using APFs proved their effectiveness in power quality and system efficiency improvement [3].

To minimize cost and rating constraints, hybrid filters with passive and active components are also proposed. Although these types of systems can provide better harmonic suppression and reactive compensation capabilities than passive filters, these systems are also limited by control complexities and accuracy of sensors and converter bandwidths. Hence, it would still be difficult to preserve the possibility of unity power factor with these systems under dynamic environments [4].

D. *FACTS Devices: SVC and STATCOM*

Flexible AC Transmission System (FACTS) based compensation using Static VAR Compensator (SVC) and Static

Synchronous Compensator (STATCOM) can contribute reactive power at an electrical grid or substation level. Specifically, STATCOMs have a faster response time with better performance characteristics during a low-voltage condition than SVCs. Despite the benefits, the cost structure related to installation as well as operation for the FACTS devices is generally greater since they are typically used in transmission or substations. Furthermore, the compensation provided by the FACTS devices does not target a specific loading problem but the system, hence their limitations with harmonics or rapid load variation [5].

Summary of Current Methodology from the reviewed literature, it has been concluded that the current power factor correction methods are effective enough to enhance the efficiency of the power system, but none of them have the capability to achieve a unity power factor. This is because both the passive approaches are not adaptable enough and have the limitation of discrete control levels. On the other hand, the advanced approaches are not cost-effective.

IV. Research Gap

The conventional method of shunt capacitor compensation is quite effective but cannot vary according to changing load conditions quite often due to difficulties of precise control through automation. Automatic Power Factor Correction (APFC) Panels are quite useful and help in improving the efficiency of the system through discrete switching actions according to the power factor; moreover, there are limitations on the fast response of the system due to fixed capacitor values.

More advanced technologies, including Active Power Filters (APFs) and hybrid compensation systems, provide better reactive power and harmonic compensation through real-time control. Although these systems are effective, they are costlier and more complex from a control perspective, limiting their use, especially for smaller systems. Likewise, higher-level grid-connected FACTS systems, including (SVCs) and STATCOMs, are mainly used for high-power grid systems and are not suited for smaller systems that are involved at a local level.

Moreover, all the previous power factor correction methods have been designed to control the power factor within an acceptable range close to unity value, not to keep it exactly at unity value. Fast changes in the loads, nonlinear loads, and an environment with more harmonics cause more adverse effects on all the above methods to reduce power losses.

Thus, a research gap is clearly available for developing a cost-effective, adaptive, and intelligent approach for power factor correction with a power factor close to unity when operating dynamically and nonlinearly.

V. Proposed Solution

A. System Overview

The proposed system is a digital automatic power factor correction (APFC) scheme employing a binary-weighted capacitor bank for reactive power compensation. The system continuously monitors the electrical parameters of an AC load, computes the instantaneous power factor, and dynamically switches capacitor banks to improve the power factor toward a predefined refernce value.

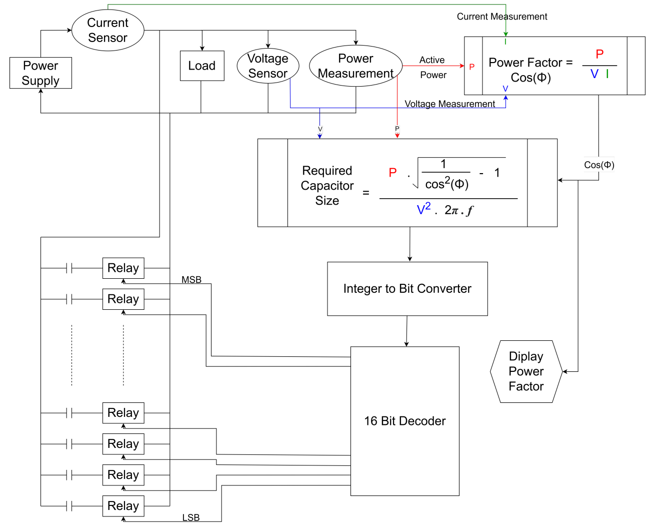

Fig. 1. Block diagram

Unlike conventional step-based APFC systems with fixed capacitor sizes, this approach utilizes capacitors scaled in powers of two, enabling fine-grained reactive power control with a reduced number of switching elements. The system operates in a closed-loop manner and is suitable for applications involving dynamically varying loads such as industrial machinery and commercial electrical installations.

B. System Architecture

The proposed automatic power factor correction (APFC) system is composed of five main functional subsystems: measurement, power computation, reactive power estimation, digital control, and capacitor switching.

*1) **Measurement Subsystem**:* The measurement subsystem consists of a voltage sensor and a current sensor connected to the supply and load, respectively. The voltage sensor provides the root-mean-square (RMS) value of the supply voltage V, while the current sensor measures the RMS load current I. These signals are appropriately scaled and conditioned before being supplied to the processing stage.

*2) **Power and Power Factor Computation**:* The apparent power consumed by the load is computed using the measured voltage and current values. The power factor of the load is then calculated as

$$\cos\phi = \frac{P}{VI} \tag{5}$$

where P denotes the real power, V is the RMS voltage, and I is the RMS current.

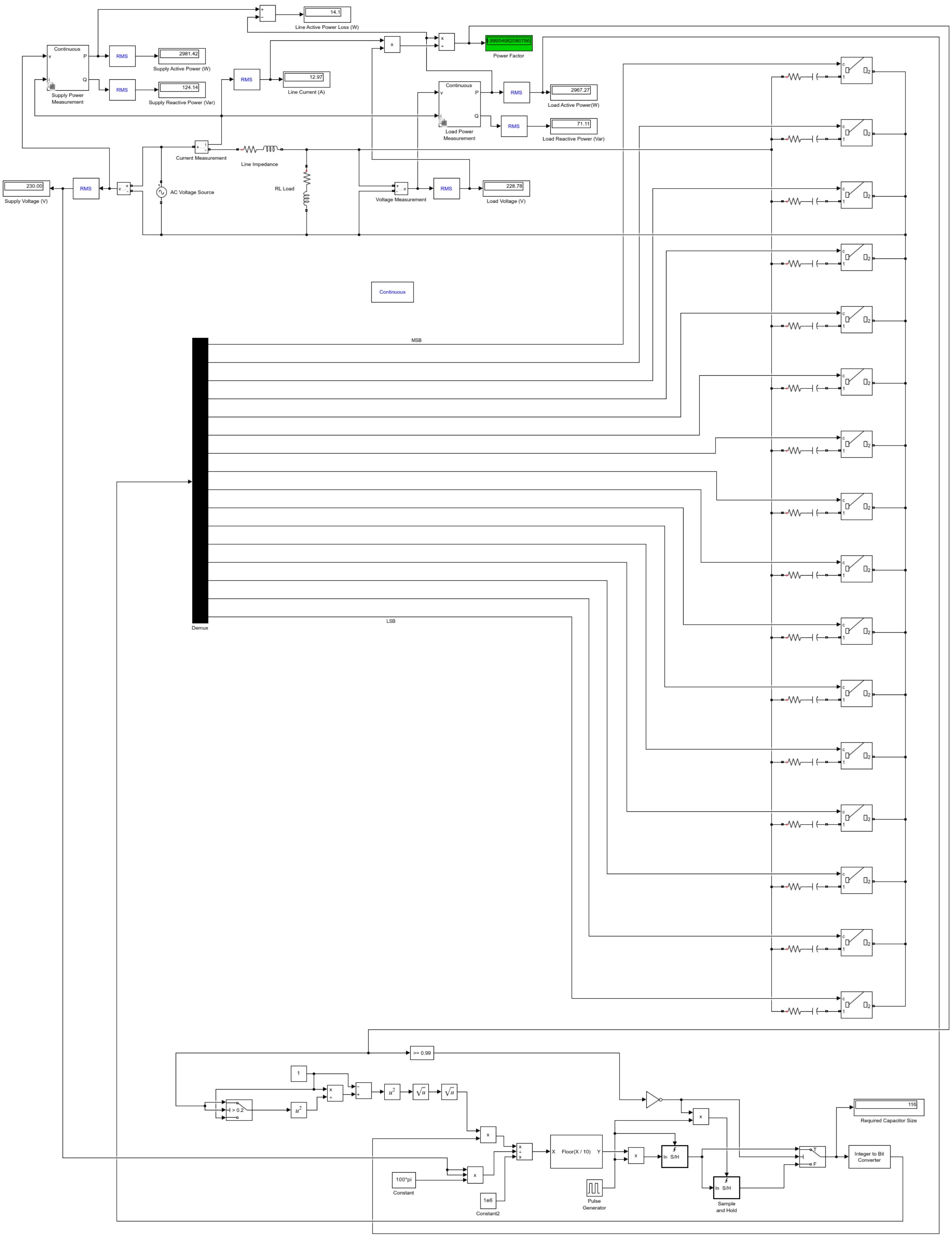

Fig. 2. Overall Simulink architecture of the proposed adaptive APFC system

*3) **Reactive Power and Capacitance Estimation**:* Based on the measured power factor, the reactive power compensation required to improve the power factor is determined. The equivalent capacitance required for compensation is calculated using The power factor is defined as

$$\cos\phi = \frac{P}{\sqrt{P^2 + Q^2}}$$

where the reactive power is

$$Q = P \tan\phi$$

For a capacitive compensator,

$$Q = \frac{V^2}{X_c}$$

where the capacitive reactance is

$$X_c = \frac{1}{2\pi f C}$$

Substituting and rearranging, the required capacitance for power factor correction is obtained as

$$C = \frac{P \tan\phi}{2\pi f V^2}$$

Definition of Terms

- P : Active (real) power in watts (W)
- Q : Reactive power in volt-ampere reactive (VAR)
- ϕ : Power factor angle (radians)
- $\cos\phi$: Power factor
- V : RMS supply voltage (V)
- X_c : Capacitive reactance (Ω)
- C : Capacitance required for power factor correction (F)
- f : Supply frequency (Hz)

*4) **Digital Control and Switching Logic**:* The calculated capacitance value is converted into a digital integer representation. An integer-to-binary conversion is performed to generate a binary control word corresponding to the required capacitor combination. A binary decoder processes this control word and generates switching signals for the relay drivers.

*5) **Binary-Weighted Capacitor Bank**:* The capacitor bank is composed of individual capacitors scaled in powers of two (e.g., $1\,\mu$F, $2\,\mu$F, $4\,\mu$F, $8\,\mu$F, etc.). Each capacitor bank is connected to the supply through a relay. This binary-weighted configuration allows fine resolution in reactive power compensation while minimizing the number of switching elements.

C. Operating Principle

During operation, the system continuously monitors the power factor of the connected load. When the measured power factor drops below the reference value(0.99), the control unit calculates the required reactive power compensation and switches appropriate capacitor units into the circuit. If the power factor exceeds the reference value, capacitor units are disconnected to avoid overcompensation.

The use of smaller capacitor steps allows the system to closely track load variations, improving correction accuracy compared to conventional APFC systems. This adaptive behavior reduces excessive current draw, minimizes I^2R losses, and improves voltage regulation. Additionally, by incorporating harmonic-aware control or de tuned capacitors, the proposed system mitigates resonance risks commonly associated with passive capacitor banks.

D. Expected Performance Benefits

The proposed solution is expected to provide the following benefits:

- Improved power factor maintenance close to unity under varying load conditions.
- Reduction in line current and associated copper losses.
- Improved voltage regulation and equipment utilization.
- Lower implementation cost compared to fully active power factor correction systems.
- Reduced exposure to utility power factor penalties.

By balancing performance, cost, and control complexity, the proposed adaptive APFC-based solution effectively addresses the limitations of existing power factor correction techniques while remaining suitable for practical industrial and commercial applications.

TABLE I
EXPECTED PERFORMANCE IMPROVEMENT AFTER POWER FACTOR CORRECTION

Parameter	Before PFC	After Proposed PFC
Power Factor (PF)	0.75 – 0.80	0.99 – 1.00
Line Current	High	Reduced
I^2R Losses	High	Significantly Reduced
Voltage Regulation	Poor	Improved
System Utilization	Low	Improved
Utility Penalties	Applicable	Eliminated / Reduced
Overall Efficiency	Low	High

VI. CONCLUSION

Poor power factor remains a significant challenge in modern electrical power systems due to the increasing use of inductive and nonlinear loads. This paper analyzed the technical and economic impacts of poor power factor, including increased reactive power demand, excessive current flow, higher I^2R losses, poor voltage regulation, reduced system capacity, and utility penalty charges. A comprehensive review of existing power factor correction techniques revealed that although conventional and advanced solutions can improve system performance, each exhibits inherent limitations under dynamic and harmonic-rich operating conditions.

Based on the identified research gap, an adaptive power factor correction approach was proposed to maintain the power factor close to unity. The proposed solution enhances conventional Automatic Power Factor Correction systems by incorporating real-time power factor monitoring and fine-grained reactive power compensation using small-step switched capacitor banks. This approach improves correction accuracy, reduces current-related losses, and enhances voltage regulation while avoiding the high cost and complexity associated with fully active compensation systems.

The proposed system offers a practical and cost-effective solution suitable for industrial and commercial applications where load conditions vary continuously. Future work may include simulation-based performance evaluation, hardware prototyping, and the integration of advanced control algorithms to further improve response speed and harmonic immunity. Overall, the proposed approach effectively addresses the limitations of existing power factor correction techniques and contributes toward improved efficiency and reliability of electrical power systems.

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