Department of Electrical Engineering

University of Moratuwa

EE3204 – Engineering System Design

Project Report:

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

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1. Introduction

1.1 Project Overview

This project was undertaken as part of the EE3204 – Engineering System Design module in the Department of Electrical Engineering, University of Moratuwa. The main objective of the project was to analyze the problem of **power loss due to poor power factor** in electrical systems and to design a feasible solution within the given academic timeframe and resource constraints.

The project focused on developing an adaptive Automatic Power Factor Correction (APFC) concept that could improve power factor close to unity under varying load conditions. Emphasis was placed not only on the technical solution but also on project planning, task allocation, time management, and achievement of project objectives.

1.2 Project Objectives

The primary objectives of the project were:

- To understand the causes and impacts of poor power factor in electrical power systems
- To analyze existing power factor correction methods and identify their limitations
- To propose a practical and cost-effective solution for power factor improvement
- To manage the project effectively within the allocated time and academic constraints

To demonstrate teamwork, planning, and engineering decision-making skills.

1.3 Project Scope

The scope of the project was limited to **conceptual design and analysis** of an adaptive APFC system. The project did not involve hardware fabrication due to time and laboratory constraints. Instead, the focus was placed on:

- Problem identification and analysis
- Review of existing industrial solutions
- Conceptual system design and operation
- Expected performance evaluation

The project scope ensured that all objectives could be realistically achieved within the semester duration.

2. Background

Electrical power systems are engineered to distribute electrical energy in an efficient, reliable, and economical way. The power factor represents the key indicator of the phase relationship between voltage and current and is a measure of a system's effective power utilization. At ideal conditions, voltage and current are in perfect phase; thus, unity power factor develops, but in realistic conditions regarding industrial and commercial environments with highly inductive nature of most of the loads, a major chunk of loads comprises motors.

Induction motors, transformers, fluorescent lighting, welding machines, and power electronic converters all need reactive power for magnetic and electric field establishment. The demand for reactive power makes the load current lag the supply voltage; this is the cause of poor power factor. With greater penetration of inductive and nonlinear loads, poor power factor has become one of the most pervasive and persistent power quality issues in today's electrical systems.

If the power factor is low, it implies that the current drawn is higher for the same level of actual power transmitted. The consequence is increased I^2R losses in the conductors, higher voltage drops, overheating of electrical equipment, and poor use of generators, transformers, and the power distribution system measured in kVA units of apparent power. Apart from the technical problems associated with poor power factor values, many power utilities also charge economic penalties on consumers whose power factor values are not acceptable and are generally set at 0.9 or higher.

3. Past/Related Work

The fundamentals of power factor correction were studied as part of the EE2034-Power Systems 1 module, with emphasis on the causes and consequences of poor power factor in AC power systems. Theoretical concepts such as reactive power, inductive loading, and capacitive compensation were covered to understand their impact on system efficiency and power transfer capability.

In addition to theoretical study, a laboratory experiment on transmission line compensation was conducted to investigate the effects of series and shunt capacitors. The practical work, supported by MATLAB/Simulink simulations, demonstrated the role of capacitor banks in improving voltage regulation, reducing line current, and enhancing real power transfer. This prior knowledge and experimental experience provide the foundation for the present work on the design and implementation of an automatic power factor correction system.

4. Project Management

4.1 Project Planning

At the initial stage, we identified **power loss due to poor power factor** as a common and practically relevant engineering problem. A project plan was then developed to guide the execution of tasks throughout the semester.

The project was divided into multiple phases:

1. Problem identification and topic selection
2. Background study and impact analysis
3. Review of existing solutions
4. Identification of limitations and research gap
5. Development of a proposed solution and validating by a simulation
6. Documentation and report preparation

Regular discussions were conducted among team members to monitor progress and ensure timely completion of tasks.

4.2 Project Timeline

The project was completed within the allocated academic period. The estimated timeline is shown below:

Week	Activity
Sep 4th Week	Problem identification and topic selection
Oct 2nd Week	Background study and impact analysis
Dec 1st Week	Review of existing solutions
Dec 2nd Week	Identification of limitations and research gap
Dec 3rd Week	Development of a proposed solution and validating by a simulation
Dec 4th Week	Documentation and report preparation

The project progressed according to the planned schedule without major delays.

5. Resource Management

5.1 Human Resource

The project was carried out by **three team members**, with responsibilities distributed to ensure balanced workload and effective collaboration.

Team Member Responsibilities

230511A - Rajapaksha J.S.W.

- Development of the proposed system concept for the adaptive Automatic Power Factor Correction (APFC) solution
- Design and organization of the proposed simulation model
- Compilation and structuring of the final project report, including technical and project results sections

230516T - Rajapakshe R.P.M.T.

- Investigation of the technical and economic impacts of maintaining a poor power factor
- Investigation of current techniques used for power factor regulation.
- Technical document compilation in Overleaf according to IEEE publication standards ensuring the proper format.

230517X - Rajapakshe W.R.K.L.M.H.N.

- Validation of the simulation for expected performance
- Analyzed limitations of existing methods and contributed to the identification of the research gap
- Interpretation of simulation outputs and contribution to the Project Results and Analysis section

All members actively participated in discussions, decision-making, and documentation.

5.2 Technical resource

The following resources were utilized during the project:

- EE2034-Power System 1 lecture slides.
- IEEE and research publications
- Online technical documentation (Overleaf) and standards
- Simulation tools (MATLAB Simulink) for conceptual validation
- Personal computers and internet resources

No specialized laboratory equipment was required for this project stage.

6. Technical Section

This section presents the technical aspects of the proposed solution and focus is on explaining the design concept, supporting calculations, and key terminology used in the project rather than detailed implementation or advanced control theory.

6.1 Design Details

The proposed solution is an **adaptive Automatic Power Factor Correction (APFC) system** designed to improve the power factor of electrical installations experiencing inductive loading. The system is cost-effective, adaptive and intelligent to operate automatically with minimal human intervention while maintaining the power factor close to unity.

A block diagram designed to give a rough idea of the proposed solution is shown below.

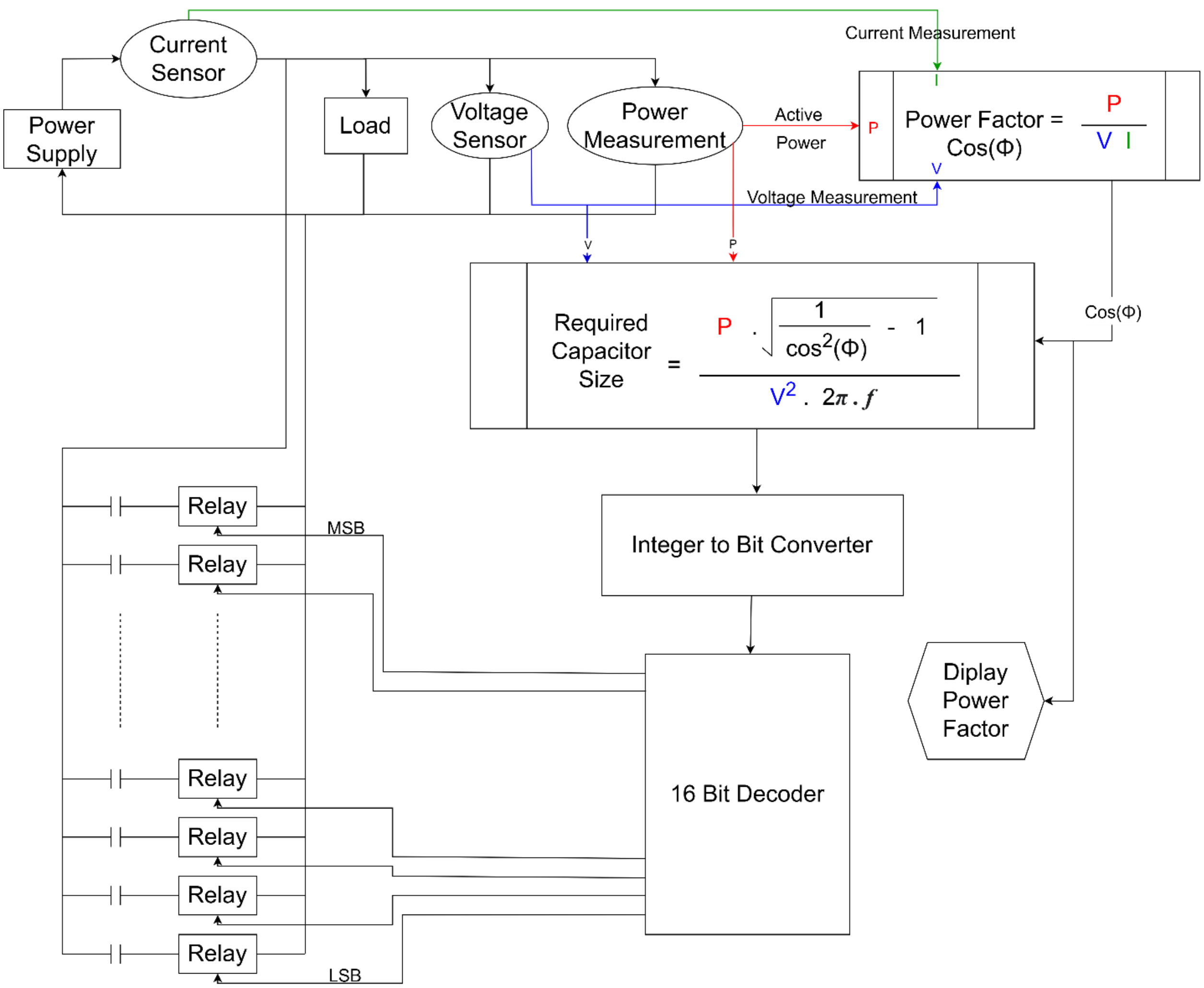


Figure 1 - Block Diagram

The design consists of five main functional blocks:

1. **Measurement Unit**
   The measurement unit continuously monitors the supply voltage and load current using suitable voltage and current sensors. These sensors provide scaled RMS values that represent the electrical operating condition of the system.

2. **Power and Power Factor Computation Block**
   Using the measured voltage and current values, the system computes the real power consumed by the load and the corresponding power factor. This information forms the basis for deciding whether power factor correction is required.

3. **Reactive Power Estimation Block**
   When the measured power factor falls below the reference value (0.99), the system calculates the amount of reactive power required to compensate for the lagging component of the load current.

4. **Digital Control and Decision Logic**
   The calculated compensation requirement is processed by a digital control unit. This unit determines the appropriate combination of capacitor banks needed to achieve the desired correction. The control logic ensures that overcompensation is avoided.

5. **Binary-Weighted Capacitor Bank**
   The capacitor bank is arranged in binary-loaded steps (e.g. 1μF, 2μF, 4μF, 8μF). This configuration allows for fine control of reactive power compensation and minimizes the number of switching elements. The capacitors are switched using relays or contactors based on the control signal.

This modular design approach ensures adaptability to varying load conditions, simplicity of implementation, and scalability for different system ratings.

6.2 Calculations

The following calculations illustrate the basic method used to determine the required capacitance for power factor correction. These calculations are representative and intended to demonstrate the design approach.

Power Factor

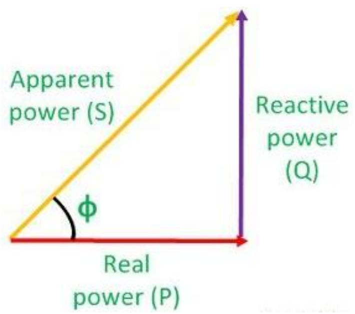
The power factor is defined as:

$$PF = \cos\,\phi = \frac{P}{S} = \frac{P}{VI}$$

where:
P = Real power (W)
S = Apparent power (VA)
V = RMS voltage (V)
I = RMS current (A)

Reactive Power

Reactive power is calculated using:



$$Q = P\tan(\phi)$$

A higher phase angle results in higher reactive power demand.

Required Compensation

To improve the power factor to a desired value (close to unity), the reactive power supplied by the capacitor bank must equal the reactive power demanded by the load.

For capacitive compensation:

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

where the capacitive reactance is:

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

Rearranging, the required capacitance is given by:

$$C = \frac{Q_c}{2\pi f V^2}$$

Example Calculation

Assume:

- Supply voltage $V = 230\,V$
- Frequency $f = 50\,Hz$
- Load power $P = 2\,kW$

- Initial power factor $PF = 0.8$

$$\phi = \cos^{-1}(0.8)$$
$$Q_c = P\tan(\phi) = 1.5\ kVAR$$

Using the calculated reactive power, the required capacitance:

$$C = \frac{Q_c}{2\pi f V^2} = 90.25\ \mu F$$

The resulting capacitance is then implemented using the nearest binary-weighted capacitor combination which are 64 μF, 16 μF, 8 μF and 2 μF capacitors using relay switches.

6.3 Terminology

The following terms are frequently used throughout this project:

- Power Factor (PF):
  The ratio of real power to apparent power in an AC system. It indicates how effectively electrical power is utilized.
- Real Power (P):
  The actual power consumed by a load to perform useful work, measured in watts (W).
- Reactive Power (Q):
  Power that oscillates between the source and reactive elements of the load, measured in volt-ampere reactive (VAR).
- Apparent Power (S):
  The vector sum of real and reactive power, measured in volt-amperes (VA).
- Automatic Power Factor Correction (APFC):
  A system that automatically adjusts reactive power compensation to maintain the power factor within a desired range.
- Binary-Weighted Capacitor Bank:
  A capacitor arrangement where capacitance values follow powers of two, allowing fine control using digital logic.
- Overcompensation:
  A condition where excessive capacitive reactive power causes the power factor to become leading.
- I^2R Losses:
  Power losses in conductors caused by current flow, proportional to the square of the current.

6.4 Simulation

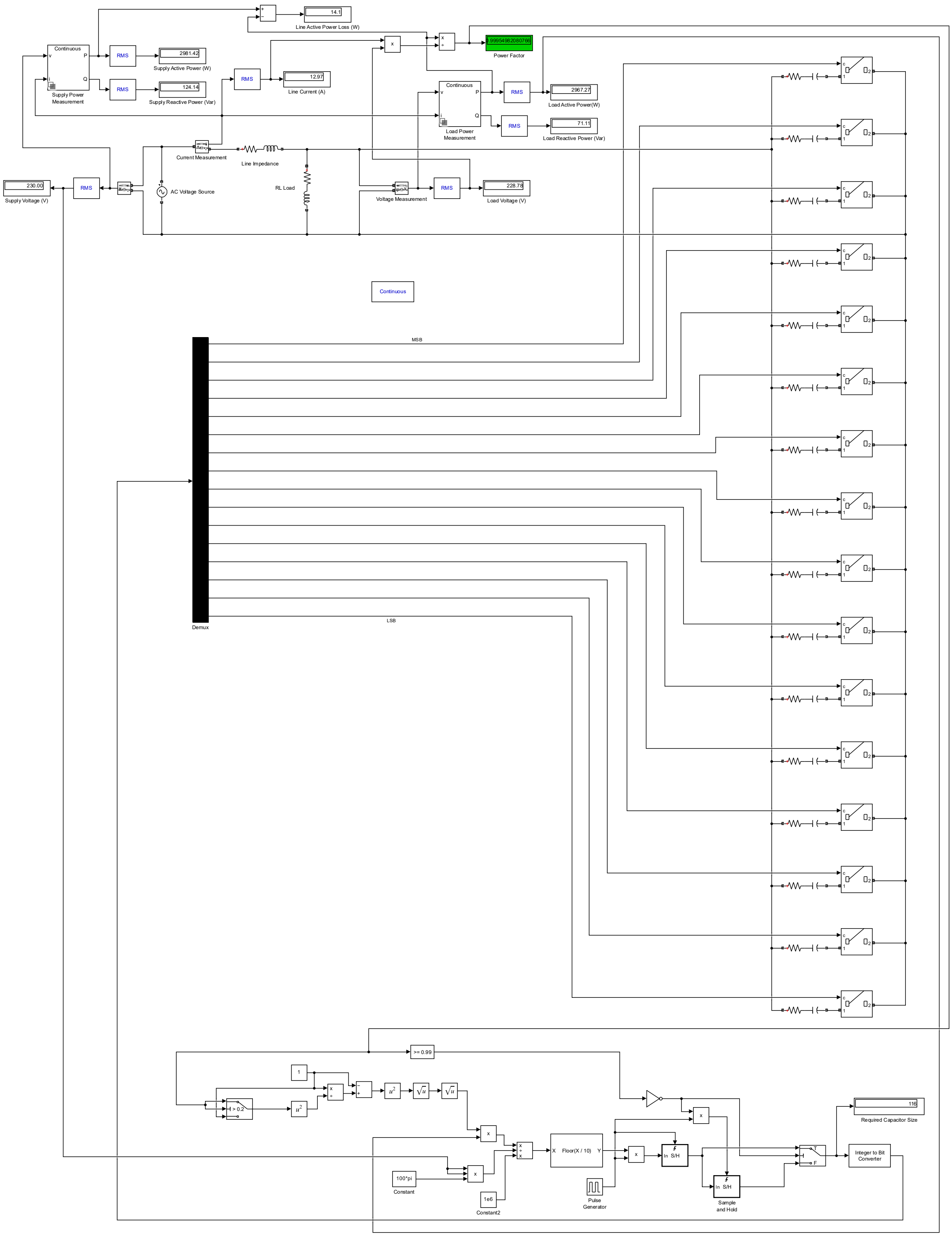


Figure 2 – Simulink Simulation

7. Project Results and Analysis

The primary objective of this project was to analyze the problem of power loss due to poor power factor and develop a feasible and adaptive solution within the given study time frame. The project successfully achieved its defined objectives through systematic planning, analysis and design.

As a result of the proposed adaptive automatic power factor correction (APFC) system, the expected improvement in power factor under different load conditions is in the typical range of 0.75–0.80 to approximately 0.99–1.00. This improvement directly contributes to the reduction of line current, thereby reducing copper (I^2R) losses and improving voltage regulation throughout the power system.

The conceptual design demonstrates that by using a binary weighted capacitor bank and digital control logic, fine-grained reactive power compensation can be achieved with a relatively small number of switching components. Compared to traditional step-based APFC systems, the proposed approach provides smooth correction and minimizes power factor oscillations around the target value.

From a project management perspective, the project was completed within the allocated time frame and adhered to the defined scope. All planned milestones were successfully achieved, including problem identification, analysis, solution development, and documentation.

8. Challenges and Limitations

Several challenges and limitations were encountered during the execution of the project:

1. **Time Constraints**
   The limited duration of the semester limited the extent to which hardware implementation and experimental validation could be performed. As a result, the project focused on conceptual design and theoretical analysis.

2. **Software Constraints**
   Some blocks in Simulink could not change their values while the model was running. So, the model could not be tested during real-time simulation. Also, blocks in Simulink's Electrical/ Passives library could not be linked with blocks in Electrical/ Specialized Power Systems/ Passives library. Therefore, it was not possible to add an active filter to the simulation for total harmonic distortion.

3. **Balancing Technical Depth and Project Management Requirements**
   Careful structuring and content selection were required to ensure that the report maintained a balance between technical explanation and management-focused documentation.

4. **Coordination Among Team Members**
   Coordinating schedules and workload distribution among team members while managing other academic commitments posed a challenge. This was addressed through regular discussions and task allocation.

Despite these challenges, effective planning, teamwork, and communication allowed the project to proceed smoothly and achieve its intended goals.

9. Recommendations and Future Works

Based on the outcomes of this project, several recommendations and future enhancements are suggested:

- **Simulation-Based Validation**
  The proposed APFC system can be further validated using detailed simulations in software platforms such as MATLAB/Simulink to analyze dynamic performance under varying load conditions.
- **Hardware Implementation**
  Future work may include developing a hardware prototype using a microcontroller-based control system, relays or solid-state switches, and practical capacitor banks.
- **Advanced Control Algorithms**
  The incorporation of intelligent control techniques, such as fuzzy logic or adaptive control, could improve response time and correction accuracy.
- **Harmonic Consideration**
  Integration of harmonic filtering or detuned capacitor banks is recommended to enhance system performance in environments with nonlinear loads.
- **Performance Evaluation in Real Installations**
  Testing the system in industrial or commercial environments would provide practical insights into reliability, efficiency improvement, and economic benefits.

These future developments would further enhance the practicality and robustness of the proposed system while building upon the foundation established in this project.

10. Conclusion

The problem undertaken by this project is very significant, as it deals with the issue of loss of power owing to poor power factor in the modern power system. The problem was analyzed in a proper manner, and the effects associated with the poor power factor were noted, such as the increased need for reactive power, excessive current, I^2R losses, voltage regulation, capacity, and penalties.

From a thorough survey and analysis of existing power factor correction methods, it was found that though conventional and modern techniques offer improvement in system performance, each of these techniques was found to have limitations related to adaptability, resolution, cost, and complexity. An adaptive Automatic Power Factor Correction System based on a binary-weighted switched capacitor bank was proposed based on the research gap found.

The proposed system provides additional benefits to the conventional APFC systems since the system will offer fine-grained reactive power compensation and the ability to adapt to the changes in the load levels. The system will ensure that the power factor is close to unity; therefore, the system will reduce line currents and ensure a high system efficiency without the costs involved in active compensation systems.

Although the project was limited to conceptual design and theoretical analysis due to time and resource constraints, it successfully achieved its academic objectives and demonstrated a practical engineering solution. The proposed adaptive APFC approach provides a solid foundation for future work on validation through simulation and hardware, along with further enhancement that can be realized using advanced control techniques. Overall, the project would contribute toward the betterment of efficiency, reliability, and economic performance of electrical power systems.