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# Adaptive Fuzzy Logic Controller for Static VAR Compensator (SVC) in PV/Wind Hybrid Systems

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**Abstract:** *The increasing integration of photovoltaic (PV) and wind energy into modern electrical grids has introduced significant challenges in maintaining voltage stability and reactive power balance due to the intermittent nature of renewable energy sources. Conventional PI controllers used in Static Var Compensators (SVCs) have limited adaptability under rapidly changing operating conditions. This project proposes an Adaptive Fuzzy Logic Controller (FLC) for SVC to provide intelligent reactive power compensation and maintain stable grid voltage in PV/Wind hybrid systems. The fuzzy controller processes voltage error and change in voltage error through a set of predefined linguistic rules to generate appropriate control signals for the SVC. Based on these signals, the SVC injects or absorbs reactive power to regulate the grid voltage effectively. The proposed system offers faster dynamic response, reduced voltage overshoot, shorter settling time, improved power factor, and lower Total Harmonic Distortion (THD) compared to conventional PI-based methods. The controller is suitable for real-time implementation using microcontrollers such as ESP32 or Arduino, making it an efficient solution for future smart grid applications.*

**Keywords:** SVC; FLC; PV/Wind hybrid systems.

## I. INTRODUCTION

The increasing penetration of renewable energy resources into modern electrical power systems has significantly transformed conventional power generation and distribution networks. Among various renewable technologies, solar photovoltaic (PV) and wind energy have become the most widely deployed because of their environmental sustainability, declining installation costs, and ability to support decentralized electricity generation. However, the intermittent and unpredictable nature of renewable energy sources introduces considerable challenges related to voltage regulation, reactive power compensation, power quality, and grid stability. Rapid variations in solar irradiance, wind speed, and consumer load demand frequently result in voltage fluctuations, poor power factor, increased Total Harmonic Distortion (THD), and reduced system reliability.

Conventional reactive power compensation techniques employing capacitor banks, fixed reactors, and traditional proportional-integral (PI) controllers often exhibit limited dynamic performance under rapidly changing operating conditions. Commercial power quality management platforms such as ABB Ability™, Siemens SICAM, and Schneider Electric EcoStruxure provide advanced grid monitoring and compensation capabilities; however, these systems generally require expensive industrial hardware and sophisticated supervisory control infrastructure, making them less suitable for research laboratories, microgrids, and distributed renewable energy installations. Furthermore, conventional PI controllers require manual parameter tuning and cannot effectively adapt to continuously changing renewable operating conditions. Therefore, there is an increasing need for an intelligent adaptive reactive power compensation system incorporating a Static Var Compensator (SVC), an Adaptive Fractional-Order PI (AFOPI) controller, to achieve stable voltage regulation, improved power quality, and enhanced grid stability within hybrid renewable energy systems.

## II. PROBLEM STATEMENT

Despite significant advancements in renewable energy integration, maintaining stable voltage and acceptable power quality within hybrid renewable energy systems remains a major technical challenge. The intermittent characteristics of solar photovoltaic generation and fluctuating wind energy continuously alter the reactive power demand of the electrical network, resulting in voltage instability, reduced power factor, increased harmonic distortion, and inefficient utilization of electrical infrastructure. Conventional reactive power compensation methods primarily rely on fixed capacitor banks or classical PI-controlled Static Var Compensators whose controller parameters remain constant despite continuously changing operating conditions. Consequently, these controllers frequently exhibit excessive voltage overshoot, prolonged settling time, reduced dynamic response, and suboptimal compensation performance during sudden renewable generation changes or rapid load variations. Furthermore, manual tuning of controller parameters is time-consuming and cannot maintain optimal system performance throughout varying grid conditions.

Grid operators therefore experience reduced voltage regulation capability, lower power quality, increased electrical losses, and decreased system stability, while industrial consumers may encounter equipment malfunction, reduced operational efficiency, and increased maintenance costs. The absence of adaptive controller optimization, intelligent reactive power compensation, real-time monitoring, and fast thyristor switching collectively limits the performance of conventional voltage regulation systems. These limitations establish the need for an intelligent adaptive control strategy capable of continuously optimizing controller parameters and dynamically compensating reactive power to improve grid reliability and renewable energy integration.

### III. RESEARCH OBJECTIVES

The primary objective of this research is to design and develop an intelligent reactive power compensation system employing an Adaptive Fractional-Order Proportional-Integral controller for voltage stabilization in hybrid renewable energy systems. First, the proposed research aims to develop a Static Var Compensator capable of dynamically injecting and absorbing reactive power to maintain stable grid voltage under varying operating conditions. Second, the study seeks to implement an Adaptive Fractional-Order PI controller that provides improved dynamic performance, higher control accuracy, and superior robustness compared with conventional integer-order PI controllers. Third, the proposed system aims to integrate Fuzzy Logic Controller for continuous online optimization of controller parameters, enabling automatic adaptation to changing renewable generation and load conditions without manual tuning. Fourth, the research intends to implement zero-crossing synchronized thyristor firing control using an ESP32-based high-speed digital controller to ensure accurate switching, reduced electrical stress, and reliable operation of the Static Var Compensator. Fifth, the system seeks to continuously monitor voltage, current, power factor, and reactive power to evaluate system performance and facilitate intelligent compensation decisions. Sixth, the proposed research aims to evaluate improvements in voltage regulation, settling time, overshoot reduction, Total Harmonic Distortion power factor [2] correction, and overall system stability under varying solar irradiance, wind generation, and load conditions. Finally, the developed system will be assessed for its suitability in microgrids, distributed renewable energy systems, and industrial smart grid applications. Collectively, these objectives contribute toward the development of an intelligent adaptive compensation system capable of enhancing renewable energy integration while improving power quality and electrical network stability

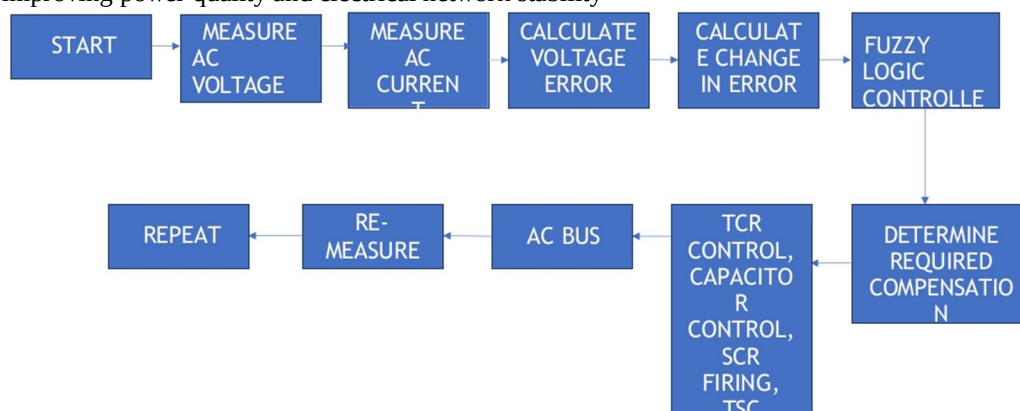
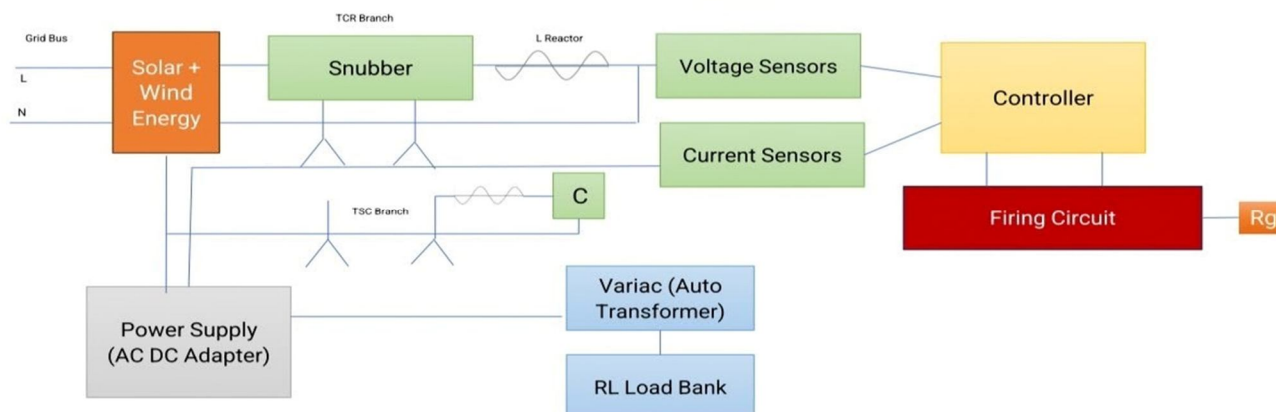


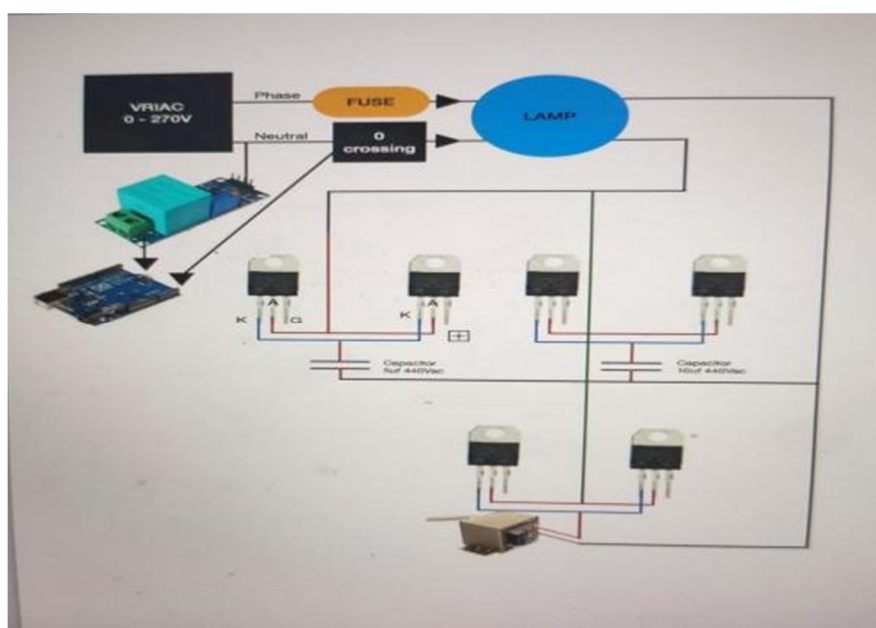
Fig. 1. Block diagram of TCR Branch

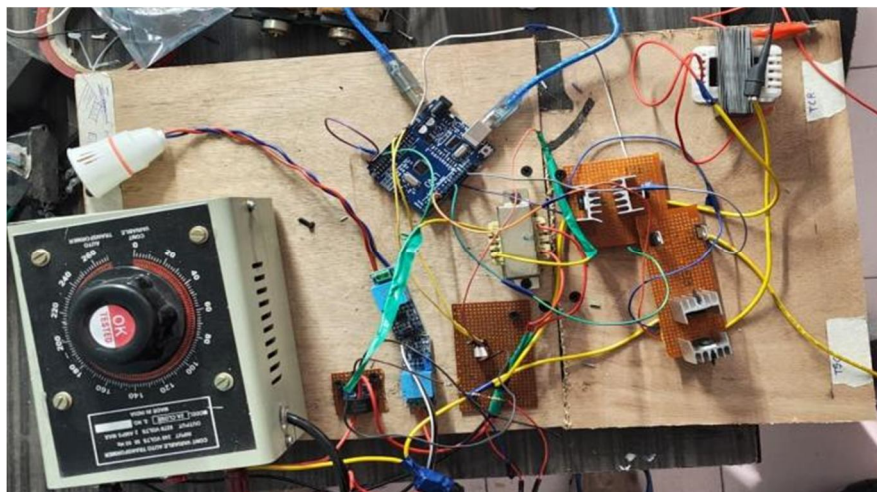


The proposed reactive power compensation system adopts an Adaptive Fractional-Order Proportional-Integral controller because conventional PI controllers [1] exhibit limited adaptability under rapidly changing renewable energy conditions. Fractional-order controllers introduce additional tuning flexibility through fractional integration orders, enabling more precise regulation, improved robustness, reduced overshoot, and faster transient response compared with classical integer-order controllers. However, determining suitable controller parameters manually becomes increasingly difficult as operating conditions continuously vary. Consequently, a Genetic Algorithm is incorporated to perform online optimization of controller parameters, enabling the controller to automatically adapt to changing grid conditions without operator intervention. The Static Var Compensator provides dynamic reactive power injection and absorption, maintaining stable voltage and improving power factor even during sudden variations in renewable generation or load demand. Furthermore, the implementation of zero-crossing synchronized thyristor firing [3] minimizes switching transients, reduces electrical stress, and improves compensation efficiency. The ESP32 microcontroller serves as a high-speed digital controller capable of acquiring real-time measurements of voltage, current, and power factor while executing adaptive control algorithms with minimal computational delay. The integration of adaptive fractional-order control, Genetic Algorithm optimization, intelligent reactive power compensation, synchronized thyristor switching, and real-time monitoring distinguishes the proposed system from conventional SVC control strategies by providing superior voltage regulation, enhanced power quality, improved renewable energy integration, and greater electrical network stability.

Table I. What Happens When the System Starts

| Step | Action                                                                                  |
|------|-----------------------------------------------------------------------------------------|
| 1.   | The variac supplies the AC bus.                                                         |
| 2.   | The isolated sensing transformer measures the bus voltage.                              |
| 3.   | The rectifier/ADC provides a voltage measurement to the Arduino/ESP32.                  |
| 4.   | The zero cross detector tells the controller when each 10 ms half- cycle begins.        |
| 5.   | The controller compares measured RMS voltage with the reference voltage.                |
| 6.   | The controller decides whether more capacitive or inductive reactive power is required. |
| 7.   | Isolated gate drivers send controlled pulses to the SCRs.                               |
| 8.   | The TSC/TCR changes reactive current and therefore influences bus-voltage regulation.   |
| 9.   | The controller measures the bus again and repeats the process continuously.             |





#### IV. CONCLUSION

The scope of this research includes the modelling, design, implementation, and performance evaluation of an Adaptive Fractional-Order PI controlled Static Var Compensator for intelligent reactive power compensation in hybrid solar photovoltaic and wind energy systems. The proposed architecture consists of an ESP32-based digital controller, zero-crossing detection circuitry, synchronized thyristor firing unit, Static Var Compensator, voltage and current sensing circuits, power factor measurement, and Genetic Algorithm-based adaptive controller optimization. The developed controller continuously monitors electrical parameters including voltage, current, reactive power, and power factor while dynamically controlling thyristor switching to inject or absorb reactive power as required. The Adaptive Fractional-Order PI controller continuously adjusts compensation performance through online Genetic Algorithm optimization, enabling improved voltage stabilization during fluctuating renewable generation and varying load conditions. System performance is evaluated through simulation and experimental analysis using parameters such as voltage regulation accuracy, overshoot, settling time, power factor improvement, Total Harmonic Distortion reduction, and reactive power compensation efficiency. The proposed system is intended for hybrid renewable energy plants, industrial power systems, microgrids, distributed generation networks, and smart grid applications.

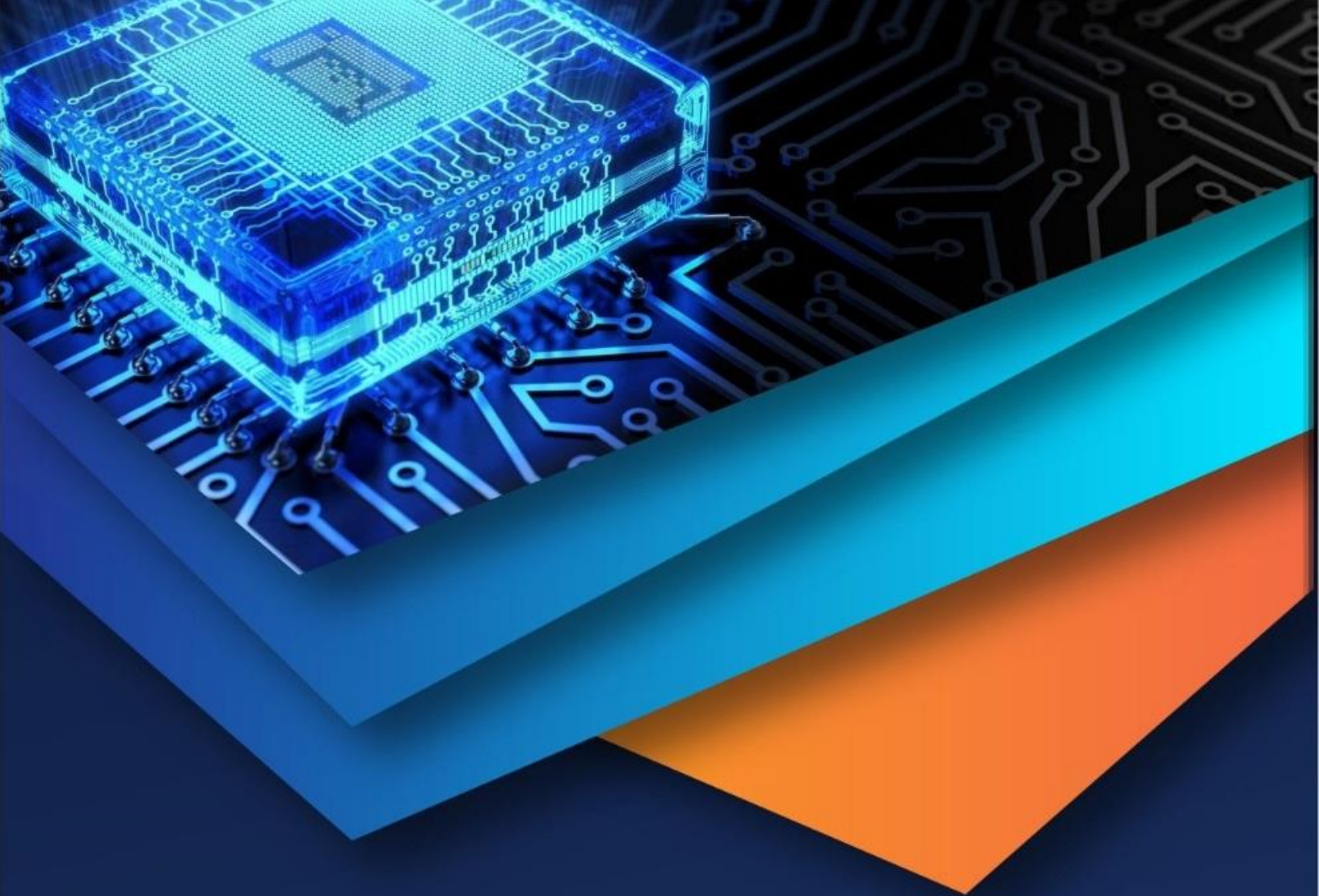
#### V. ACKNOWLEDGMENT

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