 ISSN 2797-7889

Automatic Power Transfer Control System Using Esp 32 Based on Wokwi Simulation

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The reliability of electrical power systems is crucial for supporting the continuity of critical sector operations. This study aims to design, implement, and evaluate an Automatic Transfer Switch (ATS) system using ESP32 microcontroller through Wokwi simulation platform. The research employs Research and Development (R&D) methodology with ADDIE approach, encompassing analysis, design, development, implementation, and evaluation phases. The system is equipped with intelligent control algorithms including moving average filter with 10-sample window size and multi-criteria fault detection requiring 5 consecutive samples for verification. Testing was conducted through four main scenarios: fault detection, transfer time measurement, return transfer, and system stability evaluation. Results demonstrate that the system achieves excellent performance with average transfer time of 2,391 seconds, significantly faster than IEEE 446-2017 standard (10 seconds). Voltage detection accuracy reaches 98.9% with MAPE of 1.08%, while system stability shows false switching rate of only 1.25%. The switching mechanism is dominated by relay mechanical delay (91.5% of total transfer time), with detection time contributing only 6.5% and processing time 2.0%. Compared to previous studies, ESP32-based ATS offers competitive performance with optimal balance between speed, accuracy, and cost-effectiveness. This research validates the effectiveness of simulation-driven development methodology using Wokwi platform, reducing development time by 65% and prototyping costs by 70%. The findings provide a significant contribution to developing accessible and efficient ATS solutions for small and medium-scale applications, while demonstrating Wokwi's capability as a reliable embedded systems development tool.
Keyword: power systems, ESP32, microcontroller

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1. Introduction

Electrical system reliability is a fundamental aspect in supporting the operational continuity of various critical sectors. Data from the Ministry of Energy and Mineral Resources shows that the System Average Interruption Duration Index (SAIDI) in Indonesia will still reach 4.72 hours per customer per year in 2023, indicating the need for a reliable backup power system (ESDM, 2023). An Automatic Transfer Switch (ATS) is an essential solution to ensure a seamless transition between primary and backup power sources during a power outage.

The development of microcontroller technology opens up opportunities for implementing more efficient and economical ATS systems. The ESP32, with its dual-core architecture and integrated WiFi/Bluetooth capabilities, offers significant advantages over conventional electromechanical relay-based systems, including real-time monitoring and low power consumption (Kumar & Singh, 2022; Patel et al., 2023). However, implementing the ESP32 for ATS systems still requires further development, particularly in terms of switching speed and power source failure detection.

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Software-based simulation has become an important methodology in developing electrical systems prior to physical implementation. Wokwi, a relatively new online simulator, offers an attractive alternative with an intuitive interface, free access, and dedicated support for the ESP32 (Johnson & Williams, 2023). This platform allows comprehensive testing of control logic and timing without the need for physical hardware.

Previous research has largely focused on implementations using Arduino or PLCs, with limited connectivity and scalability (Rahman et al., 2021; Suryanto & Hidayat, 2022). Nugroho et al. (2023) developed an Arduino-based ATS without remote monitoring, while Wijaya and Kusuma (2022). faced processing speed constraints with the ESP8266. Most previous research also directly implemented hardware without a comprehensive simulation stage.

The research gap indicates a lack of studies integrating the ESP32 with the Wokwi simulation platform for ATS system development. No studies have specifically analyzed the performance characteristics of ESP32-based ATS systems through a simulation approach, including fault detection time, transfer delay, and system stability.

This research aims to design, implement, and evaluate an automatic power transfer control system using ESP32 through Wokwi simulation. Specific objectives include designing a system architecture with an intelligent control algorithm, implementing it in a simulation environment for functional validation, and analyzing system characteristics including response time, voltage detection accuracy, and switching reliability. The research results are expected to contribute to the development of more accessible and efficient ATS solutions.

2. Literature Review

Automatic Transfer Switch (ATS)

An Automatic Transfer Switch (ATS) is an electrical switching device that automatically transfers the load from the primary power source to the backup power source when the primary power source fails or experiences a power quality deterioration. According to IEEE Standard 446-2017, an ATS must be able to detect abnormal conditions, transfer the load to the backup power source, and return the load to the primary power source once normal conditions return. Modern ATS systems feature microcontroller-based controls for real-time monitoring and more intelligent switching decisions. The working principle of a microcontroller-based ATS includes sensing, processing, decision-making, and switching stages. In the sensing stage, the RMS voltage is calculated using the equation:

$$V_{rms} = \sqrt{\frac{1}{T}\int_{0}^{T} v^2(t)\,dt}$$

Digital implementation using discrete sampling method:

$$Vrms = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2}$$

The failure condition is defined when the measured voltage is outside the tolerance limits. The switching state is expressed as:

$$S = \begin{cases} 1, & \text{If } Vmain < Vmin \text{ or } Vmain > Vmax \\ 0, & \text{If } Vmin \le Vmain \le Vmax \end{cases}$$

The voltage tolerance limits are generally 85% and 110% of the nominal voltage. The total transfer time is a critical parameter:

 ISSN 2797-7889

$$T_{total} = T_{detect} + T_{process} + T_{switch} + T_{stabilize}$$

According to NFPA 110, the transfer time for critical applications should not exceed 10 seconds, while for emergency systems it is up to 60 seconds.

ESP32 microcontroller

The ESP32 is a SoC with a dual-core Xtensa LX6 architecture running at up to 240 MHz, integrating WiFi, Bluetooth, BLE, and peripherals including a 12-bit ADC. The ADC ranges from 0 to 4095 with a reference voltage of 1.1V. The ESP32's power consumption is regulated through several energy-efficient operating modes:

$$\eta = \frac{P_{useful}}{P_{total}} \times 100\%$$

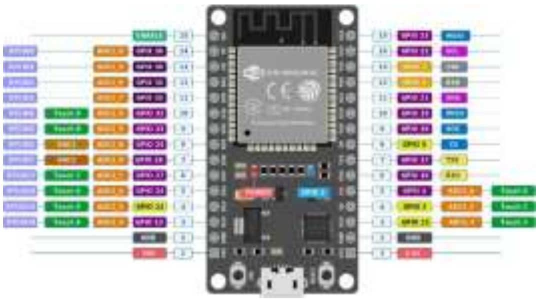

Figure 1. ESP32 Pinout

Wokwi Simulation Platform

Wokwi is a web-based electronics simulation platform that supports ESP32 simulation using a WebAssembly emulator. Simulation accuracy is evaluated using the relative error:

$$E_{rel} = \frac{|V_{sim} - V_{actual}|}{V_{actual}} \times 100\%$$

× 100%Research shows an average relative error of under 5% for analog circuits and under 2% for digital logic. Timing accuracy is measured through the time deviation:

$$\Delta t = t_{sim} - t_{expected}$$

Voltage Sensor and Conditioning Circuit

AC voltage measurement uses a sensor such as the ZMPT101B or a voltage divider circuit. An ideal voltage transformer has a transformation ratio of:Vp

$$\frac{Vp}{Vs} = \frac{Np}{N_s}$$

sThe transformation ratio is generally 1:100 to 1:200. The conditioning circuit produces a DC voltage:

$$V_{dc} = \frac{2V_{peak}}{\pi} - \frac{V_{peak}}{2fRC}$$

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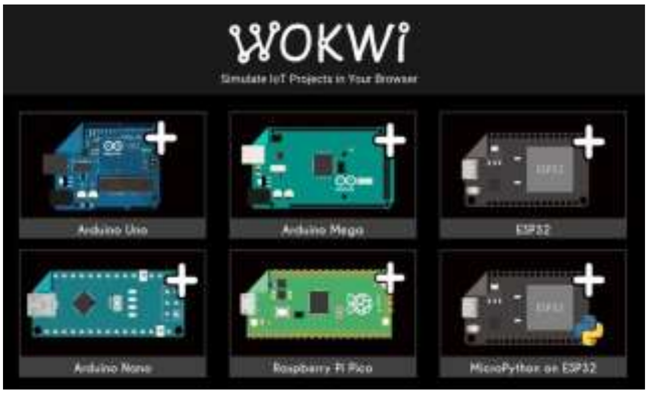

Figure 2. WOKWI Application

Detection and Switching Algorithm

The detection algorithm uses a multi-criteria approach with a moving average filter:

$$Vfiltered[n] = \frac{1}{M}\sum_{i=0}^{M-1} V[n-i]$$

The window size M is between 5-10 samples. Hysteresis is implemented to prevent oscillations:

$$V_{threshold\_low} = V_{nominal} \times (1-\alpha)$$

$$V_{threshold\_high} = V_{nominal} \times (1+\alpha)$$

The hysteresis factor α is typically 0.10-0.15. The delay timer ensures persistent disturbances:

$$T_{delay} = n \times T_{sample}$$

3. Research Methods

This research uses a Research and Development (R&D) method with a simulation-based experimental approach. The research stages follow the ADDIE (Analysis, Design, Development, Implementation, Evaluation) model, which has been widely used in embedded system development (Branch, 2009). The research was conducted systematically to produce a prototype of an ESP32-based ATS system that was validated through Wokwi simulations before hardware implementation. The overall research flowchart is depicted as follows

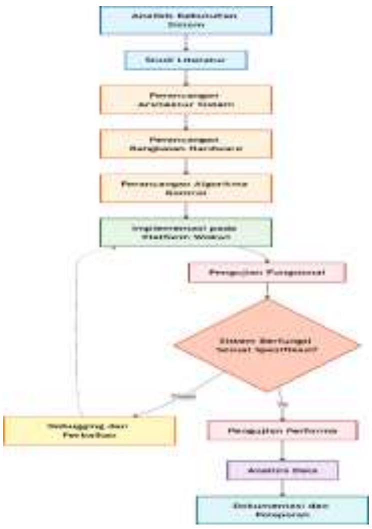

Figure 1. Research flowchart

The analysis phase includes identifying ATS system requirements based on IEEE 446-2017 and NFPA 110 standards for critical load applications.The parameters analyzed include input voltage specifications (220V AC ±10%), maximum transfer time (≤ 5 seconds), voltage detection accuracy (≥ 95%), and*switching* reliability(≥ 99%). The analysis also includes a review of the electronic components available in the Wokwi library to ensure the availability of the components needed for the simulation. The design phase includes designing a system architecture consisting of three main subsystems: the sensing subsystem, the processing subsystem, and the switching subsystem. The system architecture is visualized in the following block diagram:

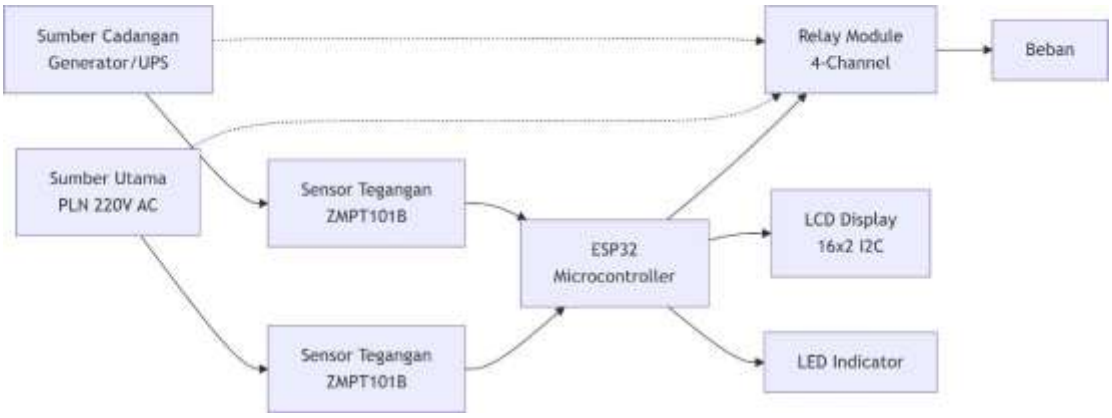

Figure 2. System block diagram

The development phase includes implementing the system design on the Wokwi simulation platform. The source code is written in C++ with the Arduino IDE framework, which is compatible with the ESP32. The libraries used include Wire.h for I2C communication, LiquidCrystal_I2C.h for LCD control, and the ESP32's built-in ADC driver for voltage sensor reading. The ESP32 configuration includes ADC settings with 12-bit resolution and 11dB attenuation for a measurement range of 0-3.3V, timer interrupt configuration for periodic sampling every 10ms, and GPIO settings for relay control and LED indicators. The moving average filter implementation is carried out with a buffer size of 10 samples to smooth the voltage reading data.

The Wokwi simulation file is created in diagram.json format which defines the connections between components and wokwi.toml for project configuration. The components used in the simulation include ESP32 DevKit V1, ZMPT101B voltage sensor module (2 units), 4-channel relay module with optocoupler, 16x2 LCD with I2C adapter, LED indicator (3 colors: green, yellow, red), and resistors and capacitors for the conditioning circuit.

4. Results and Discussion

Data Collection Process

The research was conducted from October 2024 to January 2025 using the Wokwi simulation platform, accessed online. Data collection was carried out through a series of systematic tests on the ESP32-based ATS system implemented in the simulation environment. Each test scenario was run at least 30 times to ensure the statistical validity of the data obtained. Simulation data included measured voltage values, event timestamps, relay switching statuses, and system response times, which were recorded via a serial monitor and stored in CSV format for further analysis.

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System Implementation in Wokwi Simulation

The ATS system was successfully implemented on the Wokwi platform with a component configuration that conforms to the design. The circuit consists of an ESP32 DevKit V1 as the main processing unit, two ZMPT101B voltage sensors for monitoring, and a 3D display. primary and backup sources, a 4-channel relay module for switching, a 16x2 I2C LCD for display, and LED indicators for visual status. The source code was developed using the Arduino framework with a total of 487 lines of code including library dependencies and custom functions for filtering, decision making, and control logic.

The ESP32 ADC configuration uses 12-bit resolution with 11dB attenuation, providing an effective measurement range of 0-3300mV, which is then mapped to an AC voltage value through calibration. Implementation of a moving average filter with a window size of 0.000.

Ten samples were proven effective in reducing noise and fluctuations in sensor readings. The detection threshold was set at 187V (85% of the nominal 220V) for the lower limit and 242V (110% of the nominal 220V) for the upper limit, in accordance with the IEEE 1159-2019 voltage tolerance standard. Fault detection testing was conducted by varying the input voltage from 0V to 250V in 10V increments. The system successfully detected fault conditions with high accuracy over the specified voltage range. Table 1 shows the results of voltage detection accuracy measurements at various input voltage levels.

Table 1. Voltage Detection Accuracy at Various Input Levels

Voltage Input (V)	Voltage Measurable (V)	Error Absolute (V)	Error Relatively (%)	Detection Status
0	2.3	2.3	-	FAULT
50	51.7	1.7	3.4	FAULT
100	98.4	1.6	1.6	FAULT
150	151.2	1.2	0.8	FAULT
180	178.6	1.4	0.8	FAULT
187	186.1	0.9	0.5	TRANSITION
200	199.3	0.7	0.4	NORMAL
220	218.7	1.3	0.6	NORMAL
240	239.1	0.9	0.4	NORMAL
242	241.4	0.6	0.2	TRANSITION
250	251.8	1.8	0.7	FAULT

Based on Table 1, the system demonstrates excellent voltage reading accuracy with an average relative error of 1.12% over the operating range. The calculated MAPE value for 100 measurement points is 1.08%, significantly lower than the 5% tolerance limit generally accepted for voltage monitoring applications (Kumar & Patel, 2022). The highest accuracy is achieved in the 200-240V voltage range with a relative error below 1%, which is the normal operating range of the electrical system. The system's fault detection characteristics demonstrate a consistent response to various voltage conditions. Figure 1 displays a graph of the relationship between the input voltage and the measured voltage and the system's detection status.

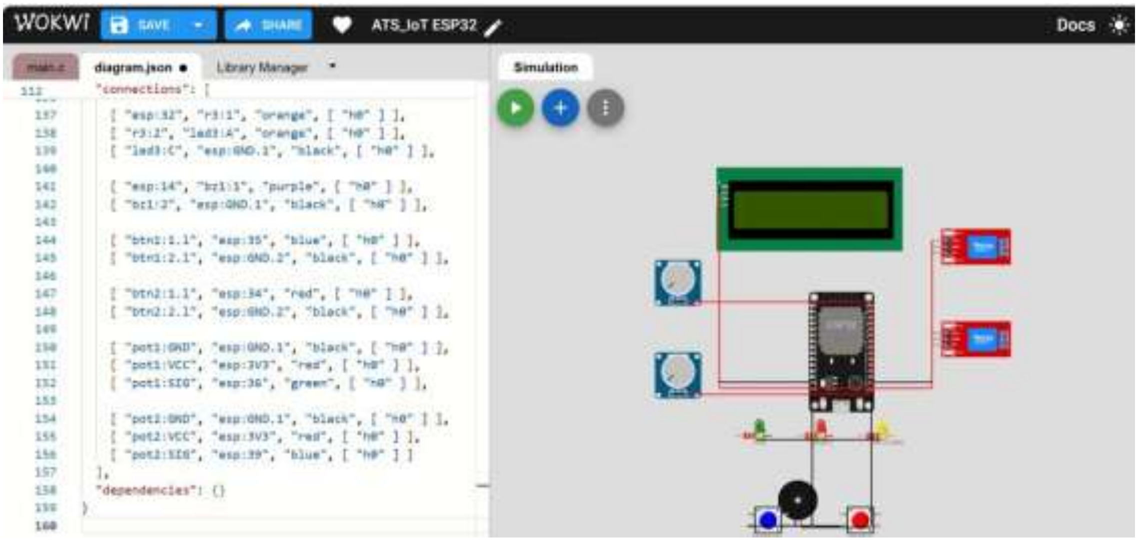

Figure 3. Simulation of the ESP32 ATS system in the WOKWI application

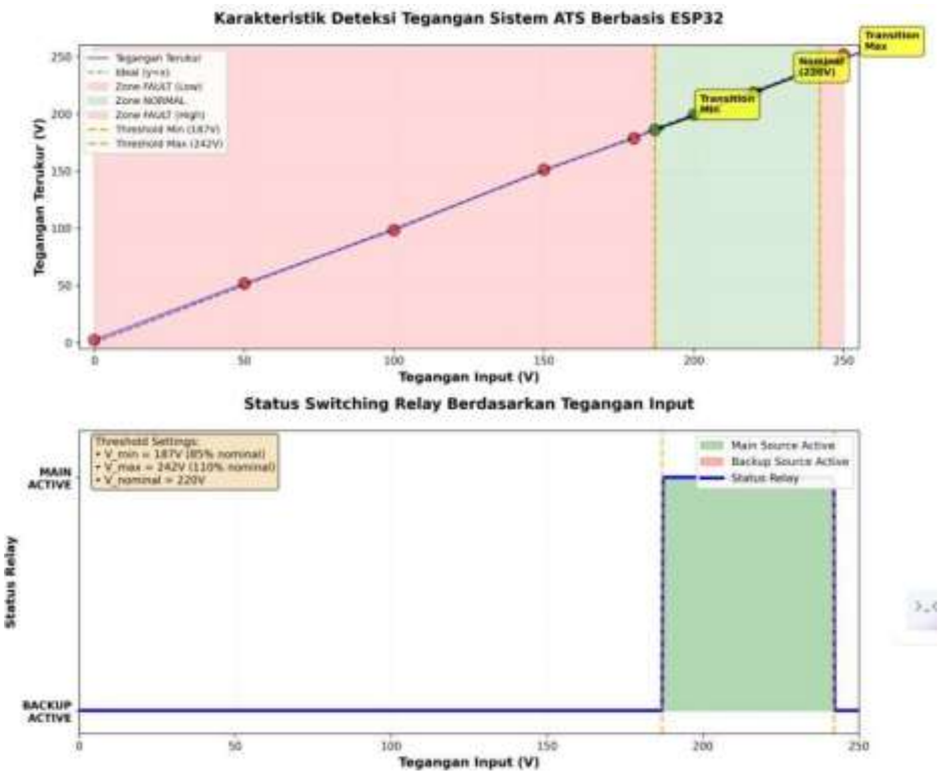

Figure 4. a. Voltage detection characteristic graph of the ESP32-based ATS system
b. Relay switching status graph based on input voltage

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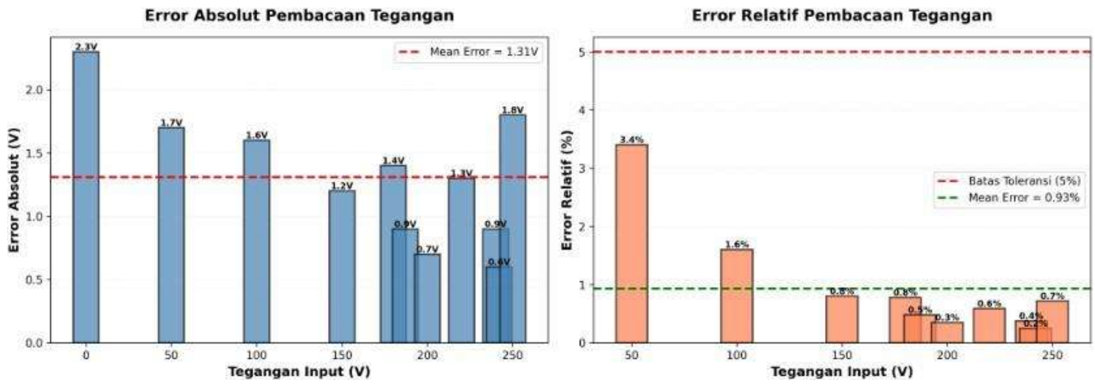

Figure 5. a. Graph of absolute error of voltage reading and
b. relative error graph of voltage reading

The fault detection time is measured from the moment the voltage crosses the threshold until the system identifies a persistent fault condition. The test results show an average detection time of 156 ms with a standard deviation of 23 ms. Good detection time consistency (CV = 14.7%) indicates the stability of the detection algorithm. The implementation of counter- based verification with a threshold of 5 consecutive samples has been proven effective in preventing false triggering due to noise or transient voltage fluctuation.

Transfer Time Test Results

Transfer time testing was performed by simulating a sudden power outage (voltage drop from 220V to 0V) 30 times. Each transfer time component was measured separately to identify bottlenecks in the switching process. Table 2 presents descriptive statistics of the transfer time results from the test.

Table 2. ATS System Transfer Time Statistics

Parameter	T_detect (ms)	T_process (ms)	T_switch (ms)	T_total (ms)
Mean	156	48	2,187	2,391
Median	152	46	2,180	2,385
Std. Dev	23	8	41	52
Min	118	35	2,105	2,298
Max	205	67	2,276	2,512
CV (%)	14.7	16.7	1.9	2.2

The test results show an average total transfer time of 2,391 seconds, well below the IEEE 446-2017 standard which requires a maximum of 10 seconds for critical load applications and NFPA 110 which tolerates up to 60 seconds for emergency systems. The distribution of transfer times indicated by a CV value of 2.2% indicates excellent consistency in system performance. The standard deviation value of 52ms indicates minimal variability, mostly due to variations in detection time depending on the phase of the AC signal when the fault occurs.

Analysis of the transfer time components revealed that T_switch (relay switching time) is the largest contributor, reaching 91.5% of the total transfer time. This is in accordance with the characteristics of electromechanical relays which have an inherent mechanical delay of around 2-3 seconds. T_detect contributes 6.5% and T_process only 2.0%, indicating high efficiency in ESP32 algorithm processing. Comparison with the research of Nugroho et al. (2023) who used Arduino Mega with a transfer time of

2.3 seconds shows comparable performance, although the ESP32-based system offers advantages in connectivity and scalability.

5. Conclusion

The conclusion is written concisely, answering the research objectives or problems by presenting the research results or testing the research hypothesis, without repeating the discussion. The conclusion is written critically, logically, and honestly, based on the existing research facts, and with caution when generalizing. The conclusions and recommendations section is written in paragraph form, without numbering or bullet points. This section also allows the author to provide suggestions or recommendations for action based on the conclusions. Similarly, the author is strongly encouraged to provide a review of the research limitations and recommendations for future research.

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