

Design and Development of a Smart Energy Management System Based on Hybrid Demand Side Management for 1100 Wp Off Grid Solar Power Plant Battery Optimization

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ABSTRACT

Off-Grid solar power plant systems often face battery life degradation due to deep discharge cycles. This research aimed to design a Smart Energy Management System (SEMS) based on an ESP32 microcontroller and PZEM-017 sensors to monitor and control load dispatch. The system supplied a 3,420 Wh daily load using 1,100 Wp solar panels and a 25.6V 100Ah (2,560 Wh) LiFePO4 battery. The applied strategy was Hybrid Demand Side Management (DSM), integrating Load Shifting and Load Shedding. Test results indicated the sensors operated exceptionally well with an average error rate of 1.44%. The system successfully executed Load Shifting by directly powering heavy loads during abundant solar production ($P_{pv} > 500W$). Conversely, it executed priority Load Shedding by disconnecting non-essential loads during power-saving mode ($20\% \leq SoC \leq 50\%$). Furthermore, the system automatically switched the power source to the utility grid when the battery reached a critical condition $SoC < 20\%$. The evaluation proved this system effectively prevented 100% deep discharge and limited the maximum Depth of Discharge (DoD) to 80%, significantly extending the LiFePO4 battery's cycle life.



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1. INTRODUCTION

The utilization of off-grid solar power plants has become a strategic solution for achieving energy independence, particularly in remote areas. In off-grid systems, the sustainability of the power supply relies heavily on energy storage units (batteries) [1]. However, batteries represent the highest investment cost and are the most vulnerable component to performance degradation caused by poor discharging management. Operating heavy electrical loads when battery capacity is running low frequently triggers a deep discharge condition. This practice massively reduces the battery's cycle life, especially if the Depth of Discharge (DoD) limit is continuously violated [2], [3].

Various studies related to Automatic Transfer Switch (ATS) systems in solar power plants generally still employ conventional, non-selective logic [4]. Such systems unilaterally shift the entire electrical load to the utility grid (PLN) when the battery reaches its minimum voltage limit, without classifying load priorities. Furthermore, energy inefficiency frequently occurs due to the battery's round-trip losses (approximately 15% - 20%) during the charge-discharge cycles. System efficiency can be

significantly improved through a direct self-consumption strategy, which involves operating high-power loads directly during peak solar energy production [5]. Nevertheless, the absence of real-time solar irradiance data often causes users to miscalculate the peak power period, resulting in a massive current draw from the battery during cloudy weather.

To address this gap, the integration of Internet of Things (IoT) devices into the Energy Management System (EMS) instruments is absolutely necessary [6], [7]. While several previous studies have implemented smart sensors in solar power systems, the majority focused solely on remote monitoring functions without executing autonomous load-side management actions based on actual real-time data[8], [9].

Therefore, this research developed a Smart Energy Management System (SEMS) based on the ESP32 microcontroller and the PZEM-017 high-precision DC parameter reader module. This system offers novelty through the implementation of an automated Hybrid Demand Side Management (DSM) algorithm. Unlike conventional ATS, this algorithm utilizes the actual power value (P_{pv}) from the solar panels to trigger Load Shifting during the day, and analyzes the estimated State of Charge (SoC) of the LiFePO4 battery using polynomial regression to perform priority Load Shedding at night. This hybrid approach aims to maximize the self-consumption ratio while drastically extending the economic cycle life of the battery by keeping the DoD within safe limits.

2. RESEARCH METHOD

This research was conducted comprehensively to design, develop, and validate a Smart Energy Management System (SEMS) intended for an off-grid solar power plant. The research methodology was divided into several key stages, as illustrated in the research flowchart.

The research methodology was divided into several key stages: system architecture design, hardware integration, algorithm development based on Hybrid Demand Side Management (DSM), and experimental evaluation. The object of this research was an off-grid solar installation located in Palembang, South Sumatra, which utilized two 550 Wp monocrystalline solar panels (total 1,100 Wp) and a 25.6V 100Ah LiFePO4 battery as the primary energy storage unit.

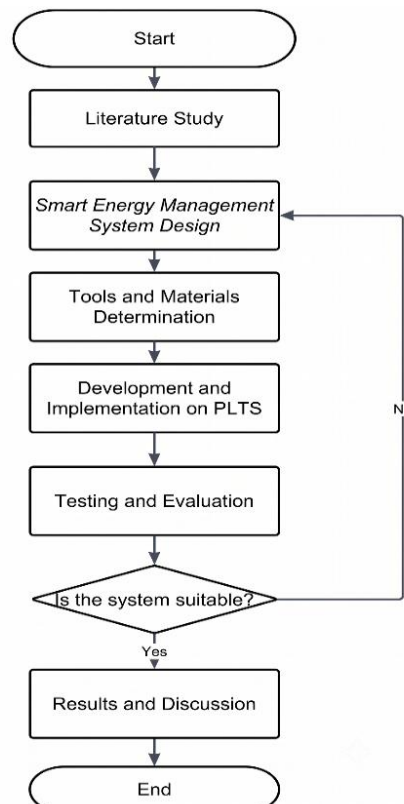


Figure 1. Research flow

2.1. System Architecture and Hardware Integration

The system architecture, as illustrated in the block diagram, consists of three main stages: input, process, and output. The input stage comprises the solar panels acting as the primary energy source and the utility grid (PLN) functioning as a backup. The processing stage is the core of the Smart Energy Management System (SEMS). The main control center utilizes an ESP32 microcontroller, which processes sensor data and executes the switching logic[10]. The data acquisition system relies on two precision PZEM-017 (DC) instruments connected via a Modbus RTU (RS485 to TTL) communication interface to ensure accurate voltage and current tracking [11].

The first sensor (PZEM-017 1) is installed at the solar panel output with the assistance of a 100A shunt resistor to monitor Voltage, Current, and Generation Power (P_{pv}). The second sensor (PZEM-017 2) is installed at the battery terminal to read voltage fluctuations and charge/discharge currents. The power control execution (actuator) at the output stage is managed using a 5V/10A 4-Channel Relay module that connects or disconnects the 220V AC line from the inverter to the priority loads, non-priority loads, and regulates the backup source interlock from the utility grid (PLN).

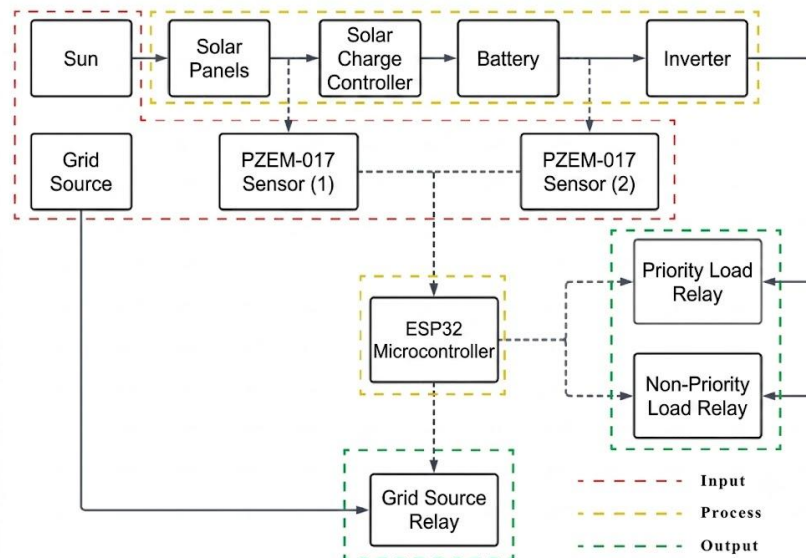


Figure 2. SEMS hardware block diagram

2.2. Algorithm and Hybrid DSM Strategy

The State of Charge (SoC) estimation of the LiFePO4 battery on the ESP32 does not use a linear percentage mapping. Instead, it utilizes a 4th-Order Polynomial Regression computation:

$$SoC = aV^4 + bV^3 + cV^2 + dV^1 + e \quad (1)$$

This mathematical approach (1) was specifically selected to accurately accommodate the highly flat plateau characteristic of the LiFePO4 battery's voltage drop curve. The Hybrid DSM algorithm continuously loops, utilizing the PV power (P_{pv}) and the battery SoC to execute three main operational scenarios:

1. Load Shifting Strategy: If the system detects abundant solar power production where $P_{pv} > 500W$, the status of both the Priority Relay and Non-Priority Relay will be connected (ON). The solar panel power is maximized to supply all heavy loads through direct consumption, shifting energy usage from nighttime to daytime.
2. Load Shedding Strategy: If the solar power generation decreases ($P_{pv} < 500W$), the system shifts its reliance to the battery and continuously evaluates the SoC:
 - Safe Mode ($SoC > 50\%$): All priority and non-priority loads are kept ON.
 - Power-Saving Mode ($20\% \leq SoC \leq 50\%$): The ESP32 automatically disconnects the Non-Priority Relay (OFF) to conserve energy. Essential priority loads continue to receive power (ON) from the battery.

3. Critical Protection Strategy ($SoC < 20\%$): The interlock algorithm is triggered. The inverter line is completely disconnected, and the system automatically switches to the Grid Source Relay contactor (ON). This serves as an absolute protection mechanism (limiting the Depth of Discharge to 80%) to safeguard the battery from experiencing a damaging 100% deep discharge.

2.3. System Evaluation Setup

The experimental testing was divided into two phases. The first phase focused on validating the accuracy of the instrumentation. The voltage and current readings from both PZEM-017 sensors were compared against calibrated standard measuring instruments (a digital multimeter and a clamp meter) to determine the percentage error. The maximum allowable error margin was set at $\leq 2\%$, following industrial standards.

The second phase evaluated the reliability of the control logic. The tests involved simulating various solar power and battery SoC conditions to observe the ESP32's response. The success criteria were based on the accurate execution of relay transitions corresponding to the predefined thresholds for Load Shifting, targeted Load Shedding, and the final safety switch to the utility grid.

3. RESULTS AND DISCUSSION

Testing was conducted to validate the precision of the PZEM-017 sensor data acquisition and the reliability of the Hybrid DSM control logic in responding to actual fluctuations in energy production and battery capacity.

3.1. Sensor Stability and Accuracy Validation

The accuracy of electrical data reading is highly crucial, considering that a voltage computation error on the LiFePO4 battery could trigger incorrect relay switching. Prior to operation, both PZEM-017 units underwent a software-based zero-offset calibration stage to eliminate parasitic impedance (-0.6A on the solar side and -0.5A on the battery side).

Sensor stability testing was conducted for 7 consecutive days, compared with standard, calibrated measuring instruments (Digital Multimeter). The testing results are summarized in Table 1.

Table 1. Average sensor accuracy testing results (7 Days)

Day	Test Point	Parameter	Standard Measuring Instrument	PZEM-017 Sensor	Difference	Error (%)
1	Sensor 1 (PV)	Voltage (V_{DC})	75,90 V_{DC}	77,3 V_{DC}	1,40	1,84%
		Current (A)	5,20 A	5,3 A	0,10	1,92%
	Sensor 2 (Battery)	Voltage (V_{DC})	26,41 V_{DC}	26,7 V_{DC}	0,29	1,10%
		Current (A)	15,42 A	15,6 A	0,18	1,17%
2	Sensor 1 (PV)	Voltage (V_{DC})	75,20 V_{DC}	75,6 V_{DC}	0,40	0,53%
		Current (A)	1,06 A	1,1 A	0,04	3,77%
	Sensor 2 (Baterai)	Voltage (V_{DC})	24,43 V_{DC}	24,5 V_{DC}	0,07	0,29%
		Current (A)	4,41 A	4,5 A	0,09	2,04%
3	Sensor 1 (PV)	Voltage (V_{DC})	80,00 V_{DC}	81,4 V_{DC}	1,40	1,75%
		Current (A)	2,89 A	2,9 A	0,01	0,35%
	Sensor 2 (Baterai)	Voltage (V_{DC})	27,08 V_{DC}	27,4 V_{DC}	0,32	1,18%
		Current (A)	7,23 A	7,4 A	0,17	2,35%
4	Sensor 1 (PV)	Voltage (V_{DC})	79,50 V_{DC}	80,7 V_{DC}	1,20	1,51%
		Current (A)	4,01 A	4,1 A	0,09	2,24%
	Sensor 2 (Baterai)	Voltage (V_{DC})	27,32 V_{DC}	27,5 V_{DC}	0,18	0,66%
		Current (A)	9,08 A	9,2 A	0,12	1,32%
5	Sensor 1 (PV)	Voltage (V_{DC})	73,70 V_{DC}	74,8 V_{DC}	1,10	1,49%
		Current (A)	6,29 A	6,4 A	0,11	1,75%
	Sensor 2 (Baterai)	Voltage (V_{DC})	28,16 V_{DC}	28,3 V_{DC}	0,14	0,50%
		Current (A)	7,68 A	7,8 A	0,12	1,56%
		Voltage (V_{DC})	85,70 V_{DC}	87,3 V_{DC}	1,60	1,87%

Day	Test Point	Parameter	Standard Measuring Instrument	PZEM-017 Sensor	Difference	Error (%)
6	Sensor 1 (PV)	Current (A)	4,82 <i>A</i>	4,9 <i>A</i>	0,08	1,66%
	Sensor 2 (Baterai)	Voltage (V_{DC})	27,87 V_{DC}	28,2 V_{DC}	0,33	1,18%
		Current (A)	12,36 <i>A</i>	12,5 <i>A</i>	0,14	1,13%
7	Sensor 1 (PV)	Voltage (V_{DC})	85,40 V_{DC}	86,5 V_{DC}	1,10	1,29%
		Current (A)	6,17 <i>A</i>	6,3 <i>A</i>	0,13	2,11%
	Sensor 2 (Baterai)	Voltage (V_{DC})	27,96 V_{DC}	28,1 V_{DC}	0,14	0,50%
		Current (A)	18,09 <i>A</i>	18,3 <i>A</i>	0,21	1,16%
Average Error (%)						1,44%

Based on Table 1, the average overall error percentage of the reading system was 1.44%. According to the Indonesian National Standard (SNI IEC 60051-1:2011), the error tolerance limit for industrial-grade panel electrical instruments is in the range of $\pm 1.5\% - 5\%$ [12]. The error value of 1.44% indicates that the SEMS instrumentation is highly precise and possesses valid high reliability as a reference for the DSM algorithm. Furthermore, power quality testing at the Hybrid Inverter output also demonstrated highly stable Alternating Current (AC) voltage regulation ranging from 229.3VAC to 230.3VAC, with an extreme error tolerance below 0.30%.

3.2. Evaluation of the Hybrid DSM Algorithm

The control logic execution test was performed by manipulating field parameters to observe the relay switching response. Table 2 illustrates the scenarios successfully handled by the ESP32 microcontroller.

Table 2. Verification of hybrid DSM relay execution

No	Test Parameter	Condition during Testing	Relay			Compliance
			Priority	Non-Priority	PLsN	
1	Active Load Shifting (Abundant solar production) $P_{PV} > 500W$ $SoC \geq 50\%$	$P_{PV} = 552 W$ $SoC = 80\%$	ON	ON	OFF	Match
2	Normal Operation (Night/Cloudy, Safe Battery) $P_{PV} \leq 500W$ $SoC \geq 50\%$	$P_{PV} = 338 W$ $SoC = 80\%$	ON	ON	OFF	Match
3	Load Shedding (Battery energy saving) $P_{PV} \leq 500W$ $20\% \leq SoC \leq 50\%$	$P_{PV} = 218 W$ $SoC = 50\%$	ON	OFF	OFF	Match
4	Critical Condition (Protection) (Deep Discharge Prevention) $P_{PV} \leq 500W$ $SoC < 20\%$	$P_{PV} = 10 W$ $SoC = 19\%$	OFF	OFF	ON	Match

During hot daytime scenarios $P_{PV} > 500W$, the system successfully executed the Load Shifting strategy. Heavy loads such as an iron or a washing machine (non-priority) continued to receive electricity from the abundant solar energy, preventing this power from being wasted.

Towards evening or during heavily overcast weather ($P_{PV} \leq 500W$), the algorithm relied on the battery value. When the battery reached 50% SoC, the Load Shedding phase was activated. The system immediately and autonomously disconnected the Non-Priority Relay, while the Priority Relay remained ON. This action shed excess load, significantly slowing down the State of Charge (SoC) decline rate at night.

As the final layer of protection, when the battery hit an SoC below 20%, the system identified a critical condition. The interlock algorithm completely halted current draw from the inverter and automatically transferred the household load to the PLN utility line.

3.3. Impact on Battery Cycle Life

In conventional Off-Grid solar installations, uncontrolled current draw at night often causes the battery voltage to hit its lowest point (0% SoC or 100% DoD). Referring to the electrochemical characteristics of Lithium Iron Phosphate (LiFePO₄) cells [7], forcing ion extraction up to 100% DoD applies contraction stress on the electrodes, limiting the cell's lifespan to around ± 4.000 cycles [13].

Through the implementation of the designed SEMS, the system absolutely performs automatic braking and transfers the load to the grid at the 20% SoC threshold. This means the Depth of Discharge rate is successfully limited to 80%. Restricting ion movement within this safe mechanical zone, both empirically and theoretically, prevents early cell damage and projects the LiFePO₄ battery's cycle life to increase significantly to approximately ± 6.000 cycles [14]. Assuming 1 cycle per day, this system is capable of extending the economic lifespan of the battery by more than 5 additional years compared to conventional systems.

4. CONCLUSION

This research has successfully designed and implemented a Smart Energy Management System (SEMS) to address the risk of battery wear in a 1100Wp Off-Grid solar system. Based on empirical testing, the PZEM-017-based measurement devices operated with high precision, recording an average error of 1.44%, fully complying with instrument quality standards. The ESP32 microcontroller proved reliable in executing the Hybrid DSM logic, autonomously optimizing excess energy production through Load Shifting during the day and conserving power through priority Load Shedding at night. The utmost effectiveness of this system lies in its proven ability to absolutely secure the LiFePO₄ battery from deep discharge conditions. Based on empirical validation where the system consistently and autonomously transferred the electrical load to the backup utility grid exactly at the 20% SoC threshold, the maximum Depth of Discharge was physically locked at 80%. By strictly enforcing this verified operational boundary, theoretical and electrochemical data project the battery's cycle life to be drastically extended to approximately $\pm 6,000$ cycles. This smart intervention not only maintains electrical continuity but provides a strong empirical basis for an economic lifespan extension of over 5 years compared to conventional systems.

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