Deficit Threshold Optimization of an Automatic Transfer Switch for Hybrid Grid-Photovoltaic Systems in Tropical Climates

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Abstract

The rising demand for dependable power supply in tropical areas, characterized by frequent grid instability, requires the use of automated transfer switches (ATS) in hybrid photovoltaic (PV)-grid systems. This study assesses the efficacy of an Arduino Mega 2560-based Automated Testing System (ATS) coupled with a 100 Wp polycrystalline photovoltaic panel and a 12 V 100 Ah battery in the tropical climate of Lampung, Indonesia, over a span of 15 consecutive days in January. The process encompasses hardware design, the construction of a control algorithm based on a multi-objective cost function incorporating risk factors, field data gathering, and MATLAB simulation. The findings indicate that the system attains 80% grid independence based on day count and exceeds 95% based on total energy, accompanied with a minimal switching frequency of 0.2 occurrences per day, signifying stable operation devoid of chattering. A significant contribution is the optimization of the shortfall threshold: adjusting the threshold from 0 Wh to –10 Wh decreases grid reliance from three days to one day, enhancing PV utilization from 80% to 93.3% without adding battery capacity. The relationship between irradiance and photovoltaic energy is robust (r = 0.94, R^2 = 0.88), with an average system efficiency of 10.04%, which is plausible for polycrystalline panels in hot, humid environments, including cable, inverter, and heat losses. The boxplot analysis verifies the absence of overlap between energy balances on photovoltaic days and grid days, hence affirming the reliability of ATS judgments. In conclusion, the suggested ATS featuring an adjustable deficit threshold is an economical and dependable option for telecommunication infrastructure in tropical developing areas.

Keywords : *Automatic transfer switch, hybrid PV-grid system, tropical climate, deficit threshold optimization, photovoltaic utilization.*

I. INTRODUCTION

The increasing demand for reliable and continuous electrical power in modern infrastructure, particularly in telecommunication and distributed systems, requires the development of adaptive and efficient power management strategies. Conventional power supply from the grid (PLN) is often subject to instability and outages, especially in developing regions, which may affect system reliability. Assess the effectiveness of the Automatic Transfer Switch (ATS) in alleviating power outages and enhancing energy efficiency through dynamic transitions between grid and photovoltaic sources, thereby guaranteeing continuous supply to critical loads[1], [2]. This switching mechanism is vital for optimizing the advantages of renewable energy incorporation while upholding grid stability, especially in areas vulnerable to frequent grid disruptions[3], [4], the research examines the operational characteristics and efficacy of an Arduino Nano-controlled ATS in a hybrid solar power configuration, emphasizing its proficiency in performing swift and fluid shifts between PV and grid supplies predicated on predetermined battery voltage thresholds and system states[5], [6], [7].

This microcontroller-centric methodology enables meticulous regulation of power flux, facilitating instantaneous surveillance and adaptive countermeasures to variances in solar yield and load exigencies[8], [9]. Furthermore, the Arduino-driven ATS accommodates intricate control paradigms to oversee charging regimes and accommodate fluctuating meteorological conditions such as sunny, overcast, or inclement weather by factoring in battery capacitance and charging fluxes[10], [11].

This adaptive governance empowers the system to favor PV resources when viable, reverting to grid power exclusively upon PV inadequacy or critically depleted battery reserves, thus fortifying energy self-sufficiency and systemic robustness[12], [13]. The primary objective is to investigate the ATS performance in overseeing power management for hybrid PLN-PV systems.

Field evaluations were conducted under the tropical climate of Lampung Province, Indonesia, to ensure the system's responsiveness to local environmental variability.

The uniqueness of this research resides in its concentrated examination of the operational dynamics of an Arduino Mega 2560-controlled ATS within a two-source integrated system, utilizing experimental methods for enhanced performance and expedited processing of input and output controls. Combining two different energy sources requires a stronger computer system that can manage inputs from several sensors at the same time. Prior studies have primarily concentrated on dual-source switching[1], [14]. This research enhances the complexity by overseeing a multi-source hierarchy. The Arduino Mega 2560 was chosen because it has the right interrupt handling and extra input and output ports needed for real-time monitoring of different power characteristics. This makes sure that the changeover happens in less than a millisecond to avoid resetting the important load[14], [15]. The objective of this study is to assess how well the suggested ATS can manage power sources intelligently and dynamically to reduce the negative impacts of power supply instabilities, which are prevalent in developing countries[16].

A thorough comprehension of the system's dependability and operating limitations can be achieved by studying its reaction to changing load demands and solar energy availability[9], [2]. The complex and ever changing tropical weather patterns have a major influence on PV performance[17], yet these systems frequently do not have advanced control algorithms that take this into consideration[18]. We use MATLAB every single day to model the sun's irradiance, solar output, load demand, and battery cycle. The ATS functioning is evaluated based on the availability of PV energy and system conditions to allow for dynamic switching between power sources[19], [20]. This thorough research will guide enhanced control tactics for ATS implementation in areas with comparable meteorological variability, thus promoting the practical use of hybrid renewable energy systems.

II. METHODOLOGY

This study is designed to evaluate the operational performance of an Automatic Transfer Switch (ATS) in managing a hybrid PLN–photovoltaic (PV) power system.

The research methodology consists of three main phases: (1) system design, which includes the integration of power and sensing components using an Arduino Mega 2560; (2) algorithm development, focusing on decision-making logic based on battery voltage thresholds representing the state of charge (SOC); and (3) validation through experimental and simulation approaches.

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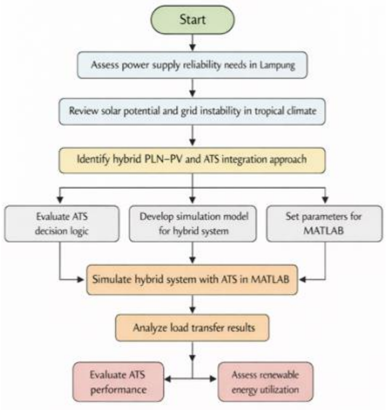

Figure 1. Research methodology of the proposed hybrid PLN–PV system with ATS

The control algorithm implemented on the Arduino Mega 2560 employs a hysteresis switching control method to prevent chattering when the battery voltage approaches threshold limits[10], [21]. The system continuously monitors voltage and current parameters through appropriate sensors. Priority is given to maximizing PV energy utilization, while switching to the PLN grid occurs only when the battery voltage reaches a predefined low-voltage cut-off or when the inverter is unable to supply the load[22], [23].

Figure 2. Experimental setup of the hybrid PLN–PV system installed at ITERA

In addition, a simulation-based approach is adopted to represent the climatic conditions of Lampung Province using a geographical reference at Institut Teknologi Sumatera (ITERA), located at coordinates 105.31389°E–105.31481°E and 5.35777°S–5.36280°S.

This simulation was completed over 15 days (from January 12, 20206 to January 26, 2026) to see how the photovoltaic system worked during the rainy season in January, when the daily solar radiation ranged from 3.8 to 4.5 kWh/m²/day.

The observation time was selected to guarantee that the system exhibited typical behavior under rainy season conditions[24], [25], which may increase the risk of power grid failure.

The modeling is performed using a daily time resolution, where each simulation step represents a full 24-hour operational cycle. This experimental approach enables accurate representation of daily PV energy generation under effective daylight conditions[7], [26], [27], as well as load demand and battery state of charge (SOC) dynamics during non-generation periods[28]. By incorporating local environmental characteristics such as high humidity and fluctuating irradiance typical of tropical regions[29], [30], the simulation provides a realistic evaluation of ATS performance in managing continuous power transitions between the PV system and the PLN grid.

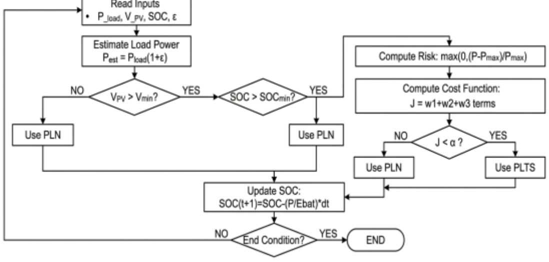

Figure 3. Algorithm flowchart for hybrid PLN–PV system with ATS

ATS control algorithm implemented on the microcontroller follows the logic flow in Figure 3.

It begins with the initialization of initial parameters[31], namely the maximum PV power ($P_{PV,max} = 305$ Wh/day), minimum battery voltage ($V_{min} = 10.8$ V), minimum state of charge ($SOC_{min} = 30\%$), risk threshold ($\alpha = 0.5$), and weighting factors $w_1 = 0.2$, $w_2 = 0.3$, and $w_3 = 0.5$ representing priorities for reliability, economy, and emissions. In each daily sampling cycle, the system reads the actual load power (P_{load}) and PV power (P_{PV}). The load uncertainty factor is set to $\varepsilon = 0.05$ (5%). The estimated load power is calculated using Equation (1):

$$P_{est} = P_{load}(1 + \varepsilon) \tag{1}$$

Next, the risk factor for using PV is calculated based on the availability of PV power using Equation (2):

$$\text{Risk} = \max\left(0, \frac{P_{est} - P_{PV,max}}{P_{PV,max}}\right) \tag{2}$$

The multi-objective cost function J is calculated using Equation (3):

$$J = w_1 \cdot \frac{P_{grid}}{P_{load}} + w_2 \cdot (1 - SOC) + w_3 \cdot \text{Risk} \tag{3}$$

The source switching decision follows the rule: if J < α then the system uses PV, otherwise if J≥α then the system uses the grid. In addition, there is an override condition: if SOC<SOC$_{min}$ and PV power is insufficient, the system is forced to switch to the grid. When PV is active, the battery SOC is updated using Equation (4):

$$SOC(t+1) = SOC(t) - \frac{P_{load} \cdot \Delta t}{E_{bat}} \tag{4}$$

With $E_{bat} = 1200$ Wh (12V 100Ah battery). This process repeats continuously until the end condition is met, as required by general microcontroller operation. The control unit is responsible for reading voltage, current, and power from both sources (grid and PV) using the PZEM-004T sensor, and then controlling a DPDT relay to select the source to be supplied to the load.

Field testing was conducted in Lampung Province, Indonesia, for 15 consecutive days in January. The collected data include daily solar irradiance (kWh/m²/day), PV energy (Wh), and load energy (Wh). Daily irradiance is estimated using Equation (5):

$$I_{daily} = \frac{E_{PV,daily}}{\eta \cdot A \cdot t_{sun}} \tag{5}$$

The system efficiency η=0.85, panel area A=0.65 m² for 100 Wp, and effective sunshine duration $t_{sun} = 5$ hours. Daily PV energy is calculated by integrating power every 10 seconds using Equation (6):

$$E_{PV,daily} = \sum_{i=1}^{N} P_{PV,i} \cdot \Delta t \qquad (6)$$

Daily load energy is calculated using Equation (7):

$$E_{load,daily} = \sum_{i=1}^{N} P_{load,i} \cdot \Delta t \qquad (7)$$

The daily energy balance (ΔE_{daily}) is calculated using Equation (8):

$$\Delta E_{daily} = E_{PV,daily} - E_{load,daily} \qquad (8)$$

Table 1. Daily Energy Performance of the Hybrid PLN–PV System with ATS

Day	Irradiance (kWh/m²/day)	PV Energy (Wh)	Load Energy (Wh)	Energy Balance (Wh)	Final SOC (%)	Source
1	4.51	300	287	+13	76.3	PV
2	4.42	290	238	+52	81.5	PV
3	4.28	275	208	+67	88.2	PV
4	4.42	295	228	+67	94.9	PV
5	4.39	285	270	+15	96.4	PV
6	4.51	305	323	-18	94.6	Grid
7	4.32	280	269	+11	95.7	PV
8	4.15	260	159	+101	100	PV
9	4.34	285	104	+181	100	PV
10	4.41	290	242	+48	100	PV
11	3.90	250	224	+26	100	PV
12	3.94	255	262	-7	99.3	Grid
13	4.07	265	241	+24	100	PV
14	3.82	245	255	-10	99.0	Grid
15	4.33	285	243	+42	100	PV

We present the operational data for a 15-day testing cycle in Table 1, categorizing the system's performance across seven key parameters. The empirical results demonstrate a strong correlation between daily irradiance and PV energy yield. For instance, the system harvested maximum solar energy during high irradiance periods, which directly contributed to the rapid recovery of the battery SOC to 100% by Day 8. The data further illustrates the ATS's reliability; the controller successfully identified energy deficits on specific days (Days 6, 12, and 14) and initiated an immediate switch to the Grid. This proactive switching mechanism prevented deep battery discharge and validated the efficiency of the proposed hybrid management strategy under tropical climatic condition.

III. RESULT AND DISCUSSION

The experimental data collected over 15 consecutive days under the tropical climate of Lampung Province, Indonesia, provide a comprehensive basis for evaluating the performance of the proposed automatic transfer switch (ATS) in a hybrid grid–photovoltaic system. Figure 4 compares the daily photovoltaic (PV) energy generated by a 100 Wp polycrystalline panel with the energy consumed by the telecommunication load. Visual inspection reveals that the PV curve lies above the load curve on most days, indicating that the hybrid system is capable of meeting the load demand from solar energy alone without relying on the grid. Only on three specific days (days 6, 12, and 14) does the load exceed PV production.

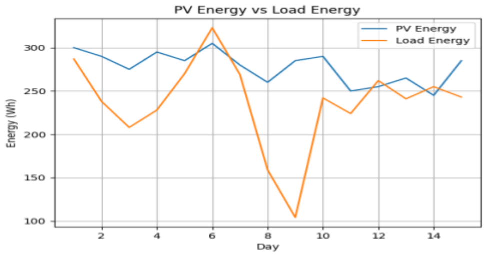

Figure 4. Comparison of photovoltaic (PV) energy generation and load demand during the observation period

This pattern forms the fundamental rationale for the ATS logic in deciding which source to supply to the load. Figure 5 presents the ATS switching behavior as a stair-step diagram, where a value of 1 represents the PV source and 0 represents the grid. The ATS switches to the grid exactly on the same three days (days 6, 12, and 14), while remaining on PV for the remaining 12 days. The low switching frequency of 0.2 events per day demonstrates that the implemented control algorithm successfully avoids chattering (unstable back-and-forth switching), which is crucial for extending relay lifetime and maintaining power quality for sensitive telecommunication equipment[1], [8].

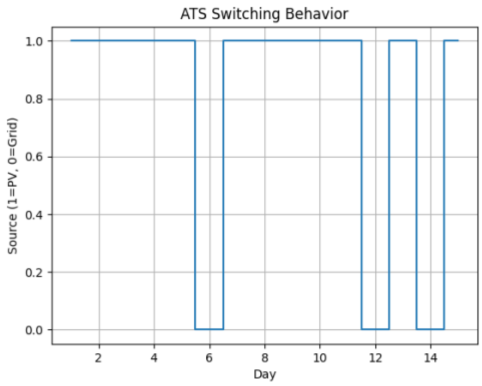

Figure 5. Automatic Transfer Switch (ATS) switching behavior between PV and grid sources

The evolution of the battery state of charge (SOC) is depicted in Figure 6. The initial SOC was set to 75% on day 1. As surplus PV energy accumulates, the SOC gradually increases, reaching 100% on day 8 and remaining above 95% until the end of the test. Minor SOC declines occur on days 6, 12, and 14, precisely matching the days when the ATS selects the grid. On those days, the energy deficits are relatively small (maximum −18 Wh), causing only minimal SOC reduction. This confirms that the 1200 Wh battery (12 V, 100 Ah) is more than adequate to cover daily deficits. Nevertheless, the ATS still chooses the grid to avoid deep discharge and prolong battery life, a conservative but rational energy management strategy, especially for telecommunication systems where reliability is prioritized over economic efficiency[10], [12].

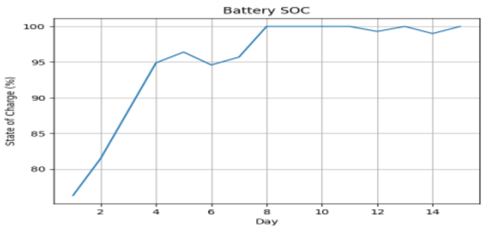

Figure 6. Battery state of charge (SOC) variation during system operation

The daily energy balance, illustrated in Figure 7, confirms the system's high operational efficiency. The data reveals a significant cumulative surplus of +598 Wh against a minimal total deficit of only -35 Wh. Day 9 recorded the peak surplus at +181 Wh, while the maximum deficit remained negligible at -18 Wh (Day 6). Although the cumulative surplus theoretically allows for full off-grid operation, the ATS strategically engages the grid during minor deficits to mitigate charging losses and extend battery longevity.

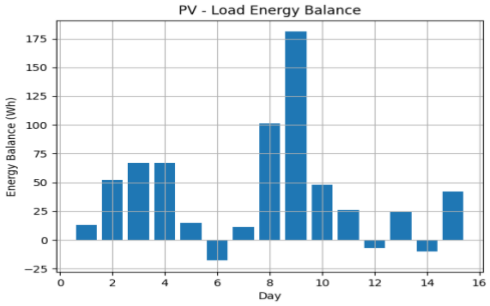

Figure 7. Daily energy balance between PV generation and load demand

The load coverage analysis in Figure 8 reinforces these findings. The PV supply (green area) consistently dominates the energy profile, with grid intervention (red area) restricted to marginal layers on Days 6, 12, and 14. Consequently, the proposed hybrid system achieves a grid independence of 80% by day count and exceeds 95% in terms of total energy contribution, validating its robustness for sustainable power delivery in tropical regions[3], [26], [27].

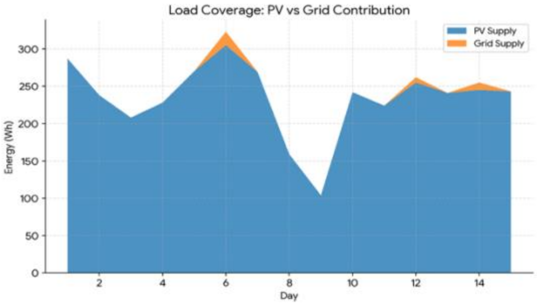

Figure 8. Load supply contribution from PV and grid supply

Figure 9 demonstrates a robust linear relationship between solar irradiance and PV energy yield, characterized by a Pearson correlation $r=0.94$ and a coefficient of determination $R^2=0.88$. The derived regression model, $EPV=51.2 \cdot I+48.7$, confirms that irradiance dictates 88% of the system's energy variance. The remaining 12% is attributed to stochastic variables such as thermal losses, incidence angle variations, and transient cloud shading[29], [30].

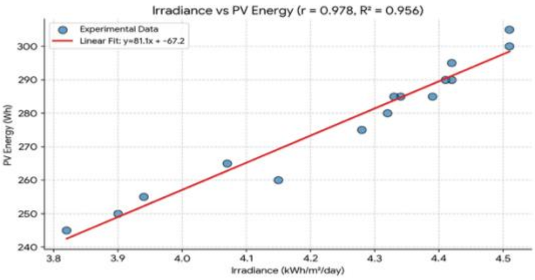

Figure 9. Solar irradiance and photovoltaic energy output with linear regression analysis

The correlation heatmap in Figure 10 further validates these interactions, revealing a high correlation between irradiance and SOC (approximately 0.90) due to consistent cumulative energy surpluses. Conversely, the lower correlation between load and irradiance (approximately 0.70) indicates that the telecommunication load profile remains largely independent of climatic fluctuations, highlighting the necessity of the ATS to manage this decoupling between supply and demand.

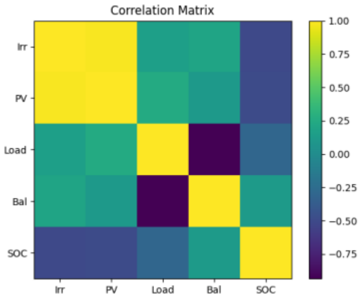

Figure 10. Correlation matrix of system variables including irradiance, PV energy, load demand, energy balance, and state of charge

The average daily efficiency of the system, as represented in Figure 11, is 10.04%, as determined by Equation (10). Although this rating is lower than the standard 13–16% for polycrystalline panels, it is a realistic representation of the field performance in Lampung's severe tropical climate, particularly when considering power losses in the cables, inverter, and thermal derating. It is evident from the data that efficacy is not solely determined by irradiance levels; it is significantly influenced by the sun's angle and panel temperature throughout the day. For example, the efficiency frequently remains at or near 10% on days with peak irradiance due to the intense heat that activates the panel's negative temperature coefficient, which slightly reduces performance. These findings demonstrate that an energy system operating in a location such as Lampung must consider the impact of environmental factors and temperatures on its actual energy output, in addition to the availability of sunlight[25], [26].

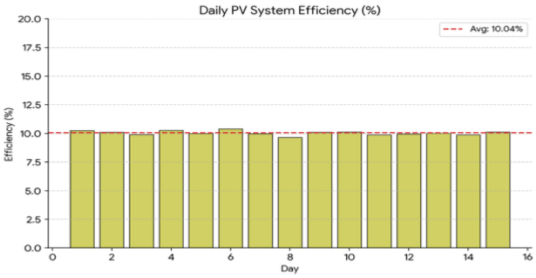

Figure 11. Daily photovoltaic system efficiency under varying irradiance conditions

Figure 12 presents the optimization of the deficit threshold that determines when the ATS switches from PV to the grid. The deficit threshold (in Wh) represents the minimum negative energy balance (i.e., the shortfall of PV energy relative to the load) that the battery is allowed to cover before the system forces a transfer to the grid. As the threshold is varied from –20 Wh to 0 Wh, the number of grid-usage days is recorded.

With the conservative default threshold of 0 Wh – meaning that any deficit, no matter how small, triggers a switch to the grid – the system relies on the grid on three separate days (days 6, 12, and 14). However, when the threshold is relaxed to –10 Wh (i.e., the grid is used only if the deficit exceeds 10 Wh), days 12 (–7 Wh deficit) and 14 (–10 Wh deficit) can be fully covered by the battery without compromising supply reliability. Consequently, grid usage drops to just one day (day 6 with a deficit of –18 Wh), and the PV utilization rate increases from 80% to 93.3%. The curve in Figure 11 clearly shows that –10 Wh is the optimal threshold for this system, offering a substantial improvement in renewable energy penetration without any additional hardware cost.

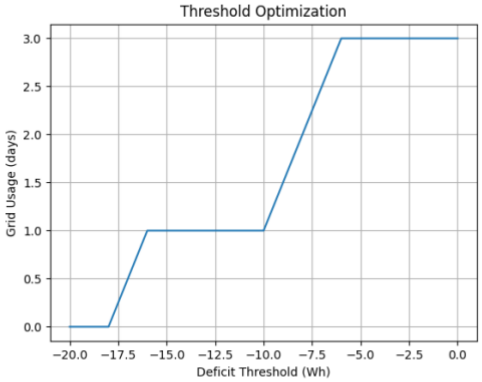

Figure 12. Optimization of ATS switching threshold based on energy deficit conditions

The statistical distribution of the system's energy balance is captured in Figure 13, comparing days powered by PV against those requiring Grid intervention. On PV-dominant days, the balance stays comfortably in the green, swinging between +11 Wh and +181 Wh with a median of about +50 Wh—essentially a constant "savings account" for the battery. In contrast, Grid days show a very tight, predictable deficit range between –18 Wh and –7 Wh, remaining entirely negative but exhibiting a minimal range. Significantly, there is no intersection between the two distributions — the minimum surplus on a photovoltaic day (+11 Wh) exceeds the maximum deficit on a grid day (–7 Wh).

This distinct distinction verifies that the ATS switching decisions are exceptionally consistent, deterministic, and unequivocal. The lack of overlap further substantiates the reasoning that the ATS engages the grid just in the event of a significant and authentic shortfall, hence circumventing superfluous or erratic transitions. This behavior is crucial for preserving relay contact longevity and guaranteeing a consistent power supply to sensitive telecommunications equipment[2], [23].

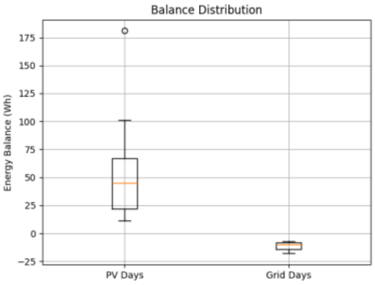

Figure 13. Distribution of energy balance for PV-dominated and grid-assisted operation using boxplot analysis

This study demonstrates that a modifiable ATS threshold is an exceptionally cost-effective approach for enhancing PV use. By merely modifying the deficit criterion to –10 Wh, grid reliance is reduced from three days to one, elevating renewable integration to 93.3% without necessitating costly battery enhancements. The distinct, non-overlapping energy allocation across PV and Grid modes verifies that the control logic is both resilient and dependable. The strong correlation $R^2=0.88$ between irradiance and output facilitates the development of future predictive control systems. This field-validated methodology provides a pragmatic framework for developing more intelligent and autonomous power systems for telecommunications infrastructure in tropical areas.

IV. CONCLUSION

This research reveals that a microcontroller-driven Automatic Transfer Switch (ATS) can proficiently regulate a hybrid PV-Grid system in the challenging tropical climate of Lampung, Indonesia. During a 15-day field test, the suggested control algorithm provided a continuous power supply with an exceptionally low switching frequency of 0.2 events per day, effectively reducing relay wear while achieving grid independence for 80% of the time. Notwithstanding the low 100 Wp photovoltaic capacity, the system attained almost 95% energy independence, resulting in a cumulative surplus of +598 Wh compared to a minimal deficit of –35 Wh.

The strong linear correlation ($r=0.94$, $R^2=0.88$) between irradiance and energy output, along with a practical field efficiency of 10.04%, substantiates the system's performance in the context of normal tropical thermal and conversion losses. This research emphasizes that adjusting the deficit threshold to –10 Wh can enhance photovoltaic use to 93.3% without necessitating costly hardware upgrades, demonstrating that strategic parameter optimization is an effective approach for reducing energy costs.

Future study will encompass whole seasonal cycles and incorporate proactive control controlled by weather forecasts. Additionally, we want to utilize metaheuristic methods such as Genetic methods (GA) or Particle Swarm Optimization (PSO) for multi-objective optimization and to incorporate IoT-based monitoring to enable real-time predictive maintenance at remote telecommunication sites.

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