

DESIGN AND DEVELOPMENT OF A SINGLE-PHASE ELECTRICAL PROTECTION SYSTEM WITH FAULT IDENTIFICATION USING CURRENT AND VOLTAGE DETECTION METHODS

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ABSTRACT

Keywords:

Electrical Protection System,
Arduino Mega 2560,
Over Voltage,
Under Voltage,
Overload / Short Circuit,
Data Logging.

Electrical faults such as Over Voltage, Under Voltage, Overload, and Short Circuit can reduce the safety and reliability of low-voltage single-phase electrical systems. This study develops a prototype protection system that detects, identifies, and records fault conditions using current and voltage parameters. The system uses an Arduino Mega 2560 with PZEM-004T, ACS712, SCT-013-030, and ZMPT101B sensors, a Solid State Relay (SSR) for load disconnection, a 4×4 keypad for threshold setting, an LCD for status display, and RTC–Micro SD data logging in CSV format. The prototype was evaluated under normal operation and four fault conditions. Short Circuit identification combines Current Ratio and Voltage Sag with thresholds of $\geq 2.0\times$ and $\geq 25\%$, respectively, and an 80 ms Definite Time. The test results show that the SSR remains ON under normal conditions and successfully disconnects the load when faults are detected. In the short-circuit simulation using 220 Ω , 100 Ω , 68 Ω , and 47 Ω fault resistances, the system produced the status “TRIP SC - DEF.TIME” for all tested events. Sensor response testing selected SCT-013 as the main current sensor and ZMPT101B as the main voltage sensor, while ACS712 and PZEM-004T support validation, monitoring, and logging. The main novelty is local fault-type identification on the LCD combined with fault-history data logging.

INTRODUCTION

Electrical energy plays a vital role in modern activities, including household and industrial applications. As dependence on electrical energy increases, the safety and reliability of electrical systems become increasingly important. Poor power quality can cause disturbances and damage to electrical equipment and distribution systems (Galla et al., 2022; Gunawan & Sahar, 2024). In low-voltage single-phase installations used in residential and small-scale buildings, disturbances may occur in the form of Overload, Short Circuit, Over Voltage, and Under Voltage. These conditions can interrupt electrical service and may contribute to equipment damage, insulation deterioration, temperature rise, and fire risk (Saodah et al., 2019; Galla et al., 2022).

Conventional protection in low-voltage single-phase installations generally relies on Miniature Circuit Breakers (MCBs). An MCB provides automatic disconnection for excessive current caused by Overload or Short Circuit. However, the conventional protection approach does not primarily address Over Voltage and Under Voltage, and it does not provide explicit information about the type of fault that caused the disconnection. This limitation can make fault diagnosis and subsequent handling less informative (Saodah et al., 2019; Anwar, 2021). A protection system that combines sensing, fault classification, and local information can therefore provide additional diagnostic value beyond a simple trip function.

Previous studies have explored microcontroller-based protection and monitoring systems. Research has addressed three-phase overcurrent and Over/Under Voltage protection using Arduino-based systems, while other studies have investigated Over Voltage and Under Voltage protection using ZMPT101B and IoT platforms (Gunawan & Sahar, 2024; Mohamed Ayub et al., 2022). Other works have used Solid State Relay (SSR) for automatic disconnection or focused on monitoring current and voltage parameters using PZEM-004T (Hardiansyah et al., 2023; Kautsar et al., 2024). A single-phase disturbance relay based on Arduino has also been reported, but the protection focus remains on disturbance detection and load disconnection rather than combining several fault classes in one local diagnostic system (Muhammad & Elektro, 2020). The sensing strategy is also important because protection requires both sufficiently fast detection and informative measurement. SCT-013 has been applied as a non-invasive current sensor, while ACS712 provides analog Hall-effect current measurement. PZEM-004T provides a wider set of electrical parameters, including voltage, current, power, power factor, frequency, and energy, but uses digital communication. ZMPT101B provides an analog voltage signal suitable for rapid processing. Studies included in the proposal demonstrate the use of SCT-013 for electrical monitoring and ZMPT101B together with current sensing for electrical measurement applications (Sembiring et al., 2020; Habib et al., 2024; Nur Fauzan et al., 2024). These characteristics motivate the use of multiple sensors with different roles rather than forcing one sensor to serve all functions.

Based on these conditions, this study proposes a single-phase low-voltage protection prototype that integrates multi-sensor measurement, automatic load disconnection, local fault-type identification, and data logging. The system uses SCT-013 and ZMPT101B on the fast protection path, while ACS712 and PZEM-004T support validation, monitoring, and recording. Fault evaluation is organized from the highest-priority Short Circuit detection using Current Ratio and Voltage Sag, followed by voltage-fault evaluation and Overload evaluation using threshold and time characteristics. The novelty stated in the proposal is the combination of visual fault identification on the LCD and fault-history data logging, which extends the function of conventional protection by providing local diagnostic information. Therefore, the objective of this study is to design and develop an Arduino Mega 2560-based single-phase electrical protection prototype that (1) integrates current and voltage sensors, SSR, LCD, keypad, RTC, and Micro SD Card; (2) identifies the operating load under a single-active-load condition using electrical parameters; (3) detects and identifies Over Voltage, Under Voltage, Overload, and Short Circuit using Threshold, Current Ratio, Voltage Sag, Inverse Time, and Definite Time methods; (4) analyzes sensor characteristics to assign protection, validation, and monitoring functions; and (5) implements HMI and data logging for real-time operating and fault information.

RESEARCH METHOD

The study uses an Engineering Design (Rancang Bangun) method with an experimental approach. The research aims to develop a functional single-phase protection prototype and evaluate its performance through laboratory tests under normal operation and

simulated electrical faults. The research workflow consists of literature study, problem identification, system design, hardware assembly, component testing, software development, software testing, whole-system integration, evaluation, data analysis, and reporting.

The protection hardware integrates an Arduino Mega 2560 as the processing unit; SCT-013-030 and ACS712 as current sensors; PZEM-004T for electrical monitoring; ZMPT101B as the main voltage sensor; SSR-25DA as the switching actuator; LCD 16×4 I2C and a 4×4 keypad as the human-machine interface; RTC DS3231 and a Micro SD Card module for time-stamped CSV data logging; and a 5 V DC backup supply for the control subsystem. A Variac is used to vary the input voltage for Over Voltage and Under Voltage testing, while different electrical loads and controlled resistive fault elements are used during system evaluation.

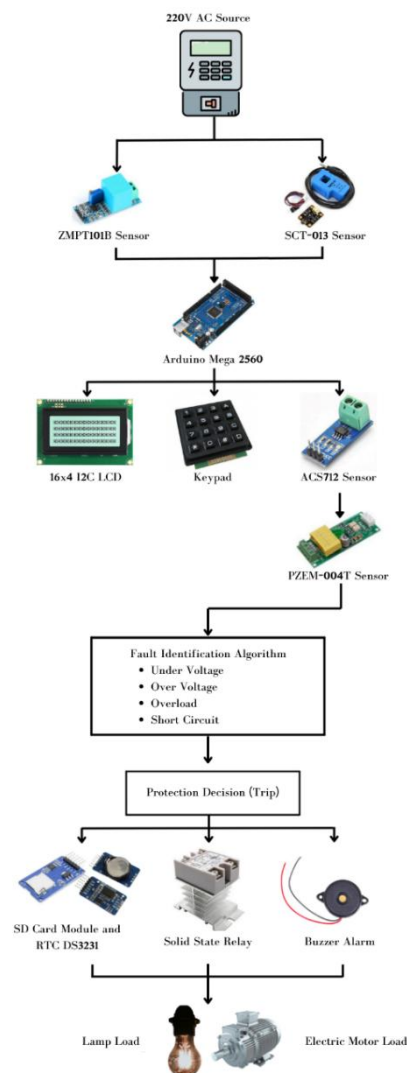


Figure 1. Functional Block Diagram Of The Proposed Single-Phase Protection System.

The sensor roles are determined from the proposal test results. SCT-013 is assigned as the main current sensor for the protection algorithm, ACS712 is used for current validation and comparison, PZEM-004T is used for monitoring and data logging, and ZMPT101B is

assigned as the main voltage sensor. The program is implemented as a state machine so that normal operation, fault indication, trip, verification, recovery, and logging can be processed in an organized sequence.

Short Circuit is evaluated with the highest priority. SCT-013 is used to calculate the Current Ratio relative to the current baseline, while ZMPT101B is used to calculate Voltage Sag. A Short Circuit candidate is formed when Current Ratio is at least $2.0\times$ and Voltage Sag is at least 25%. The candidate must persist for a Definite Time of 80 ms before the system classifies the event as Short Circuit, turns the SSR OFF, activates the buzzer, displays the fault on the LCD, and stores the event. Short Circuit remains latched until a manual reset is provided. For voltage faults, the ZMPT101B value is compared with V_{min} and V_{max} ; the proposal sets Under Voltage below 198 V and Over Voltage above 242 V, with a 2s definite delay. Overload is evaluated by comparing the current with the protection threshold and using an inverse-time characteristic.

System performance is evaluated from sensor response, measurement error, successful trip response, trip time, and recorded fault status. The prototype is tested under normal operation, Under Voltage, Over Voltage, Overload, and controlled Short Circuit conditions. Current and voltage readings are compared with reference instruments, and the internal data logger stores sensor values, event time, and protection status for subsequent analysis.

RESULTS AND DISCUSSION

Sensor Response and Functional Assignment

Sensor response testing was used to establish the protection priority. For current disturbance detection, SCT-013 had the fastest measured response at 262.10 ms, followed by ACS712 at 521.03 ms and PZEM-004T at 1,385 ms. For voltage disturbance detection, ZMPT101B detected the change at the first sampling cycle, recorded as 0 ms by the test timing resolution, whereas PZEM-004T showed an average response of 791.31 ms. The 0 ms value is interpreted in the proposal as first-cycle detection rather than a statement that the physical sensor response is literally zero.

Table 1. Sensor Response And Functional Assignment.

Sensor	Parameter	Response	Role
SCT-013	Current	262.10 ms	Primary protection
ACS712	Current	521.03 ms	Validation / comparison
PZEM-004T	Current / Voltage	1,385 / 791.31 ms	Monitoring / logging
ZMPT101B	Voltage	First sampling cycle	Primary voltage protection

Measurement-error tests also show that the sensors provide usable readings for their assigned functions. For voltage, ZMPT101B produced 0.18% and 0.23% error for the

motor and lamp tests, while PZEM-004T produced 0.36% and 0.41%. For current at the motor load, PZEM-004T, ACS712, and SCT-013 produced 0.74%, 0.99%, and 1.48% error, respectively. At the low lamp current of 0.15 A, the error increased to 0.67% for PZEM-004T, 6.67% for ACS712, and 13.33% for SCT-013. The proposal therefore supports the division of roles in which PZEM-004T is preferred for accurate monitoring, while SCT-013 and ACS712 are retained for fast detection and validation.

Table 2. Sensor Measurement Error Against Reference Instruments.

Test condition	Sensor	Reference	Sensor reading	Error
Motor voltage	ZMPT101B	220.0 V	220.4 V	0.18%
Motor voltage	PZEM-004T	220.0 V	220.8 V	0.36%
Lamp voltage	ZMPT101B	221.0 V	221.5 V	0.23%
Lamp voltage	PZEM-004T	221.0 V	221.9 V	0.41%
Motor current	PZEM-004T	4.06 A	4.09 A	0.74%
Motor current	ACS712	4.06 A	4.10 A	0.99%
Motor current	SCT-013	4.06 A	4.12 A	1.48%
Lamp current	PZEM-004T	0.15 A	0.151 A	0.67%
Lamp current	ACS712	0.15 A	0.16 A	6.67%
Lamp current	SCT-013	0.15 A	0.17 A	13.33%

Normal Operation

Under normal operating conditions, the system maintained the SSR in the ON state and did not issue a protection trip. The test loads included no load, lamp, motor, rice cooker, and electric pan. The recorded data in the proposal show that the system continued monitoring while the measured currents remained within the intended operating region. This normal response is important because the protection must distinguish regular load variation from fault conditions.

Under Voltage and Over Voltage Protection

The Under Voltage tests were performed by lowering the source voltage with a Variac. With a 205 V set point, all five tested load categories resulted in successful trip. The mean trip times were 2.063 s for no load, 2.072 s for rice cooker, 2.111 s for electric pan, 2.059 s for lamp, and 2.093 s for motor. The ZMPT101B readings in the Under Voltage tests followed the expected change in voltage and were sufficient to trigger the protection decision, while the event data were stored in CSV format.

The Over Voltage tests used a 242 V set point. All tested load categories also produced successful trip. The mean trip times were 2.078 s for no load, 2.086 s for rice cooker, 2.076 s for electric pan, 2.052 s for lamp, and 2.073 s for motor. The PZEM-004T and ZMPT101B readings showed similar voltage trends, while the ZMPT101B provided the fast-path

detection used by the protection algorithm. These results indicate that the definite-time logic can tolerate brief variation while still disconnecting the load when the abnormal voltage condition persists.

Table 3. Summary Of Voltage-Fault Protection Tests.

Fault	Set point	Tested loads	Trip result	Trip time
Under Voltage	205 V	No load, rice cooker, electric pan, lamp, motor	All successful	2.059–2.111 s
Over Voltage	242 V	No load, rice cooker, electric pan, lamp, motor	All successful	2.052–2.086 s

Overload Protection and Inverse-Time Characteristic

The Overload evaluation used increasing current multiple values. Loads below the protection region, including no load, rice cooker, electric pan, and lamp, did not cause a trip. When the current multiple reached $1.44\times$ with the motor, the system tripped. Higher combined-load conditions produced current multiples of $1.50\times$, $1.60\times$, $1.90\times$, and $2.00\times$ and were also tripped. The proposal compares the actual trip time with the IEC 60255 Standard Inverse calculation used in the project.

Table 4. Overload Inverse-Time Comparison.

Current (A)	Multiple	IEC trip (s)	Actual trip (s)	Error
4.50	$1.50\times$	5.57	6.69	16.74%
4.80	$1.60\times$	4.83	5.65	14.51%
5.70	$1.90\times$	3.56	3.75	5.07%
6.00	$2.00\times$	3.25	4.09	20.54%

The actual trip time decreases as the current multiple increases, following the intended inverse-time trend: larger fault current produces faster disconnection. The deviations from the IEC calculation are attributed in the proposal to sensor tolerance, microcontroller processing time, and SSR actuation characteristics. Thus, the implementation reproduces the intended direction of the Standard Inverse characteristic within the tested prototype conditions.

Short Circuit Identification Using Current Ratio and Voltage Sag

Short Circuit testing used controlled resistive fault elements of $220\ \Omega$, $100\ \Omega$, $68\ \Omega$, and $47\ \Omega$. The protection decision was based on the combination of Current Ratio and Voltage Sag, followed by an 80 ms Definite Time. The measured Voltage Sag values were 25.95%, 25.84%, 27.07%, and 37.13%, respectively, and the Current Ratio values were $2.00\times$, $2.58\times$, $2.69\times$, and $2.50\times$. Every tested group generated the status “TRIP SC - DEF.TIME” and the SSR was turned OFF.

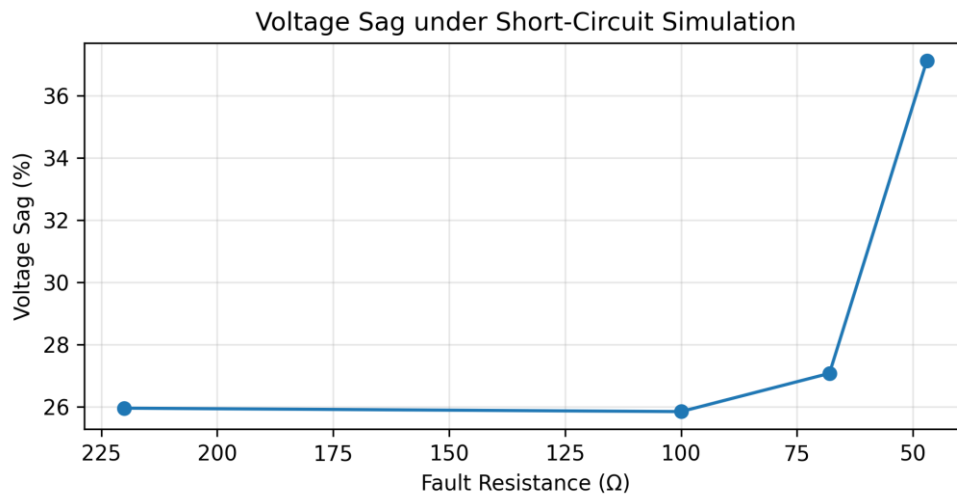


Figure 2. Voltage Sag Measured For The Four Controlled Short Circuit Resistances.

Table 5. Short Circuit Detection Results.

Fault resistance (Ω)	Voltage Sag (%)	Current Ratio	Mean trip time (ms)	Status
220	25.95	2.00×	117.0	TRIP SC - DEF.TIME
100	25.84	2.58×	128.9	TRIP SC - DEF.TIME
68	27.07	2.69×	137.9	TRIP SC - DEF.TIME
47	37.13	2.50×	131.5	TRIP SC - DEF.TIME

Across the tested resistance groups, the mean trip response was reported in the range of 117.0–137.9 ms, or approximately 0.12–0.14 s. The 80 ms Definite Time therefore represents the minimum persistence of the candidate condition, not the complete measured end-to-end response. The remaining response is influenced by acquisition, processing, state-machine evaluation, and the timing of the disturbance within the sampling cycle.

The Voltage Sag trend increases as the fault resistance decreases, although the relationship is not perfectly linear. Current Ratio also provides a sensitive indicator of the increase in current relative to the baseline. Combining the two parameters improves selectivity compared with relying on an absolute current threshold alone, while the Definite Time provides an additional persistence criterion before the trip decision.

Effect of Timer Interrupt Scheduler

The final software architecture uses a Timer4 interrupt scheduler with a 2 ms period so that protection-related tasks receive higher execution priority than slower monitoring and communication tasks. The proposal reports that this change reduced response time before and after implementation of the timer interrupt: Short Circuit improved from 1.08 s to 0.28 s, Under Voltage from 2.80 s to 2.09 s, and Over Voltage from 2.72 s to 2.05 s. The

reductions were 0.80 s, 0.71 s, and 0.67 s, respectively, with an average improvement of about 0.73 s.

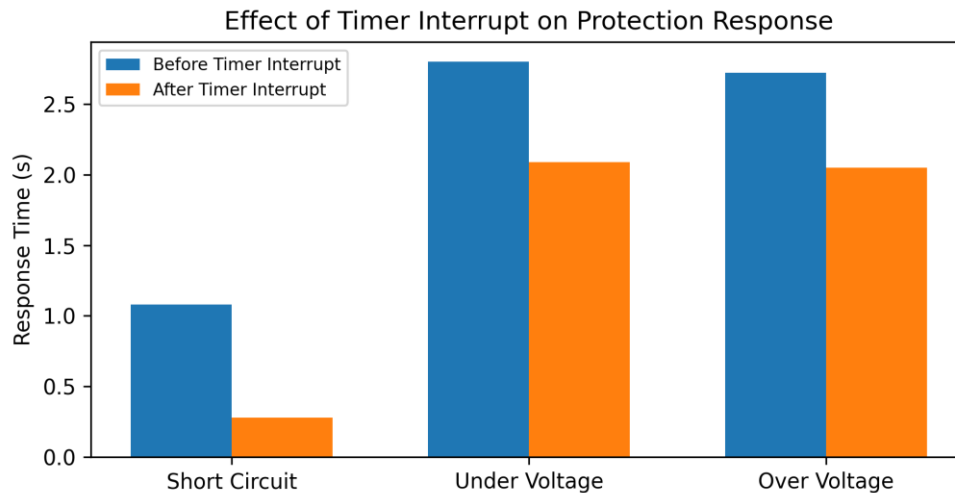


Figure 3. Protection Response Time Before And After Timer Interrupt Implementation.

Multi-Sensor Integration and System Performance

The results support a multi-sensor protection architecture in which each sensor is assigned a specific role. SCT-013 provides the rapid current path, ZMPT101B provides the rapid voltage path, ACS712 provides current validation, and PZEM-004T provides broader electrical monitoring and data logging. This assignment is consistent with the observed response times and measurement behaviour and allows protection decisions to prioritize faster analog signals while retaining richer digital measurements for monitoring.



Figure 4. Final Prototype Of The Single-Phase Electrical Protection System.

The prototype also integrates a local HMI and data logging. During fault tests, the system displays the fault condition on the LCD, activates the buzzer, controls the SSR, and records sensor parameters, event time, and status into CSV files on the Micro SD Card. The proposal identifies this local fault identification and fault-history logging as the main

novelty relative to conventional protection devices. The system is therefore not limited to disconnection; it also produces information that can be used to review the operating event.

Limitations

The short-circuit experiments were performed with controlled resistive fault elements in an isolated test arrangement rather than a dead short on a 220 V utility network. Consequently, the results validate the detection logic and prototype trip function but do not establish full-network short-circuit breaking capacity. The empirical response remains software-bound and is affected by sensor acquisition, RMS calculation, state-machine execution, and microcontroller timing. In addition, the SSR was not subjected to long-duration continuous current near its maximum rating, and the research scope is limited to low-voltage household or laboratory-scale applications rather than substation busbars or distribution-transformer environments.

CONCLUSION

The prototype single-phase electrical protection system was successfully implemented using Arduino Mega 2560 with multi-sensor acquisition, LCD and keypad HMI, SSR load disconnection, RTC time stamping, and Micro SD data logging. The system detected and identified Over Voltage, Under Voltage, Overload, and Short Circuit conditions and maintained normal operation without unnecessary trip under the tested normal-load cases. Sensor comparison established SCT-013 as the main current sensor and ZMPT101B as the main voltage sensor for the fast protection path, while ACS712 and PZEM-004T were assigned supporting validation, monitoring, and logging functions.

The Short Circuit algorithm using Current Ratio $\geq 2.0\times$, Voltage Sag $\geq 25\%$, and 80 ms Definite Time successfully produced "TRIP SC - DEF.TIME" across the tested fault-resistance groups. Detailed data show successful trip for every tested fault-resistance group, with mean responses reported around 0.12–0.14 s. Overload testing followed the intended inverse-time trend, while Under Voltage and Over Voltage testing produced successful trip responses close to their 2s definite delays. The integration of HMI and CSV data logging adds local fault identification and event history to the protection function, which is the principal novelty stated in the proposal.

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