Design And Implementation Of A Current Monitoring And Protection System Based On Pzem-004T For On-Grid Pv Systems

Enggie Faturrahman Ilham, Umi Fadlilah*

Fakultas Teknik, Program Studi Teknik Elektro − Universitas Muhammadiyah Surakarta
Surakarta, Indonesia
*uf138@ums.ac.id

Abstract − The development of renewable energy systems, especially three-phase on-grid PLTS, requires accurate current monitoring and reliable protection to ensure stable and safe operation when connected to the utility grid. This study presents the design and implementation of a monitoring and protection system using three PZEM-004T sensors to measure voltage, current, power, and energy on each phase, with an ESP8266 microcontroller serving as the central controller. A 100 WP solar panel supplies energy through a charge controller, battery, and three-phase inverter before being integrated into the PLN grid. The hardware configuration is supported by dedicated firmware capable of managing multi-sensor UART communication, calculating electrical parameters in real time, and executing relay-based protection logic during abnormal operating conditions. Experimental results demonstrate high measurement accuracy, with current deviations between 0.00–0.13 percent and voltage deviations between 0.07–0.15 percent when compared to reference instrument readings under various loading conditions. The system successfully detected current variations in the 7.10–8.30 A range and triggered automatic power disconnection during overcurrent events, confirming the reliability of the relay-based protection mechanism. Although laboratory testing was limited to 8 A, the system design supports currents up to 50 A, enabling scalability for higher-capacity on-grid photovoltaic installations. Furthermore, the integrated approach allows real-time measurement visualization through an I2C LCD while maintaining a compact and low-cost hardware footprint. Overall, the proposed system offers an effective solution for real-time monitoring and automatic current cutoff, thereby enhancing operational safety and reliability in three-phase on-grid PLTS applications. Future development may include the integration of cloud-based monitoring dashboards or long-range communication technologies such as LoRa, allowing broader deployment across distributed photovoltaic infrastructures and remote installations.

Keywords − Current; On-Grid; PZEM-004T; Protection; Three-Phase.

I. INTRODUCTION

SOLAR Power Plants (PLTS) generate electrical energy from photovoltaic modules and can supply power directly to loads or feed it into the PLN grid in an on-grid configuration [1, 2]. Compared to off-grid systems, the on-grid setup is more cost-efficient because it reduces dependence on large battery banks [2]. This economic feasibility has positioned grid-connected photovoltaic systems as one of the preferred configurations for large-scale renewable penetration, particularly in regions with established transmission infrastructure and stable grid availability. Furthermore, the increasing adoption of net-metering regulations enables consumers to obtain financial returns from exported energy,

creating additional incentives for integrating on-grid PLTS into commercial and residential facilities. As a result, the scale and operational diversity of grid-connected solar systems continue to expand, raising new technical requirements regarding supervision, automation, and reliability at the interface between photovoltaic sources and the national utility network.

However, on-grid systems require more reliable control and protection due to the switching interaction with the utility grid [3]. Unlike standalone photovoltaic installations that operate in isolation, grid-connected systems must constantly synchronize with grid voltage, frequency, and phase—parameters that fluctuate due to dynamic power exchanges across the national network. When environmental variations affect solar generation, voltage and current profiles at the inverter output may deviate from optimal ranges, increasing the likelihood of asymmetric loading and irregular current flow among phases. One common issue is phase overcurrent caused by high power output or load imbalance [4], which not

only reduces inverter performance but may also initiate cascading disturbances: excessive thermal stress on cables, accelerated wear on connectors, increased harmonic distortion, and premature aging of protection components. In extreme cases, inadequate monitoring may allow persistent current imbalance to propagate into the grid, posing safety concerns and potentially violating interconnection standards.

To mitigate these risks, effective real-time measurement and autonomous protective mechanisms are required so that abnormalities are detected and addressed before they evolve into hazardous conditions. Existing inverter integrated monitoring features are typically optimized for aggregated measurements rather than phase-level granularity, which may obscure subtle imbalances that gradually lead to operational inefficiencies. Consequently, a complementary layer of monitoring is needed outside the inverter to provide high-resolution electrical visibility while maintaining compatibility with commercial systems. Addressing this requirement, this study designs a monitoring and protection system using the PZEM-004T module installed on each phase after the three-phase inverter. The module measures voltage, current, and other electrical parameters in real time with high accuracy [5]. The microcontroller processes these measurements to detect excessive current. When the current exceeds the 50 A limit, a relay automatically disconnects the PLTS output from the grid [6], allowing rapid isolation and preventing further propagation of overcurrent disturbances.

The strategic placement of sensors at the inverter output enables comprehensive monitoring without requiring modification of inverter firmware or communication protocols, making the approach adaptable to different inverter brands and installation environments. As a result, the proposed configuration aligns with practical requirements in field deployments, where simplicity, compatibility, and ease of maintenance are essential. In addition to the protection mechanism, the proposed system provides real-time monitoring, enabling operators to observe voltage and current variations among phases. Such monitoring is essential for diagnosing load imbalance, early detection of abnormal operating conditions, and improving maintenance planning for photovoltaic installations. Historical data obtained from real-time measurements can further support predictive maintenance strategies, enabling trending analysis and enabling operators to infer early signatures of cable degradation, contact resistance buildup, or inverter malfunction.

Therefore, integrating monitoring and automatic protection contributes to safer, more efficient, and more reliable on-grid PLTS operation. By combining scalability, measurement granularity, and autonomous protection response, the proposed system establishes an accessible yet technically robust foundation for modern photovoltaic deployment—particularly in medium-scale installations where balancing cost and reliability remains an ongoing design challenge.

II.   RESEARCH METHODS

System design began with selecting the core components, starting with the inverter that converts the PLTS DC output into three-phase AC for grid connection. The PZEM-004T modules were installed on each phase to measure voltage, current, power, and energy [7]. All measurement data are processed by the microcontroller to ensure the system remains within safe operating limits. If an abnormal condition such as overcurrent occurs, the microcontroller activates a relay to disconnect the affected phase. A PCB layout was used to improve wiring efficiency, reduce jumper usage, and enhance long-term reliability, providing a consistent base for signal routing and electrical isolation between high- and low-voltage terminals.
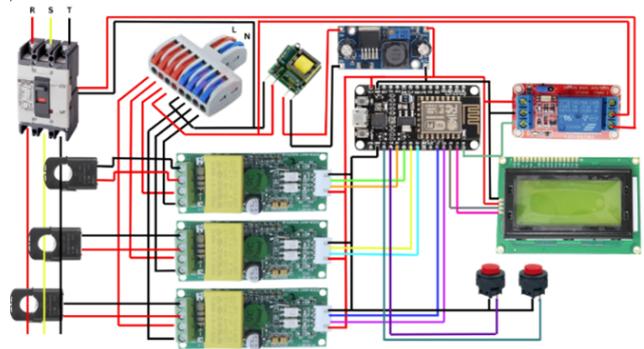

Figure 1: Component wiring

Figure 1 shows the wiring concept. The circuit is designed for real-time monitoring and protection, with the ESP8266 acting as the main controller and retrieving data from each PZEM-004T through UART (TX–RX) communication [8]. The AC supply is converted to DC through an AC–DC module and then regulated to stable voltage levels using an LM2596 buck converter, ensuring that the measurement circuitry and control components receive suitable operating power. When overcurrent is detected, the relay interrupts the corresponding phase output, providing an immediate isolation response. A 16×2 I2C LCD continuously displays voltage and current values, while a push button enables user interaction for manual reset and current limit adjustments.

The physical implementation integrates several key components into a cohesive unit. The measure-

ment subsystem relies on three PZEM-004T sensors capable of reading voltages between 80–260 VAC and currents up to 100 A at frequencies ranging from 45 to 65 Hz, enabling compatibility with typical three-phase installations. The ESP8266 microcontroller provides a compact, low-power platform with Wi-Fi support and multiple communication interfaces, allowing future expansion toward cloud-connected monitoring. The relay module operates at 5 V and is configured with active-LOW logic to control AC loads up to 10 A, functioning as the core protective actuator. A 16×2 LCD connected through an I2C interface presents real-time measurement results, while the power regulation stage is handled by the LM2596 buck converter, which steps down 7–40 V DC to stable 5 V or 3.3 V rails. An AC–DC conversion module supplies low-voltage DC power derived from the 220 VAC input, enabling off-grid testing or integration with inverter auxiliary power. Additionally, a high-current contactor rated up to 100 A provides a secondary mechanical protection layer, and the KC602 clamp meter serves as a calibrated reference instrument for validating current readings and minimizing measurement uncertainty.

Through the integration of these components, the proposed system provides accurate phase-level monitoring, stable power control, and rapid overcurrent isolation, forming a reliable foundation for real-time supervision and protection in on-grid PLTS systems. This configuration also maintains adaptability for different installation environments, allowing the measurement and control layers to operate independently from specific inverter models or communication protocols, which is beneficial when upgrading existing photovoltaic installations without altering inverter firmware.

i. *Software Development*

The software development stage focused on implementing control logic in the Arduino IDE. Each PZEM-004T module is initialized according to its phase, allowing the ESP8266 to read voltage and current with stable timing. The I2C LCD is configured to display real-time measurements, while the relay and push buttons are used for setting the current limit and activating protection.

After initialization, the program continuously collects electrical data and updates both the LCD and the Serial Monitor. Current values are compared with a user-defined threshold adjustable through the push buttons. Debounce logic ensures that button inputs register correctly. If any phase exceeds the set limit, the relay disconnects the PLTS output. The software integrates sensor communication, real-time monitoring, user input, and protection logic into a unified control system.

ii. *Hardware Implementation*

Hardware implementation involved assembling all components based on the system design. The PZEM-004T modules were installed at each inverter output phase and calibrated for accurate measurement. The microcontroller was connected via serial communication to retrieve real-time data [9]. A relay was placed on the current line to provide automatic disconnection during overcurrent.

A 3D-printed enclosure was also developed to protect and organize the components. The process included determining dimensions, modeling the casing in SolidWorks, and validating the layout before printing. The enclosure provides dust protection, proper ventilation, and structured wiring using conduit or protective sleeves, ensuring long-term hardware performance.
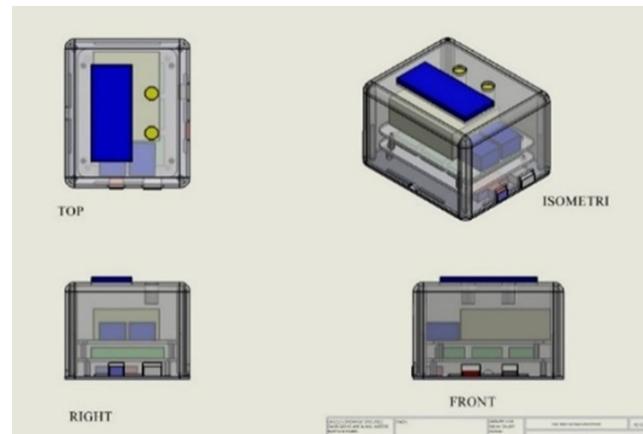

Figure 2: Hardware design enclosure showing isometric, top, right, and front views

Figure 2 shows the casing design in isometric, top, right, and front views, with dimensions of $8 \times 10 \times 15$ cm, providing safe and organized housing for the monitoring and protection unit.

III. RESULTS AND DISCUSSION

The testing phase was carried out to verify that the three-phase on-grid PV monitoring and protection system built around the PZEM-004T operates correctly and in line with the design objectives. The first aspect of testing focused on assessing measurement accuracy to determine how closely the readings from each PZEM-004T sensor matched those obtained from calibrated reference instruments such as a digital multimeter and a clamp meter [10]. Establishing this accuracy was essential to validate that the monitoring subsystem could reliably represent real electrical conditions without introducing unacceptable deviations that might mislead operational decisions.

Beyond measurement precision, the evaluation

also examined the system's capability to detect overcurrent conditions and activate the relay-based protective mechanism. During these trials, current values were gradually increased until they exceeded the predefined threshold, allowing observation of whether the protection system could accurately identify unsafe conditions and disconnect the affected phase in a timely manner. This stage was crucial for confirming that the relay control logic responded consistently and rapidly enough to prevent prolonged exposure to excessive current that might damage connected equipment.

In addition, testing was conducted to observe the overall stability of the system both under normal loading and during moments when the measured current surpassed the preset limit. These observations enabled analysis of how the system behaved under dynamic operational scenarios, including variations in three-phase balance, transient changes in load, and repeated activation of the protection mechanism. Stable operation under these conditions indicates that the system can be deployed in real installations without frequent recalibration or manual intervention.

Finally, the clarity and responsiveness of real-time monitoring were examined through the 20×4 I2C LCD interface, ensuring that voltage, current, and power values were displayed without noticeable delay or distortion. This verification confirmed that the user interface could be relied upon to support practical monitoring tasks, such as inspection, troubleshooting, and data verification during commissioning. Collectively, these evaluation elements ensured that the developed system not only measured electrical parameters with high accuracy, but also responded effectively to abnormal operating conditions while maintaining stable and accessible real-time visualization throughout the testing process.

i.   Testing Procedure

The testing procedure was structured to ensure that the monitoring and protection system could be evaluated under realistic operating conditions representative of three-phase on-grid PLTS installations. At the beginning of the experiment, the complete setup was connected to a three-phase on-grid photovoltaic source, and a combination of resistive and inductive loads was applied to simulate practical variations in power consumption. Once the system was energized, the voltage and current on each phase were measured using calibrated reference instruments, namely a digital multimeter and a clamp meter, which served as the baseline against which the PZEM-004T readings would later be compared. Establishing these reference measurements was an essential step to quantify the accuracy of the monitoring subsystem.

After obtaining baseline readings, the measurement values captured by the PZEM-004T modules were collected and compared directly with those recorded by the reference instruments to determine whether the sensors provided reliable and consistent output across different operating points. To observe the system's protective behavior, the load on each phase was gradually increased, causing the current to rise until it exceeded the predefined protection threshold of 10 A. Once the overcurrent level was reached, particular attention was given to the activation of the relay and whether it successfully disconnected the affected phase from the power line in a timely and consistent manner, confirming the responsiveness of the protective mechanism.

Throughout the evaluation, both measurement results and system responses were continuously monitored and recorded across ten independent test repetitions. Repeating the experiment multiple times allowed the assessment of system repeatability and ensured that the monitoring and protection functions did not degrade or behave inconsistently under repeated stress. This comprehensive testing workflow provided a measurable basis for evaluating the precision, responsiveness, and operational stability of the developed system during controlled yet realistic conditions.

ii.   Obstacles and Solutions

During the early design phase, one of the main challenges was finding a microcontroller capable of handling UART communication for three PZEM-004T modules at the same time. Initial trials showed that not all boards met this requirement. The ESP32, which was considered first, could only support two RX–TX pairs [11], making it suitable for just two PZEM modules. Because the system required three independent communication channels, this option had to be dismissed. After testing several alternatives, the ESP8266 proved to be the most reliable choice, as it was able to process data from all three PZEM-004T units consistently.

Another issue appeared during sensor reading, particularly when the PZEM modules received power earlier than the ESP8266. This sequence caused communication errors, resulting in invalid data and NaN values displayed on the I2C LCD [12]. To resolve this, two switches were added as a simple hardware solution. The operating procedure was adjusted so the ESP8266 is powered first, allowing it to initialize properly, and only then the second switch is turned on to connect the RX–TX lines to the three PZEM modules. With this sequence, the communication became stable and the

readings were consistently accurate.

A final challenge occurred during the physical assembly of the device. The initial enclosure (X7 box) was significantly larger than needed, making the system bulky and less practical. This led to the decision to design a new, more proportional casing with dimensions of 8×10×15 cm. The revised enclosure fit all components neatly, improved cable organization, and resulted in a more compact and efficient device that was easier to use and position during testing.

iii. Voltage Test Results

The first stage of performance evaluation focused on validating the accuracy of voltage measurements obtained from the PZEM-004T modules when compared with reference instruments [13]. A three-phase motor was used as the primary load to generate realistic operational conditions in which the phase voltages naturally vary due to mechanical and electrical characteristics inherent to induction machines. The measurement data from the PZEM-004T were subsequently compared against readings from a calibrated digital multimeter, with the numerical comparison summarized in Table 1 and the trend visualized in Figure 3. This validation ensured that the proposed monitoring system produces voltage readings consistent with standard measurement tools typically used in field commissioning and system maintenance.

As shown in Table 1, the voltage differences between the PZEM-004T module and the multimeter are relatively small across all ten samples, with the average error ranging between 0.07% and 0.15%. The readings for Phase R consistently stay within a narrow band around 228–230 V, while Phase S shows slightly lower values in several iterations, likely due to the dynamic load distribution of the three-phase motor. Phase T tends to register marginally higher values in some runs, reflecting natural phase imbalance commonly observed in three-phase supply systems connected to inductive machines. Despite these variations, the deviations remain within the standard tolerances for AC voltage measurement, confirming that the PZEM-004T provides a sufficiently accurate representation of system voltage for operational monitoring and protection use.

The graphical comparison presented in Figure 3 further reinforces this conclusion by showing that the measured voltage values maintain a consistent trend across all samples. The PZEM-004T outputs follow the same fluctuation pattern as the multimeter readings, indicating that measurement noise, offset, or drift are minimal during operation. Visual alignment between the two data sets suggests that no systematic bias is present, and the slight variations observed likely originate from

Table 1: Voltage test results for each phase

No.	R PZEM	R MM	S PZEM	S MM	T PZEM	T MM	Avg.Err (%)
1	228.4	228.6	226.5	226.9	226.9	227.0	0.10
2	227.6	228.1	219.0	218.9	234.5	235.0	0.15
3	229.1	229.4	225.8	226.0	233.2	233.5	0.11
4	228.8	229.0	224.7	225.1	232.6	232.9	0.13
5	230.2	230.5	227.9	228.2	231.4	231.7	0.13
6	227.4	227.7	223.3	223.6	234.1	234.3	0.11
7	229.6	229.8	225.1	225.3	232.8	233.1	0.10
8	228.3	228.5	224.9	225.0	233.5	233.7	0.07
9	227.9	228.2	223.7	224.0	234.2	234.5	0.13
10	229.0	229.3	225.4	225.6	232.1	232.4	0.11

inherent phase imbalance and dynamic load effects rather than measurement inaccuracy. Such graphical validation is particularly important in condition-monitoring applications, where operators rely on visual trends to detect anomalies in phase behavior over time.
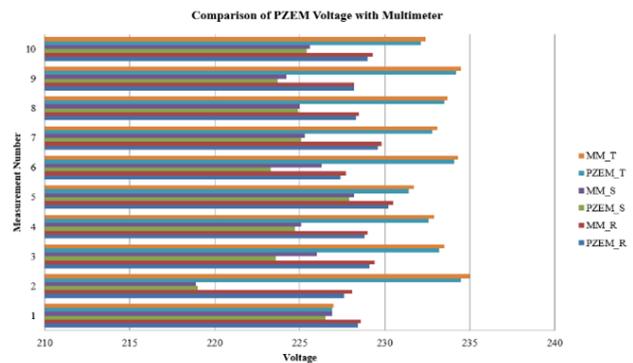

Figure 3: Comparison graph of PZEM readings vs multimeter

Based on the measurement results shown in Figure 3, the three-phase voltage readings from the PZEM modules compared with those from a digital multimeter demonstrate that the system performs with stable and consistent accuracy [5]. The voltage values on Phases R, S, and T exhibit minor deviations from the reference instrument, remaining within acceptable AC measurement tolerances. This confirms that the PZEM modules can provide reliable monitoring of three-phase voltage conditions. When compared with the study by Wijayanto et al. (2022), which reported an average error of around 0.14% [14], the results obtained in this research exhibit slightly lower deviation values. These findings suggest improved voltage measurement stability and reinforce the suitability of the proposed system for real-time IoT-based voltage monitoring and protection applications [15].

iv. Current and Protection Test Results

The second stage of evaluation investigated both the accuracy of the current readings and the responsiveness of the protection mechanism when current levels exceeded the predefined limit. Measurements were ob-

tained using a three-phase motor load operated at varying rotational speeds, enabling controlled transitions between normal and overcurrent conditions. These variations produced observable changes in phase current, allowing the developed system to be tested across a representative operational spectrum in which current imbalance or load escalation may occur. The recorded values are summarized in Table 2, while Figure 4 illustrates the comparison between measurements captured by the PZEM-004T and those obtained from the reference clamp meter.

Table 2: Current test results for each phase

| No.	R PZ	R CM	S PZ	S CM	T PZ	T CM	Err(%)	Relay	Description
1	2.58	2.58	2.60	2.60	2.59	2.59	0.00	Low	Current Active
2	2.45	2.45	2.60	2.60	2.79	2.80	0.04	Low	Current Active
3	7.10	7.10	7.80	7.80	8.09	8.10	0.09	High	Current Interrupted
4	2.50	2.50	2.70	2.70	2.78	2.79	0.06	Low	Current Active
5	7.10	7.10	7.69	7.70	8.09	8.10	0.05	High	Current Interrupted
6	2.68	2.68	2.55	2.55	2.63	2.63	0.00	Low	Current Active
7	2.42	2.42	2.58	2.58	2.75	2.75	0.00	Low	Current Active
8	7.30	7.30	7.90	7.90	8.30	8.30	0.00	High	Current Interrupted
9	2.77	2.77	2.72	2.72	2.93	2.93	0.00	Low	Current Active
10	7.05	7.05	7.60	7.60	8.19	8.20	0.13	High	Current Interrupted
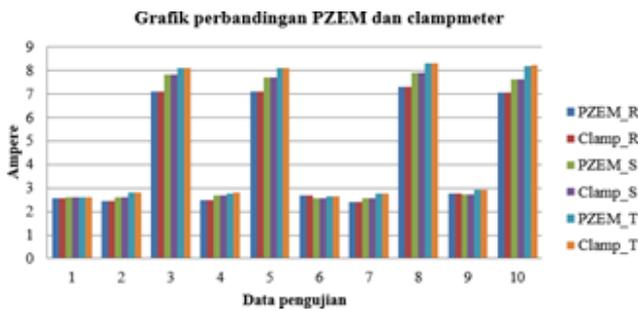
Figure 4: Comparison graph of PZEM readings vs clamp meter

As shown in Table 2, the current values recorded by the PZEM-004T closely track those obtained from the clamp meter. When the relay remained in the *Low* state, indicating normal operation, the measured current values in all three phases were consistently within the range of approximately 2.4–2.9 A. These readings represent the baseline operating condition of the motor load and verify that the system can accurately detect low-to-moderate currents without unnecessary relay engagement. Conversely, when the load was increased to induce higher current flow, the measurements rose to approximately 7–8 A, triggering the relay into the *High* condition and interrupting the circuit as designed [16]. The alternation between active and disconnected states demonstrates that the protection mechanism is both repeatable and responsive, reliably isolating the system under abnormal operating conditions to prevent damage to equipment or downstream grid components.

Figure 4 further reinforces these findings by illustrating that the measurement trends across Phases R, S, and T follow a consistent pattern between the PZEM-004T sensor and the clamp meter. The overlapping curves across all sampling points reveal that the sensor does not produce systematic offsets, spikes, or drift relative to the reference instrument. Such consistency is critical in real-time monitoring applications, where operators often rely on temporal patterns rather than standalone numerical readings to assess system behavior and identify anomalies.

Error values between the two measurement sources range from 0.00% to 0.13%, reflecting minimal deviation and demonstrating that the PZEM-004T is capable of achieving high accuracy in current measurement applications. These margins fall well within typical tolerances for field-deployed monitoring systems and indicate that the developed configuration performs more accurately than systems reported in earlier research [10, 17]. The observed alignment between measurement accuracy and protection responsiveness confirms that the monitoring subsystem does not compromise protective behavior; instead, precise detection directly contributes to reliable relay activation. Overall, the system maintains stable current monitoring across all three phases while providing an effective and repeatable mechanism for isolating overcurrent conditions, thereby validating its suitability for integration into on-grid photovoltaic installations requiring autonomous electrical protection.

IV. CONCLUSION

Overall, this study demonstrates that the three-phase voltage and current monitoring system developed utilizing the PZEM-004T sensor in conjunction with the ESP8266 microcontroller successfully fulfills the intended design objectives [18]. The system consistently achieved high accuracy in measuring voltage and current across all phases, closely aligning with reference measurements.

The experimental outcomes further substantiate the effectiveness of the implemented protection mechanism. During high-load conditions where currents increased to 7.10–8.30 A, the relay module effectively transitioned from low to high [19], automatically disconnecting the circuit and mitigating potential overcurrent risks. Voltage measurements maintained deviations within 0.07–0.15%, confirming system reliability under varying operational scenarios.

For future development, several enhancements may be implemented, including online monitoring platforms for remote access, and long-range communication technologies such as LoRa to improve scalability and performance in large-scale renewable installations [20]. These enhancements will broaden the ap-

plicability of the system and strengthen its deployment potential in three-phase on-grid photovoltaic networks.

Acknowledgment

References

[1] S. Hani, G. Santoso, S. Subandi, and N. Arifin, "Perencanaan pembangkit listrik tenaga surya (plts) on-grid dengan sistem dc coupling berkapasitas 17 kwp pada gedung," in *Pros. Semin. Nas. Teknoka*, vol. 5, no. 2502, 2020, pp. 156–163. [Online]. Available: https://doi.org/10.22236/teknoka.v5i.300

[2] A. Simorangkir and L. Halim, "On-grid vs. off-grid photovoltaic systems for smart greenhouses: a techno-economic case study," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 40, no. 2, pp. 545–557, 2025. [Online]. Available: https://doi.org/10.11591/ijeecs.v40.i2.pp545-557

[3] A. B. Pulungan, A. R. Sidiqi, and I. Yelfianhar, "Economic analysis of rooftop based on-grid and off-grid photovoltaic systems in equatorial area," *J. Appl. Eng. Technol. Sci.*, vol. 5, no. 1, pp. 460–473, 2023. [Online]. Available: https://journal.yrpipku.com/index.php/jaets/article/view/3158/2129

[4] S. Djulihenanto, M. Saputra, S. Luthfi, and D. Nabiel, "Implementasi sistem proteksi arus dan tegangan lebih pada plts," *ELPOSYS J. Sist. Kelistrikan*, vol. 12, no. 1, pp. 49–54, 2025. [Online]. Available: https://doi.org/10.33795/elposys.v12i1.6849

[5] A. Syhari and A. Bintoro, "Monitoring dan controling daya berbasis arduino uno menggunakan sensor pzem-004t," *J. Energi Elektr.*, vol. 12, no. 1, pp. 43–50, 2023. [Online]. Available: https://doi.org/10.29103/jee.v12i1.9836

[6] H. N. Ashshiddiq, D. Y. Tadeus, and F. Mangkusasmito, "Simulator otomasi sistem proteksi pada penyulang 20 kv," *Resistor (Elektronika Kendali Telekomunikasi Tenaga Listrik Komputer)*, vol. 4, no. 2, pp. 103–110, 2021. [Online]. Available: https://doi.org/10.24853/resistor.4.2.103-110

[7] M. Ulum, H. Haryanto, and D. N. Purnamasari, "Smart monitoring sistem panel surya berbasis internet of things (iot)," *Cyclotron*, vol. 7, no. 01, pp. 67–70, 2024. [Online]. Available: https://doi.org/10.30651/cl.v7i01.21175

[8] A. A. Pradana, P. Yuliantoro, and S. Indriyanto, "Perancangan sistem monitoring daya listrik 1 fasa pada rumah tangga berbasis internet of things (iot)," *J. Sist. Inf. dan Teknol. Komputasi*, vol. 1, pp. 1–9, 2024. [Online]. Available: https://doi.org/10.61124/sinta.v1i1.13

[9] W. Ahmad, D. Widiatmoko, and F. Kholid, "Design of electrical energy monitoring system using nodemcu esp8266 and pzem-004t for power usage control," *Fortech*, vol. 5, no. 1, pp. 10–18, 2024. [Online]. Available: https://journal.fortei7.org/index.php/fortech/article/view/559

[10] M. M. A. Zahra *et al.*, "Battery charging monitoring system using pzem 004t sensor and dc voltage sensor," *Int. J. Renew. Energy Res.*, vol. 13, no. 2, pp. 666–672, 2023. [Online]. Available: https://doi.org/10.20508/ijrer.v13i2.14152.g8736

[11] M. S. Muslim, R. T. Subagio, and A. Nursetyo, "Perancangan dan pembuatan interface komunikasi data antara ecu sepeda motor dan sistem android," *Tek. J. Ilmu Tek. dan Inform.*, vol. 5, pp. 86–92, 2025. [Online]. Available: https://doi.org/10.51903/teknik.v5i2.973

[12] S. Patel, P. Talati, and S. Gandhi, "Design of i2c protocol," *Int. J. Tech. Innov. Mod. Eng. Sci.*, vol. 5, no. 03, pp. 2017–2020, 2021.

[13] S. Nirwan and M. S. Hafidz, "Rancang bangun aplikasi untuk prototipe sistem monitoring konsumsi energi listrik pada peralatan elektronik berbasis pzem-004t," *J. Tek. Inform.*, vol. 12, no. 2, pp. 79–84, 2020. [Online]. Available: https://ejurnal.ulbi.ac.id/index.php/informatika/article/view/871

[14] D. Wijayanto, S. I. Haryudo, T. Wrahatnolo, and N. Nurhayati, "Rancang bangun monitoring arus dan tegangan pada plts sistem on grid berbasis internet of things (iot) menggunakan aplikasi telegram," *J. Tek. Elektro*, vol. 11, no. 3, pp. 447–453, 2022. [Online]. Available: https://doi.org/10.26740/jte.v11n3.p447-453

[15] S. K. Situmeang and S. I. Haryudo, "Plts on-grid berbasis internet of things menggunakan aplikasi telegram sebagai interface monitoring," *J. Ilm. Wahana Pendidik.*, vol. 10, pp. 970–981, 2024. [Online]. Available: https://jurnal.peneliti.net/index.php/JIWP

[16] R. Sutjipto, H. Sungkowo, and E. Epiwardi, "Analisis kinerja generator induksi 3 fasa berdasarkan regulasi tegangannya," *J. Tek. Ilmu dan Apl.*, no. 9, pp. 91–98, 2022. [Online]. Available: https://jurnal.polinema.ac.id/index.php/jtia/issue/view/197

[17] M. Irfan and R. P. Astutik, "Rancang bangun sistem monitoring dan kontrol otomatis lampu lobi kantor berbasis photocell dan timer switch di rsud ibnu sina kabupaten gresik," *E-Link J. Tek. Elektro dan Inform.*, vol. 18, no. 1, 2023. [Online]. Available: https://doi.org/10.30587/e-link.v18i1.5355

[18] S. Rahman and A. Aula, "Sistem monitoring dan proteksi pada stop kontak berbasis iot," *J. Edukasi dan Penelit. Inform.*, vol. 8, no. 1, 2022. [Online]. Available: https://doi.org/10.26418/jp.v8i1.48052

[19] S. Pambudi, V. Prasetia, and S. Rahmat, "Penerapan sistem ats (automatic transfer switch) sebagai pengendalian, pemantauan, dan perawatan berbasis iot (internet of things)," *Infotekmesin*, vol. 14, no. 2, pp. 221–230, 2023. [Online]. Available: https://doi.org/10.35970/infotekmesin.v14i2.1853

[20] P. K. Goran and M. B. Ginting, "Simulasi perancangan jaringan komunikasi long range (lora) untuk mendukung desa wisata melung," *SINTA J. Sist. Inf. dan Teknol. Komputasi*, vol. 1, pp. 138–146, 2024. [Online]. Available: https://doi.org/10.61124/sinta.v1i3.22