

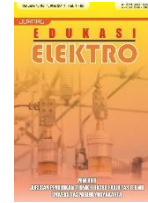


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## The Integration of Photovoltaics with an IoT-Based Automatic Transfer Switch System for Telecommunication Applications

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**Abstract**—The stability of the power supply is very important for keeping telecommunications infrastructure running smoothly. Problems with the power supply can cause network devices to lose service quality and even stop working. This study is on the development of an Internet of Things (IoT)-enabled Automatic Transfer Switch (ATS) system that can monitor and manage electrical resources in real-time over the internet. An ESP32 microcontroller, a Wi-Fi module, a ZMPT101B AC voltage sensor, an ACS712 current sensor, a DC voltage sensor, and an ADS1115 ADC were all put together to make the system more accurate. The Nuxt framework was used to construct a web interface that shows measurement data provided to the Firebase Realtime Database. The test results show that the system can consistently transition resources between the power grid and a Solar Power Plant. The error rate for AC voltage measurements is less than 2%, and the error rate for DC voltage measurements is less than 1%. The IoT-based monitoring system also has an average connection delay of 2 to 3 seconds, which is still acceptable for monitoring power supplies in telecommunications systems. The proposed system could be used as an intelligent power management solution for small to medium-sized telecommunications networks.

**Keywords:** automatic transfer switch, internet of things, power supply monitoring, telecommunications systems, photovoltaic system, ESP32.

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## 1. Introduction

Modern telecommunications infrastructure, including base stations (BTS), wireless access points, and network monitoring nodes, relies heavily on a steady and dependable electrical power supply. Interference with the power supply, whether it's caused by outages on the main electrical grid (PLN) or voltage changes caused by other technical problems, can lead to a big drop in service quality or even entire network outages[1]. The impact of these disruptions is not only operationally detrimental, but can also reduce user confidence in the services provided, especially in the digital era that demands continuous connectivity[2]. Therefore, ensuring a sustainable electricity supply is a crucial factor in maintaining the performance and reliability of telecommunications systems.

One typical way to make power supplies more reliable is to employ an Automatic Transfer Switch (ATS). This device automatically switches the load supply from the main source to the backup source when there is a problem, which keeps the service going. Initial research on ATS predominantly concentrated on electromechanical components and basic switching logic[3]. However, conventional ATS systems generally only function as automatic switches and do not provide real-time information regarding electrical conditions such as voltage, current, or power consumption[4]. These limitations make it difficult for operators to conduct performance analysis, early detection of potential disruptions, and optimization of energy use, especially when the backup source comes from intermittent renewable energy[5].

The development of Internet of Things (IoT) technology is opening up new opportunities in electrical system management. IoT enables the integration of electrical devices with data communication networks, allowing for remote monitoring and control in real time[6],[7]. The study in [8] created a prototype IoT-based solar energy monitoring system by combining an ESP32 microcontroller with a ZMPT101B voltage sensor and an ACS712 current sensor[9]. The device was able to measure voltage with an accuracy of 1% and could find power problems early on. Another study by [10] improved a hybrid solar energy system by using cloud-based real-time data capture. This showed that continuously monitoring solar irradiance and module temperature greatly improved thermal efficiency[11].

The application of IoT to ATS systems in the context of telecommunications infrastructure allows operators to obtain precise data on power supply conditions, which can be accessed at any time through a web interface or mobile app, in addition to ensuring supply continuity. The integration of solar power plants (PLTS) as an alternative energy source is becoming increasingly relevant in accordance with global efforts in the energy transition[12]. Solar power plants can be a green and long-lasting backup supply, especially in places that are far away or often lose power. Research by [13] created a hybrid energy harvesting subsystem for IoT applications in smart cities. It showed that it could convert power with an efficiency of up to 51% and produce steady voltage with enough maximum power for small telecommunications devices. This new idea could be useful for next-generation IoT applications in important parts of infrastructure[14], [15].

Several previous studies have examined the development of IoT-based Automatic Transfer Switch (ATS) and monitoring systems. Research by [16], [17] developed a smart ATS for household applications with basic monitoring features, while focused on an IoT-based three-phase electrical load monitoring system using the Firebase Realtime Database. However, studies specifically integrating IoT-based ATS with photovoltaic systems (PLTS) to support telecommunications infrastructure needs are still limited. Several important aspects, such as the accuracy of measuring electrical parameters from sources with different quality between the relatively stable conventional electricity grid and the inverter output of PLTS which potentially contains harmonics have not been explored in depth[18], [19]. Furthermore, communication latency performance for real-time monitoring in telecommunications systems that demand fast response is also rarely evaluated quantitatively in the context of IoT-based ATS. Recent research shows that the use of the Firebase Realtime Database is quite effective for IoT data synchronization, with a transmission success rate reaching 99.2% and control latency below 1.5 seconds. However, the study has not tested the system performance under resource switching conditions that can trigger momentary data fluctuations, so further evaluation in this scenario is still needed[20], [21].

A significant issue in utilizing Hall-effect current sensors like the ACS712 is its susceptibility to noise and harmonics, particularly when employed with low-quality power sources such as solar power plant inverter outputs[22]. A study by [23] shown that the implementation of digital signal processing (DSP) techniques, including moving average filters and adaptive filtering, can enhance measurement accuracy in solar power systems by as much as 15%. This facilitates the integration of signal processing techniques at the microcontroller level to enhance data reliability prior to transmission to the cloud[24].

While numerous studies have investigated IoT-based Automatic Transfer Switch (ATS) systems and photovoltaic (PV) monitoring separately, there is a paucity of study focusing on the integration

of an IoT-enabled ATS with solar systems designed for telecommunication infrastructure. Prior studies predominantly emphasize fundamental switching processes or isolated monitoring systems, lacking a thorough assessment of essential performance metrics, including switching reliability, measurement accuracy under varying power quality conditions, and communication latency[25].

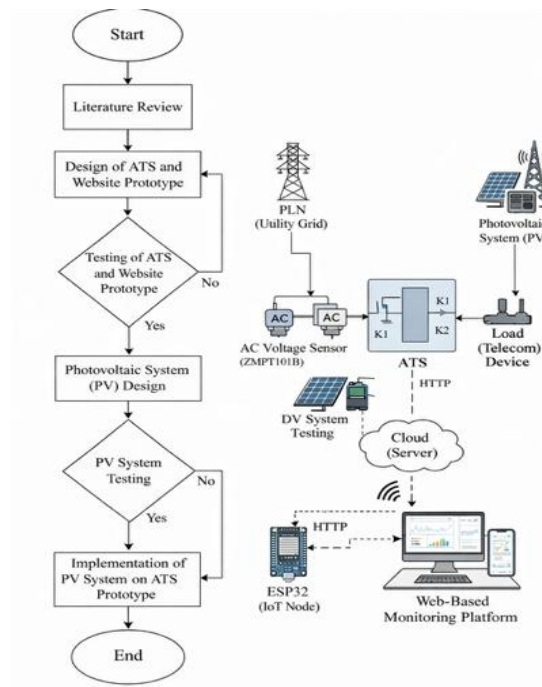
This study presents an integrated IoT-based ATS system coupled with a photovoltaic power source, specifically tailored for telecommunication applications. The primary contributions of this research are: (1) the creation of a hybrid ATS system that autonomously alternates between PLN and PV sources, (2) the improvement of measurement precision through a high-resolution ADS1115 ADC, (3) an extensive assessment of sensor efficacy under varying power quality conditions (PLN versus PV inverter), and (4) a quantitative examination of communication latency and switching efficiency in real-time IoT monitoring systems.

This research aims to provide a viable and validated intelligent power management system solution to enhance the operational stability of small to medium-sized telecommunications infrastructure, while promoting the adoption of renewable energy within the industry. Additionally, the findings of this research can serve as a foundation for further advancements, including the incorporation of machine learning-based predictive algorithms to enhance energy efficiency, the utilization of edge computing to minimize latency, and the formulation of cybersecurity protocols to safeguard data and system controls from external threats[26], [27], [28].

## 2. Method

### 2.1. Diagram and System Architecture

Figure 1 illustrates the architecture of the ATS system that is based on the Internet of Things. The system comprises two electricity sources: a photovoltaic (PV) system and the utility grid (PLN). A relay-based ATS module, which is managed by an ESP32 microcontroller, is connected to both power sources.



**Figure 1.** Flowchart of the research methodology for the proposed IoT-based ATS integrated with a photovoltaic system.

The ADS1115 external analog-to-digital converter (ADC) is utilized to enhance measurement precision relative to the internal ADC of the ESP32 microcontroller. The inbuilt ADC of the ESP32 possesses a 12-bit resolution and is recognized for its non-linearity and noise in variable voltage circumstances. The ADS1115 offers 16-bit resolution with enhanced stability and noise immunity, rendering it more appropriate for accurate electrical parameter measurements, particularly for assessing signals from photovoltaic inverter outputs that may exhibit harmonics and fluctuations.

The primary processing device is the ESP32, which is responsible for the acquisition of sensor data, the determination of switching options, and the transmission of data over a Wi-Fi grid. The ACS712 current sensor is employed to measure the load current, the ZMPT101B AC voltage sensor is employed to monitor the PLN grid voltage, and the DC voltage sensor is employed to monitor the PV system output. The system is equipped with an ADS1115 ADC module to enhance the resolution and accuracy of measurements.

## 2.2. Model for Measurement and Calculation

Electrical and communication parameters were quantitatively analyzed to assess the reliability of the Automatic Transfer Switch (ATS) power supply and the performance of the IoT-based monitoring system. The assessment emphasizes the efficacy of data communication, power consumption, measurement accuracy, load current characteristics, and effective voltage representation. In telecommunications infrastructure, where consistent power delivery and timely monitoring are essential, these parameters are essential for evaluating the suitability of the proposed system [29], [10].

The ZMPT101B sensor was employed to measure the AC voltage that was supplied to the load. The voltage was expressed in terms of its root mean square (RMS) value, as telecommunication equipment responds to the effective value of an alternating signal. The RMS voltage is a dependable indicator of supply stability, as it represents the equivalent DC voltage that delivers the same power to the load. Equation (1) was employed to determine the RMS voltage, where  $v_i$  represents the instantaneous voltage sample and  $N$  represents the total number of acquired samples.

$$V_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^N v_i^2} \tag{1}$$

The ACS712 sensor was employed to measure the load current, which produces an output voltage that is directly proportional to the current traveling through the load. Equation (2) was employed to convert the sensor output voltage to the actual current value. In this equation,  $V_{out}$  denotes the sensor output voltage,  $V_{offset}$  corresponds to the reference voltage at zero current, and  $S$  denotes the sensor sensitivity.

$$I = \frac{V_{out} - V_{offset}}{S} \tag{2}$$

The measured RMS voltage and load current were used to ascertain the electrical power consumed by the load. The energy requirements of telecommunication devices and the adequacy of the photovoltaic (PV) system when operating as an alternative power source were evaluated using the power parameter. Equation (3) was implemented to determine the discharge power.

$$P = V_{rms} \times I \tag{3}$$

Calculating the relative error between the sensor measurement values and the reference values derived from a standard measuring instrument was used to assess the monitoring system's accuracy. This analysis offers an impartial evaluation of the reliability of measurements and the performance of sensors. Equation (4) was implemented to ascertain the measurement error.

$$\text{Error}(\%) = \left| \frac{X_{\text{measure}} - X_{\text{reference}}}{X_{\text{reference}}} \right| \times 100 \tag{4}$$

The end-to-end monitoring latency was assessed in order to further analyze system performance from a telecommunications perspective. The time difference between the transmission of data by

the ESP32 microcontroller and its reception on the web-based monitoring interface is referred to as delay. This parameter is indicative of the IoT system's responsiveness and its suitability for real-time monitoring applications. Equation (5) was implemented to determine the delay.

$$\text{Delay} = t_{\text{receive}} - t_{\text{send}} \tag{5}$$

Root Mean Square Error (RMSE) quantifies the overall deviation between sensor measurements and reference instrument readings across all N test points. Unlike the percentage error in Eq. (4) which evaluates accuracy at each individual sample, RMSE provides a single aggregate metric that penalizes larger deviations more heavily due to the squaring operation. A lower RMSE indicates higher sensor consistency across the full operating range. In this study, RMSE is applied to evaluate the ACS712 current sensors across six load levels (10W–100W) for both PLN and PLTS sources, enabling a comparative assessment of sensor performance that is not biased by isolated high-error outliers at low load conditions.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_{\text{sensor},i} - X_{\text{ref},i})^2} \tag{6}$$

### 2.3. Procedure for Integrated Switching, Communication, and Testing

The Automatic Transfer Switch (ATS) functions in accordance with the primary power source's predetermined voltage threshold conditions. The system autonomously transfers the load to the photovoltaic (PV) power source when the measured utility grid voltage falls below the minimum allowable limit. If the utility voltage returns to its standard operating range, the system will revert the load to the grid supply. The ESP32 microcontroller implements this switching logic to guarantee the uninterrupted supply of power to telecommunication equipment.

At the same time, electrical parameters such as voltage, current, and power are perpetually monitored and transmitted to a cloud server via a Wi-Fi grid using the HTTP protocol. The web-based monitoring interface is used to visualize the measurement data, which are stored in the Firebase Realtime Database. The end-to-end monitoring latency, which is the time difference between data transmission by the ESP32 and data reception on the web interface, is the metric used to evaluate system performance from a telecommunications perspective. Figure 2 shows the workflow of the proposed IoT-based ATS system.

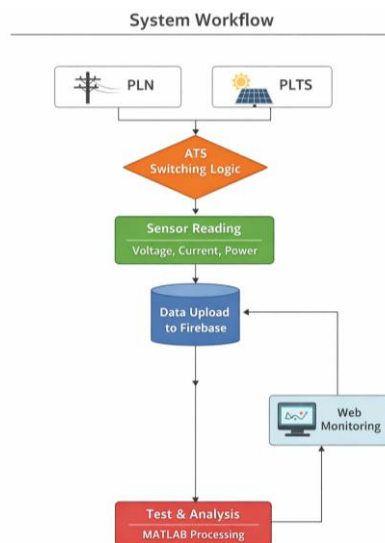


Figure 2. Workflow of the proposed IoT-based ATS system

The testing process entails the real-time monitoring of electrical parameters during simulated utility power disturbances and under normal operating conditions. Throughout the test scenarios, the following are recorded: communication latency, load continuity, and switching response time. To assess the reliability of the ATS operation and the efficacy of the IoT-based monitoring system, all data that has been collected is processed and analyzed using MATLAB.

The suggested system's integrated hardware design amalgamates automatic power source switching, electrical parameter monitoring, and IoT-based data exchange into a singular control framework, as depicted in Figure 3. The system employs two AC power sources: the utility grid (PLN) and a photovoltaic power supply (PLTS), interconnected via SPDT and DPDT relay modules to facilitate the Automatic Transfer Switch (ATS) function. The relay structure facilitates regulated and isolated switching of the live (L) and neutral (N) lines, guaranteeing secure and continuous power supply to communications loads.

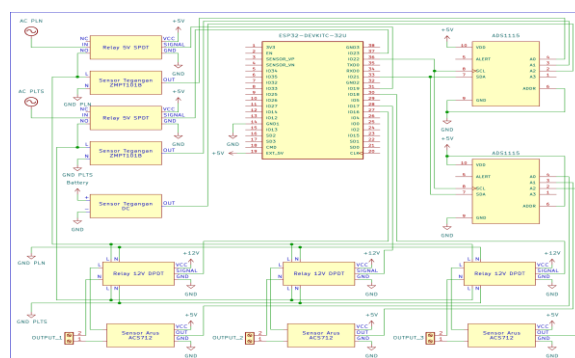


Figure 3. Integrated hardware architecture of the IoT-based ATS system

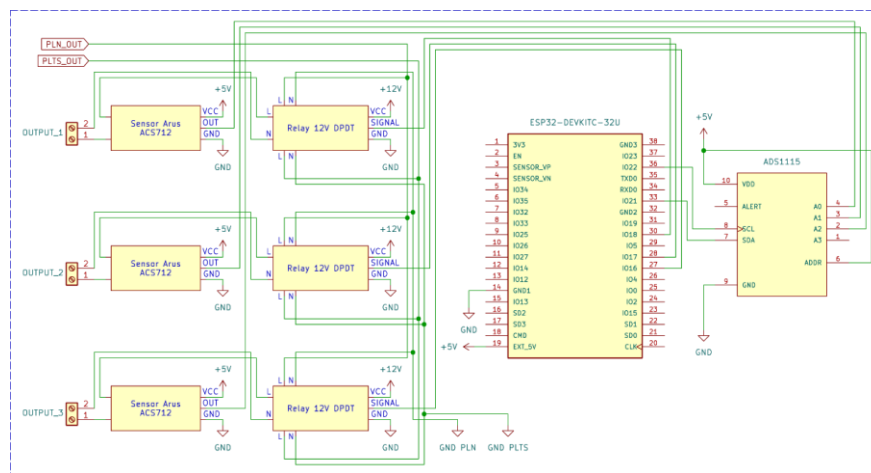
The ATS design includes additional protection components to guarantee system safety and reliability. These consist of surge protection devices (SPD) to safeguard against transient voltage increases, fuses to prevent short-circuit damage, and miniature circuit breakers (MCB) for overcurrent protection. In telecommunication environments, where system reliability is paramount, these protection mechanisms are indispensable for safeguarding both the burden and the electronic components. Voltage monitoring for both AC sources is conducted utilizing ZMPT101B voltage sensors, which deliver separate analog voltage signals that are proportionate to the input AC voltage. The signals are directed to ADS1115 analog-to-digital converters to improve measurement resolution prior to processing by the ESP32 microcontroller. The DC voltage of the battery system linked to the PLTS is monitored with a DC voltage sensor to evaluate the availability and stability of the backup power supply during grid disruptions. Figure 4 shows the prototype design of an automatic transfer switch (ATS).



Figure 4. Automatic transfer switch (ATS) prototype design

Current measurements are conducted via ACS712 current sensors positioned at various output channels. These sensors provide real-time observation of load current fluctuations during standard operations and source transition events. The recorded voltage and current data are utilized to compute electrical power consumption, which is essential for assessing the energy demands of communication equipment and the sufficiency of the PLTS capability.

The ESP32 microcontroller functions as the primary processing and communication unit, tasked with executing switching logic, acquiring sensor data, and transferring measurement results to the cloud server through a Wi-Fi connection. The choice to switch is predicated on established voltage threshold conditions of the PLN supply. When the monitored grid voltage falls outside the permissible threshold, the ESP32 engages the relay system to redirect the load to the PLTS. Upon the restoration of the grid voltage to its nominal range, the system autonomously reconnects the load to the PLN source. Figure 5 shows a detailed schematic of the proposed ATS system integrated with an IoT-based monitoring platform.



**Figure 5.** The detailed schematic of the proposed ATS system integrated with an IoT-based monitoring platform

The load used in this study is designed to represent typical telecommunication equipment, such as routers, base station controllers, and network devices. The load variation ranges from 10W to 100W, simulating different operational conditions from standby to peak usage. The system operates at a nominal voltage of 220V AC, reflecting standard telecommunication power supply conditions.

The system uses a DPDT relay setup to switch automatically between the main power source (PLN) and the backup solar system (PLTS). To keep the electricity from flowing back and forth between the two sources, the live (L) and neutral (N) lines are turned at the same time. When voltage readings from the sensing units are sent to the ESP32 microprocessor in real time, it controls the switching mechanism. The system instantly moves the load to the PLTS source when the PLN voltage drops below a certain level. On the other hand, when the PLN supply goes back to normal, the load is moved back to the grid.

Within the control logic, there is an interlock device that makes sure that at any given time, only one power source is connected to the load. This makes the system safer and more reliable. The connected loads represent telecommunication equipment such as routers, base stations, or network devices, which require continuous and stable power supply. Also, current sensors (ACS712) are put on each output line to keep an eye on how much power the load is using in real time, and voltage sensors check the state of the source. The addition of the ADS1115 high-resolution ADC improves the accuracy of measurements, especially when solar inverter outputs are changing.

Basic electrical safety parts like fuses or circuit breakers can be built into the design to make it even safer by lowering the risks of overcurrent and short-circuit situations. Overall, this design makes sure that power switching is reliable, that monitoring is always going on, and that the

telecommunications infrastructure is more stable when it comes to running. During system testing, multiple operational scenarios were implemented, encompassing standard grid operation, simulated grid failure, and grid restoration. Electrical characteristics, switching response times, and data transmission timestamps were continuously recorded. All collected data were transmitted to the Firebase Realtime Database and viewed via a web-based interface, while additional data processing, statistical analysis, and graphical representation were performed using MATLAB. This integrated technique facilitates a thorough assessment of ATS dependability, electrical performance, and IoT connectivity attributes for telecommunications power supply systems.

### 3. Result and Discussion

This section delineates the experimental outcomes derived from the execution of the proposed IoT-based Automatic Transfer Switch (ATS) system. The findings are analyzed regarding the precision of electrical parameter monitoring, ATS switching efficacy, and IoT communication attributes. All data were obtained from experimental testing of the prototype system, and statistical processing and visualization were conducted using MATLAB.

#### 3.1. Voltage and Current Monitoring Results

This section delineates the outcomes of evaluating the precision of the ACS712 current sensor functioning on a PLN power supply with a load fluctuation ranging from 10W to 100W. Eighteen sensor units were concurrently evaluated to assess the consistency and reliability of current measurements in an IoT-based monitoring system. The acquired raw data represents the percentage inaccuracy for each sensor at various load levels. Figure 6 shows the variation of ACS712 current measurement errors at various load levels.

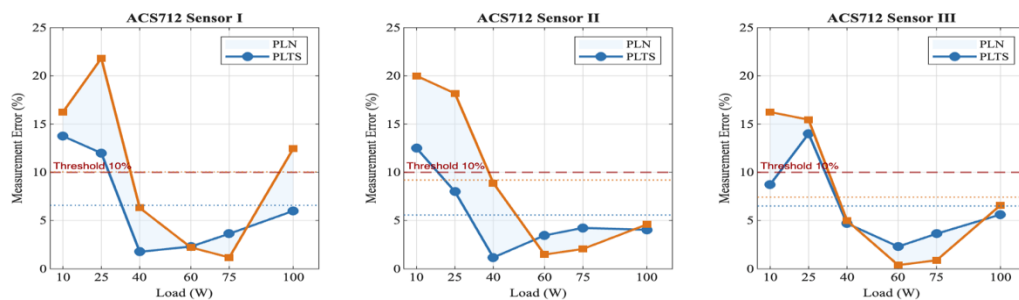


Figure 6. Variation of ACS712 current measurement error at different load levels

The data indicates a distinct correlation wherein measurement inaccuracy is inversely related to the load. At minimal loads (10W), the discrepancy between sensors fluctuates significantly, spanning from 0% to 20%. Sensor II reported the largest error at 20%, although numerous sensors, including IV, V, VI, and VII, achieved a 0% error rate. This occurrence validates the typical attributes of Hall-effect-based current sensors (ACS712), which are constrained to monitoring low currents close to their lowest specifications. At low currents, the signal-to-noise ratio (SNR) diminishes, resulting in internal noise and offset becoming more pronounced, which leads to erroneous readings.

Upon increasing the load to 25W, the inaccuracy diminishes to a range of 1–22%, but Sensor I continues to exhibit a significant error of 22%. At loads of 40W and above, most sensors (except Sensors I, II, and a few others) may attain errors below 2%, with several continuously achieving 1% accuracy. The ACS712 operates optimally at medium to high currents, consistent with the manufacturer's requirements, which are typically intended for current measurements above 1A (equal to a 220W load at 220V). In telecommunications applications, where device power consumption fluctuates between standby and full operation, our findings underscore the necessity for specialized management of low-load measurements, such as employing a sensor with enhanced sensitivity or utilizing averaging techniques.

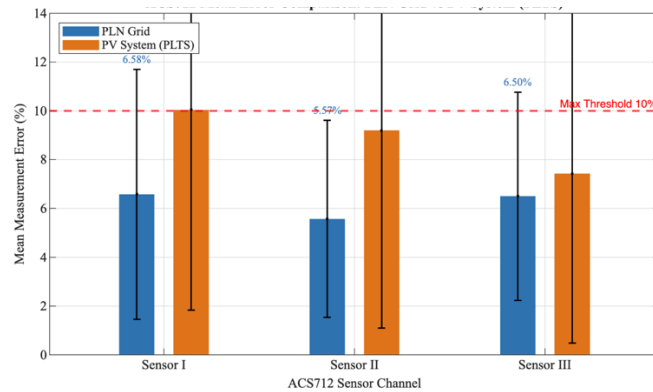
Current measurement is a vital metric in power monitoring systems, especially for maintaining load balance and identifying anomalous conditions in the power source. Table 1 provides a statistical summary of the evaluation of three ACS712 sensor units (S1, S2, S3) across two distinct power sources: the PLN grid and a solar power plant (PLTS).

**Table 1.** Overview of ACS712 current sensor precision metrics

Sensor-Source	Mean Err%	Std Dev%	Max Err%	RMSE (A)
S1-Grid	6.58%	5.12%	13.75%	0.01404 A
S1-PV	10.04%	8.21%	21.82%	0.02787 A
S2-Grid	5.57%	4.04%	12.50%	0.01159 A
S2-PV	9.20%	8.11%	20.00%	0.01584 A
S3-Grid	6.50%	4.27%	14.00%	0.01425 A
S3-PV	7.43%	6.95%	16.25%	0.01586 A

The investigation results show that all the sensors constantly had bigger measurement errors when checking the current from the photovoltaic (PV) system versus when checking the current from the grid supply. The average error of sensor S1 when measuring PV power was 10.04 percent, which is a lot more than the error it had when it was connected to the grid, which was 6.58 percent. The way this happens makes me think that the PV system's electrical output may have a big effect on how well the ACS712 current monitor measures current. Figure 7 shows a comparison of the average error between the grid and the solar panels.

One reason could be the quality of the waveforms that the PV converter makes. The inverter's process of converting DC to AC can change the output pattern and add switching noise and harmonic distortion. Such waveform features that aren't ideal may make Hall-effect current sensors less accurate, since they are sensitive to changes from a purely sinusoidal current waveform. These sensors include the ACS712. So, the differences in measurement accuracy are caused by differences in the quality of the waveforms between the grid source and the inverter output.



**Figure 7.** Comparison of average error between the power grid and solar panels

Another important thing to note is that different sensor units act differently, even when they are all working in the same measurement conditions. Sensor S2 did the best job overall when reading current from the grid source. It had the lowest average error (5.57%) and the smallest standard deviation (4.04%). When measuring PV-generated current, on the other hand, sensor S1 made the biggest mistake, hitting 21.82%.

This difference shows how factory calibration tolerances and the variability of the parts can affect the accuracy of the end measurement. Even though the sensors are all the same type, each unit may have slightly different offset voltages, sensitivity levels, or noise levels. Because of this, individual sensor calibration is necessary for large-scale or high-precision uses. It is suggested that each sensor unit be calibrated at two points to cut down on systematic measurement mistakes and make the whole system more reliable.

The experiment produced Root Mean Square Error (RMSE) numbers that were not more than 0.03 A in any of the measurement situations. In terms of amperage, this means that the difference

between the measured current and the reference number is not very big from an absolute measurement point of view.

On the other hand, when measuring PV current with sensor S1, the biggest mistake seen in the experiment was 21.82%. It's not possible to ignore a relative error that high, especially when it comes to decision thresholds or control systems. In automatic transfer switch (ATS) devices, for instance, switching decisions may go wrong if the current readings are off.

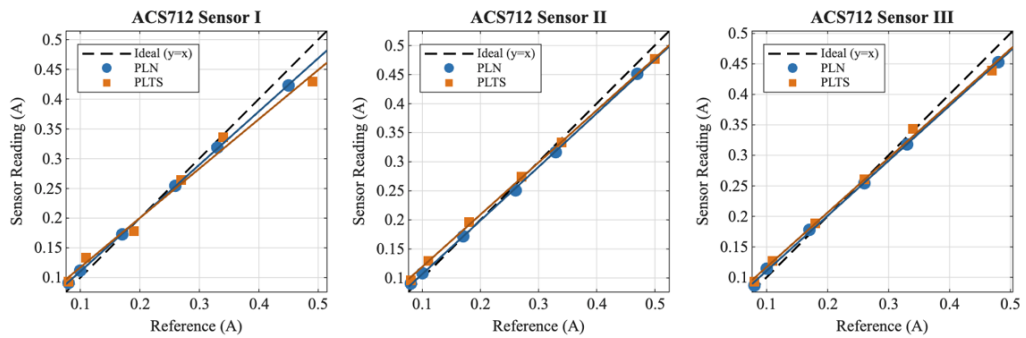


Figure 8. Sensor reading by linear regression

Overall, the results show that the ACS712 sensor can be used to track current in most situations, but it might not be as accurate when connected to power sources that don't provide ideal power quality, like PV inverter outputs. Several options can be thought about to improve the accuracy of measurements in future system builds.

First, technologies that measure current more accurately can be used, like current transformers (CTs) mixed with high-resolution external analog-to-digital converters. In power electronics settings, these sensors usually work better at blocking noise and keeping measurements stable. Second, digital signal processing methods, like digital filtering, can be used to get rid of noise and harmonics in the data being measured. In hybrid power settings with both grid and renewable energy sources, these filtering methods can make measurements much more stable and the sensing system more reliable.

Furthermore, the measurement inaccuracies observed in the PV system can also be associated with Total Harmonic Distortion (THD) introduced by the inverter. Unlike the relatively stable sinusoidal waveform of the grid supply, inverter outputs often contain harmonic components that distort the waveform. These distortions can significantly affect Hall-effect sensors such as ACS712, which rely on stable magnetic field responses. As a result, the presence of harmonics contributes to higher measurement errors in PV-based power sources.

### 3.2. Performance of IoT Communication Latency

One of the main pillars of the proposed system is its ability to monitor and control resources in real time over the internet. Table 2 delineates the communication latency recorded from the sensors to the Firebase server across four operational situations.

Table 2. Overview of IoT communication latency metrics

Scenario	Min (s)	Max (s)	Mean (s)	Std Dev (s)	Median (s)
Normal PLN	1.80	2.50	2.16	0.22	2.15
Grid Failure	2.30	3.10	2.67	0.24	2.65
Grid Restore	1.90	2.70	2.29	0.27	2.30
PLTS Mode	2.40	3.20	2.75	0.24	2.75

The average latency varied between 2.16 seconds and 2.75 seconds. In the realm of telecommunications infrastructure monitoring, this value is seen acceptable. Telecommunications systems do not necessitate millisecond-level response times for the mere monitoring of power supply. Data

refreshed every 2-3 seconds is adequate for monitoring trends and identifying alterations in power supply status. Figure 9 shows the mean of IoT communication latency.

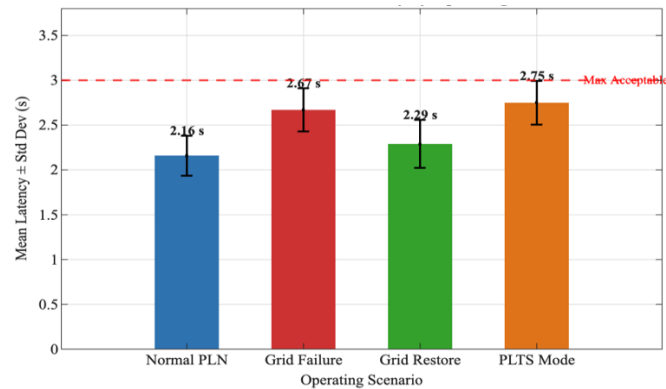


Figure 9. Mean IoT communication latency

The impact of grid and resource conditions: Data indicates that latency typically escalates in situations characterized by disruptions or alternate sources. The Grid Failure and Solar Power Plant (PLTS) scenarios had the highest latency, with averages of 2.67 seconds and 2.75 seconds, respectively. This rise is rational, as during a PLN (State Electricity Company) grid outage, the system not only transitions to PLN but may also convey more intricate status data or encounter a transient surge in communication load. Moreover, if the internet connection relies on PLN supply, during a power outage, the system must depend on an alternate connection (e.g., a modem with battery backup), which may exhibit varying performance.

The PLN Normal and Grid Restore scenarios demonstrate reduced and more consistent latency. This signifies that, under standard operational conditions, the data communication pathway is functioning efficiently. The modest standard deviation (ranging from 0.22 to 0.27 seconds) signifies that latency is consistent and exhibits minimal fluctuation. The median, closely aligned with the mean, further substantiates that the latency data distribution is likely normal, devoid of detrimental extreme outliers. This stability is crucial to guarantee that the data obtained by the user (web dashboard) is dependable for analysis.

The latency data corroborates the chosen communication architecture (ESP32 + Firebase + Nuxt). The Firebase Realtime Database has demonstrated its ability to manage data traffic efficiently. A delay of 2-3 seconds is inadequate for control applications necessitating immediate feedback, such as circuit breaker protection; nevertheless, this performance is sufficient for monitoring and decision-making by human operators. Figure 10 shows the distribution of IoT communication latency.

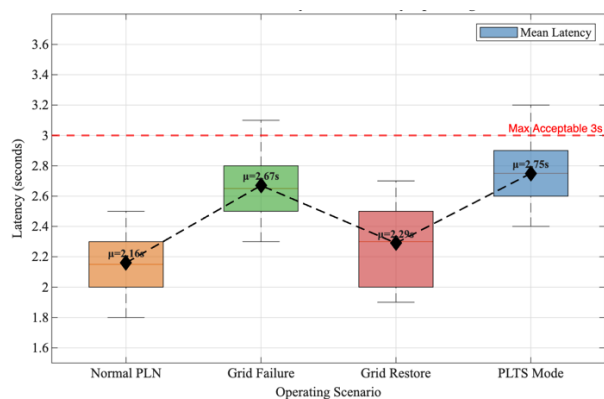


Figure 10. IoT communication latency distribution

### 3.3. ATS Switching Performance Analysis

The Automatic Transfer Switch (ATS) is a key part of making sure that telecommunication systems always have power. It does this by tracking electrical parameters and communication latency, among other things. This research looks at how the switching works in artificial grid disturbance situations, such as normal operation, grid failure, and grid restoration. Switching time is the amount of time that passes between finding a voltage drop in the main source (PLN) and successfully moving the load to the backup source (PLTS). From what we saw in the experiments, the suggested system's switching time is between 100 and 300 ms, depending on how it is working and how long it takes for the system to respond. In this delay, there is time for the sensor to notice something, the micro-controller to process it, and the relay to turn on.

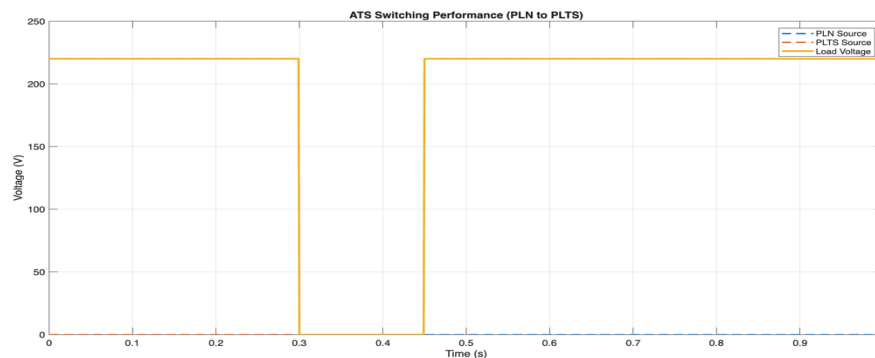


Figure 11. ATS switching performance

The switching performance that was achieved is good enough for telecommunication monitoring systems, where small interruptions of a few milliseconds don't have a big effect on how the system works, especially for non-critical loads like communication interfaces and monitoring devices. Also, the switching action matches the system latency that was seen, which is for sending data to the monitoring platform and is between 2.16 s and 2.75 s. It's important to remember that this delay in communication doesn't change how the actual switches work because the ATS only works at the controller level.

During tests, the system switched on and off steadily and the voltage at the load side didn't change much. It was seen that there was no oscillatory switching (chattering), which means that the voltage cutoff logic works well to stop unstable switching conditions. However, it has been seen that the switching delay is mostly affected by the settings for the detection threshold and the mechanical reaction of the relay. For systems that need to switch faster and more smoothly, like important phone systems, adding solid-state switching devices or predictive control algorithms can make things even better.

## 4. Conclusion

This research assessed the efficacy of the Hall-effect-based current sensor, the ACS712, within an IoT-driven Automatic Transfer Switch system connected to both a solar power plant (PLTS) and a traditional electricity grid. The test findings showed that the error rate for measuring current was usually higher when the sensor was used on the PV power plant than when it was used on the PLN grid. The inverter output characteristics of the PV system may have caused harmonics and noise during the DC-to-AC conversion process, which would have made Hall-effect sensor readings less accurate.

This study also showed that sensor units might have different performance levels, even when they are employed in the same test conditions. There are big variances in error levels between sensors, which shows that factory calibration and component tolerances affect how accurate measurements

are. So, using an individual calibration technique, like the two-point calibration approach, is an important step in making present monitoring systems more accurate.

Even though the Root Mean Square Error (RMSE) figure is tiny in amperes, the comparatively large maximum percentage error could affect the ATS system's capacity to make decisions, especially with current threshold-based switching mechanisms. If you read the wrong information, you can misinterpret the load conditions, which could lead to undesirable switching procedures.

The findings of this study demonstrate that the ACS712 sensor remains applicable for current monitoring in IoT-based ATS systems; nevertheless, its accuracy is compromised when employed with power sources exhibiting suboptimal power quality, such as solar power plants. For further system development, it is advisable to utilize current sensors with enhanced accuracy, such as current transformer-based sensors, along with the implementation of digital signal processing techniques to mitigate noise and harmonic distortion in renewable energy-based power systems. This study is limited by the absence of high-speed switching measurement tools and the use of mechanical relays, which introduce inherent delays compared to solid-state switching systems.

Future research may focus on several developmental aspects to improve the accuracy, reliability, and scalability of current monitoring systems inside IoT-based Automatic Transfer Switch systems integrated with photovoltaic systems. More studies need to look into how the quality of the electricity from solar power plant inverters influences the accuracy of current sensor measurements in more detail, especially when it comes to Total Harmonic Distortion (THD) variables and changes in the current waveform. A more in-depth study might compare several types of current sensors that are more accurate, such as current transformer-based sensors or closed-loop Hall-effect current sensors. This performance comparison across sensors is anticipated to produce superior sensor recommendations for ATS systems in hybrid energy applications, especially those using renewable energy sources. Digital signal processing (DSP) techniques are another area of research that could help make sensor reading more stable. Digital filtering, moving average filtering, or adaptive filtering are some of the ways to get rid of noise and distortion in the signal from the solar power inverter. This would make the current measurements more accurate overall.

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