
Experimental analysis of Charge Controllers: Comparative Insights into Conventional, Smart, and IoT-Based Intelligent Designs for Islanded PV Systems

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Abstract:- This paper presents the experimental and simulation implementation of an IoT-integrated intelligent MPPT (Maximum Power Point Tracking) charge controller tailored for Islanded mode photovoltaic (PV) systems. Comparatively experimentation with three charge controllers were used for standalone PV system to draw constant power of 250/500Wp from off-grid PV system on charging and discharging on intermittent weather conditions for two weeks respectively Conventional, Smart and Intelligent controllers. Adopting advanced control algorithms, real-time data monitoring, and smart decision-making, the system achieves significant improvements in efficiency, reliability, and energy management is conducted through MATLAB and PVGIS simulations. Main performance parameters such as charging efficiency, load handling, and adaptability under variable solar irradiance are evaluated. The research validates the superiority of intelligent controllers using IoT over traditional designs in islanded mode solar applications.

Keywords: *PV System, MPPT, IoT tools, Smart Load, PVGIS, MATLAB.*

1. Introduction

The demand of power in remote areas can be mitigate without adding extra units by upgrading same with the efficient and autonomous Islanded mode PV systems and overcome energy access challenges in remote areas. Traditional charge controllers lack dynamic adaptability, resulting in energy loss. MPPT techniques have enhanced performance but require integration with smart sensing and control [3]. This research introduces an IoT-based intelligent MPPT charge controller that adapts to changing solar and load conditions using real-time feedback and control. MPPT designed to optimize the PV output and efficiency of a PV array. Mostly used in an Islanded mode scenario, charge controllers are used to track, monitor and regulate the Solar array output voltage to the batteries, which store the generated power [4]. Mostly devices, applications and systems are depended on the of battery energy storage and renewable energy generating systems, the requirement to explore other possibilities to enhance the latest technological implementation is very much crucial in todays' situation where energy sustainability is important [12].

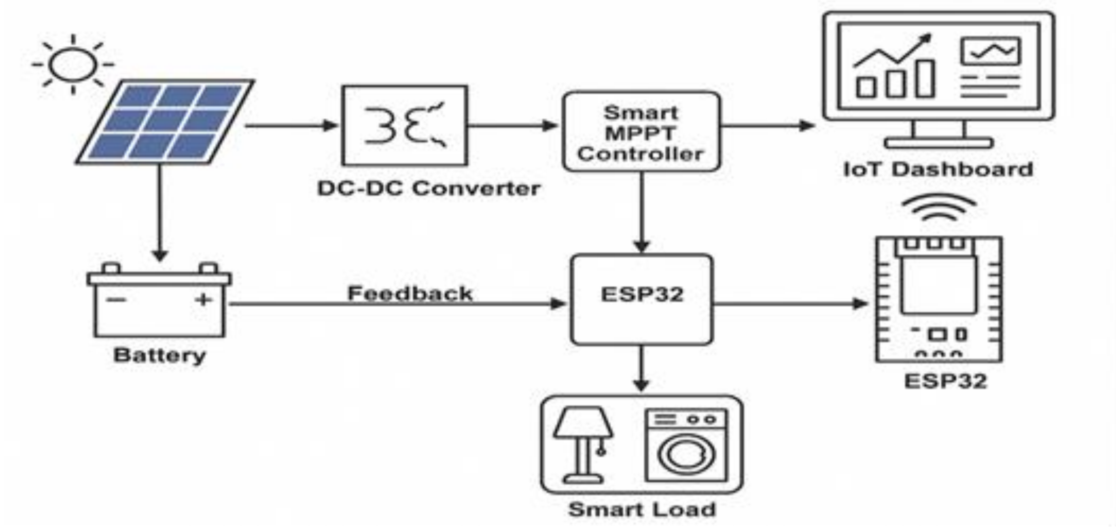

Figure 1. Block diagram of the an intelligent MPPT solar charge controller with IoT tools

2. Related Work

Efficient Maximum Power Point Tracking (MPPT) is essential in standalone systems for extracting maximum power with intermittent conditions. Perturb and Observe (P&O) and Incremental Conductance (INC) mainly adopted as base methods due to simplicity but are limited under rapidly changing irradiance and environmental. Proposed an adaptive step-size INC to address tracking delays [13], while analyzed performance Quaid pro que between P&O and INC techniques [14]. Reviewed widely used MPPT methods and share their limited adaptability in evolution condition [2]. To improve performance and efficiency, an intelligent algorithm such as fuzzy logic, neural networks, and hybrid approaches have been proposed and categorized MPPT techniques into classical, hybrid, optimal, and intelligent, emphasizing AI-driven advancements [1]. Compared fuzzy inference methods and introduce Sugeno systems more suitable for precise control in islanded mode systems [22]. Explored PV array configurations and tunning of MPPT for improved energy yield [20]. Examine various charge controller and strategies, proposed hybrid MPPT approaches enhance overall system performance [9]. Incorporating power storage and microgrid compatibility with batteries is upcoming focus. Explore MPPT and battery synchronizing for islanded PV systems [16], while Discussed voltage-frequency control interconnection with MPPT to ensure microgrid stability and performance [5, 21]. Analyzed linked battery controller models to assess efficiency across PV installations for real world [10]. A networked advancement is the integration of IoT technologies in MPPT control. Proposed and tested an IoT-enabled MPPT charge controller that provide better monitoring and efficiency [11]. Introduced an ultra-efficient MPPT design responsive for IoT smart nodes [24]. Reviewed real-time IoT-based solar monitoring systems, share its role in remote power management [12]. Underline latest AI options in MPPT, supporting for intelligent, self-learning controllers [25]. Further implementations, such as the cost-effective systems by [7-8,16]. Pv Simulation software PVGIS is open-source online software which is used to calculate various parameters of a PV system. It is mandatory to login id to use software to calculate the system output and data inputs according to installed system evaluate the daily irradiation, temperature, Battery state of charge (SoC), location, energy production, annual yield and total system losses it in the following manner https://photovoltaic-software.com/pvgis. Php [27].

3. System Description

The system installed for experimental analysis description is given in Table 1. The 500Wp rooftop Islanded mode system is selected for study. Material of PV selected Polycrystalline as per efficiency and availability. The installed PV system is of fixed stand type and have capacity to supply power a small load. The islanded system consists of PV arrays to convert solar irradiance into electric power, a solar standalone inverter to convert DC power generation into AC power as per load, a mounting stand, connectors, cabling and other electrical accessories. Schematic islanded mode PV system is shown in Figure 1. The major component of solar PV systems are two PV panels in parallel and each PV panel has 24 crystalline PV modules in series.

Table 1: System configuration for 500Wp

Modules in Parallel	2
Parallel strings	1 String
Total number of modules	2
Proposed system capacity	500Wp
Total Number of Inverter	01 of 600VA
Cable Laying (Array to Inverter)	12 AWG
Series Fuse	15 A
Module Tilt Angle	Tilt – 25 deg.

The specifications of used PV modules are given in Table 2. The off-grid PV system is installed with inverters, data logger, three charge controller, connecting cables and switches. It is with battery storge and able to supply the power requirement through the directly and using inverter to the institute lab.

Table 2: Specification of PV Module

Attribute	Specification
Types of PV Module	Polycrystalline
Nominal Rating	250Wp
Open Circuit Voltage (V_{oc})	21 V
Short Circuit Current (I_{sc})	10 A
Max Power Point Voltage (V_{mp})	18 V
Max Power Point Current (I_{mp})	9.5 A
System Voltage	1500 V (IEC)
Fill Factor	77.33%
Module Efficiency	18.81%

3.1 Geographical Location of the Site

Solar radiation increases first then decreases with the angle of the inclined plane surface. Solar power generation and efficiency influence by the tilt angle of PV array. The 250Wp and 500Wp solar power plant installed at Pusa, New Delhi, India is located at latitude 28.634055° N and longitude 77.167847° E of 10 - 15m height shown in figure 2(a) & (b) which calculated by the PVGIS open-source online simulation software, the meteorological data were collected from NSRDB. The system installed at favourable geographical location which support to get maximum solar radiation and temperature in order to generate power effectively. Total radiation on the inclined plane calculated by the equations [9]

$$H_t = H_{bt}(S) + H_{dt}(S) + H_{rt}(S) \quad (1)$$

$$H_{bt} = H_b \times R_b \quad (2)$$

$$H_{dt} = H_d \left[\frac{H_b}{H_c} R_b + 0.5 \times \left(1 - \frac{H_b}{H_0}\right) (1 + \cos S)\right] \quad (3)$$

$$H_{rt} = 0.5\rho H(1 - \cos S) \quad (4)$$

In the above equations total radiations on the: ***H*** – horizontal surface; $\boldsymbol{H_0}$ – atmosphere outer layer surface; $\boldsymbol{H_b}$ – direct on horizontal plane; $\boldsymbol{H_{bt}}$ – direct on inclined plane; $\boldsymbol{H_d}$ – amount of scattering on horizontal plane; $\boldsymbol{H_{dt}}$ – amount on the inclined plane; $\boldsymbol{H_{rt}}$ – reflection on the tilting surface.

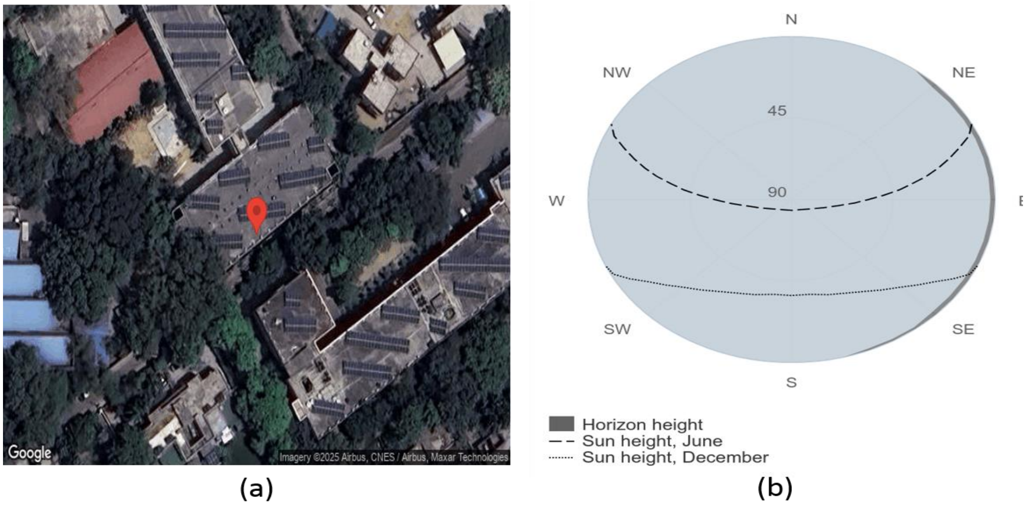

Figure 2. (a) Satellite Location, (b) Horizon

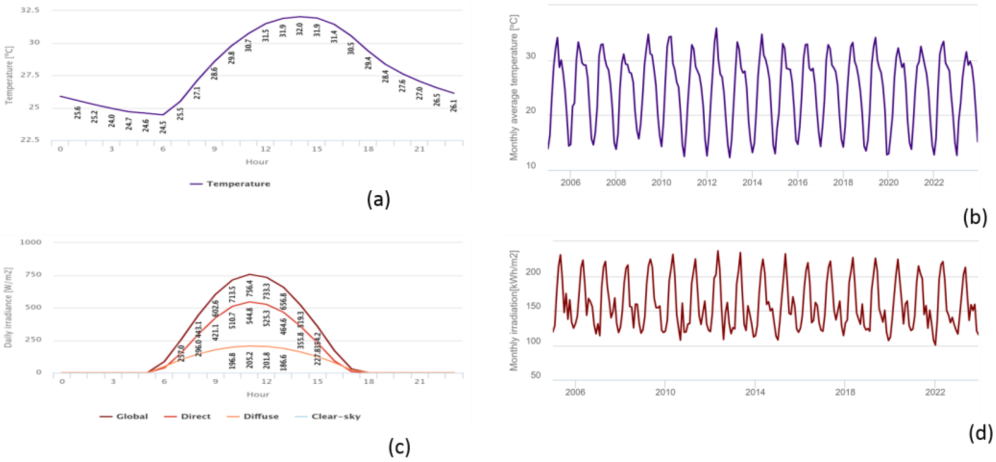

Figure 3. (a) Daily average temperature, (b) Monthly average temperature, (c) Daily average irradiance, (d) Monthly Solar irradiance estimation

4. Methodology

This research proposes an IoT-integrated intelligent MPPT model for islanded mode PV systems, utilizing two 250Wp solar panels, inverter, conventional, smart and intelligent charge controllers which validate with experimental outcomes. The system employs an MPPT algorithm enhanced with real-time battery State of Charge (SoC) feedback to optimize charging efficiency and protect battery health shown in figure 4 Charge controller parameters voltage, current, and SoC—are continuously monitored manually and transmitted via wi-fi IoT dashboard for real-time visualization and control. The controller also manages smart loads, categorized as critical, semi-critical, and non-critical, adjusting power delivery based on SoC thresholds and available solar input. When energy is limited, non-essential loads are automatically disconnected to preserve battery life. Conventional and smart charge controller monitoring in real time and IoT integrated controller is simulation using MATLAB and comparison with all controller for evolution the performance at each stage.

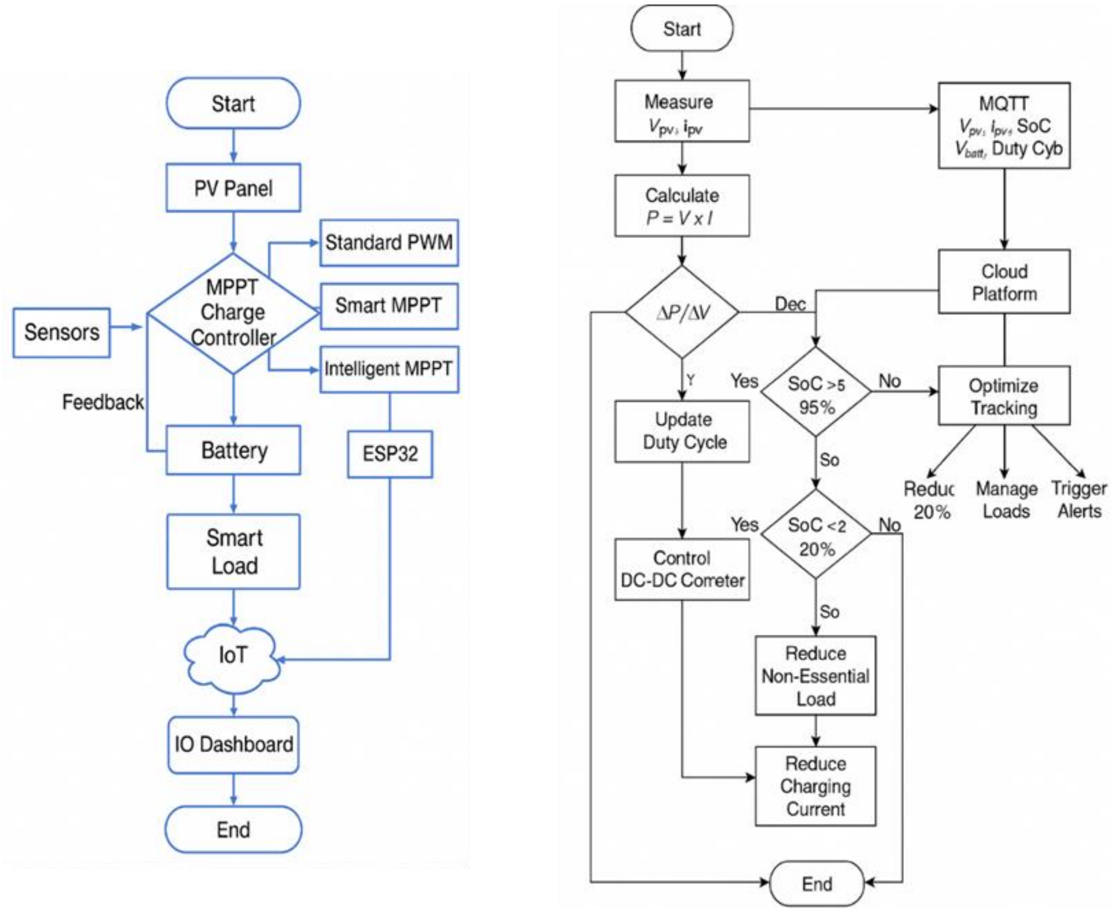

Figure 4. Flowchart of IoT enabled charge controller

5. Modelling of Photovoltaic Module and Charge Controller

The day-to-day power output generated by a PV array can be given through Eq. (1) [10] and PV I-V relation can represent through Eq. (2) [11].

$$P_{pv(t)} = \left[P_{mpp}\left(\frac{G(t)}{G_0}\right) - \mu_m[T_c(t) - T_0]\right] \times \eta_{inv} \times \eta_w \tag{5}$$

$$I_{pv} = I_{ph} - I_o\left(e^{q\left(\frac{V_{pv}+I_{pv}R_S}{nKT}\right)} - 1\right) - \frac{V_{pv}+I_{pv}R_S}{R_{sh}} \tag{6}$$

The tracking efficiency of MPPT charge controller with IoT integration can be calculated by Eq. (3-5) [11].

$$\frac{dI}{dV} = -\frac{I}{V} \; or \; P\&Q \tag{7}$$

$$V_{ref} = f\; MPPT(V, I) \; or \; V_{ref} = V_{cloud} \; (IoT \; override) \tag{8}$$

$$\eta_{tracking} = \left(\frac{P_{pv\;average}}{P_{available}}\right) \times 100 \tag{9}$$

Where, G- irradiance (W/m^{2}), T- temperature, P_{pv}- PV power output, V_{pv} -PV panel Voltage, I_{pv} – PV panel output current, G(t)- irradiance at time t, η_{inv}, η_w – inverter and wires efficiencies, Δt- time step, $P_{pv,\,average}$, $P_{available}$ are output power and output power of PV, respectively.

6. Results and Discussion

A real-time experiment on output of solar charge controllers is carried out and compared with the MATLAB simulation results. Practical setup in lab for the performance evaluation of the charge controllers is described in

Figure 5 which consist the PV array on the rooftop and components used in system and required laboratory practical setup with the power storge and solar testing equipment. Three 100 Ah lead-acid battery used for power storage and charge controller input. The generating power of the PV array is stored in the battery through the different types of charge controllers. The generating power, voltage and current as well as the battery parameters are directly recorded by the digital meter board. The PV voltage is almost 18V to 22V, that is over the range to charge the battery, so the charge controller reduces the voltage to the limit which is given in table 3 according to experimental result shown in table 4.

Table 3: Battery charging voltage

PV Voltage range	Conventional Charge Controller	Smart Charge Controller	Intelligent Charge Controller
18V – 22V	13.5V -14V	13.9V – 14.9V	14.8V to 15V

The highest voltage to be supply for charging a battery is 15V without affecting the battery protection. MPPT charge controllers output current, voltage and battery charging pattern are mentioned in Figure 8.

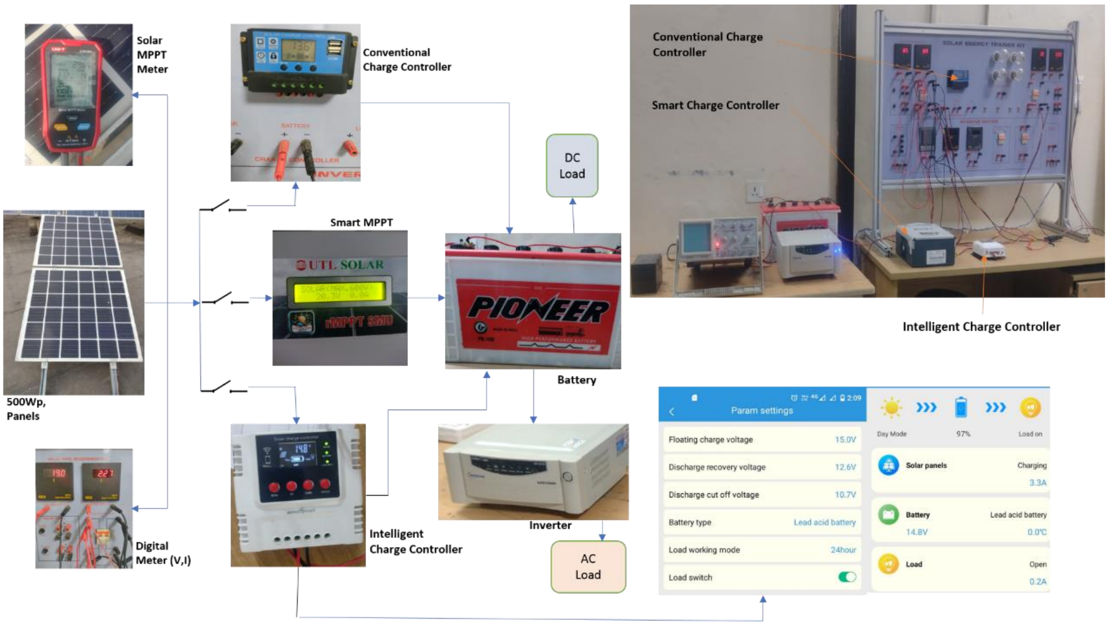

Figure 5. Complete experimental setup for the charge controller performance evaluation

The data of voltage, current related to PV panel and battery, input and output parameters of the charge controller are collected through wi-fi solar online app using the IoT concept for the intelligent charge controller, this data can be observed from a smartphone and data of conventional and smart charge controller measured by the digital voltmeter, ammeter, multi-meter and solar MPPT meter which is shown in figure 5.

The experimental results of conventional, smart and intelligent charge controllers are shown in Table 4. The practical data are recorded between the times span of 8.00 a.m. to 5.30 p.m. in average interval of 15 minutes, the values are taken directly as well as compared with the value of display in mobile.

Table 4: Experimental output of Solar Charge Controllers

Time	Conventional Charge Controller			Smart Charge Controller			Intelligent Charge Controller			Solar MPPT Meter		
	V(V)	I(A)	P_c(W)	V(V)	I(A)	P_s(W)	V(V)	I(A)	P_i(W)	V(V)	I(A)	P_{in} (W)
0	13.6	0.7	9.52	13.9	0.75	10.43	15	0.8	12	20.4	0.6	12.24
1	13.6	0.7	9.52	13.6	0.6	8.16	15	0.7	10.5	20.7	0.53	10.97

Time	Conventional Charge Controller			Smart Charge Controller			Intelligent Charge Controller			Solar MPPT Meter		
	V(V)	I(A)	P_c(W)	V(V)	I(A)	P_s(W)	V(V)	I(A)	P_i(W)	V(V)	I(A)	P_{in} (W)
2	13.9	4.6	63.94	14.82	4.8	71.14	14.9	5.2	77.48	20.9	3.9	81.51
3	13.8	4.2	57.96	14.47	4.5	65.12	15	4.7	70.5	20.5	3.5	71.75
4	13.8	3.95	54.51	14.23	4.2	59.77	15	4.5	67.5	20.7	3.5	72.45
5	13.7	2.4	32.88	14.41	2.6	37.47	14.9	2.87	42.76	20.5	2.21	45.31
6	13.7	2.3	31.51	14.24	2.6	37.02	14.9	2.8	41.72	19.6	2.28	44.69
7	13.6	1.9	25.84	13.94	2	27.88	15	2	30	20	1.8	36
8	13.7	0.6	8.22	14.05	1.05	14.75	14.8	1.1	16.28	19.7	0.85	16.75
9	13.6	0.9	12.24	14	0.95	13.3	14.8	1	14.8	20.6	0.76	15.66

*P_c, P_s, P_i power extracted by conventional, smart and intelligent charge controller when PV input is P_{in}.

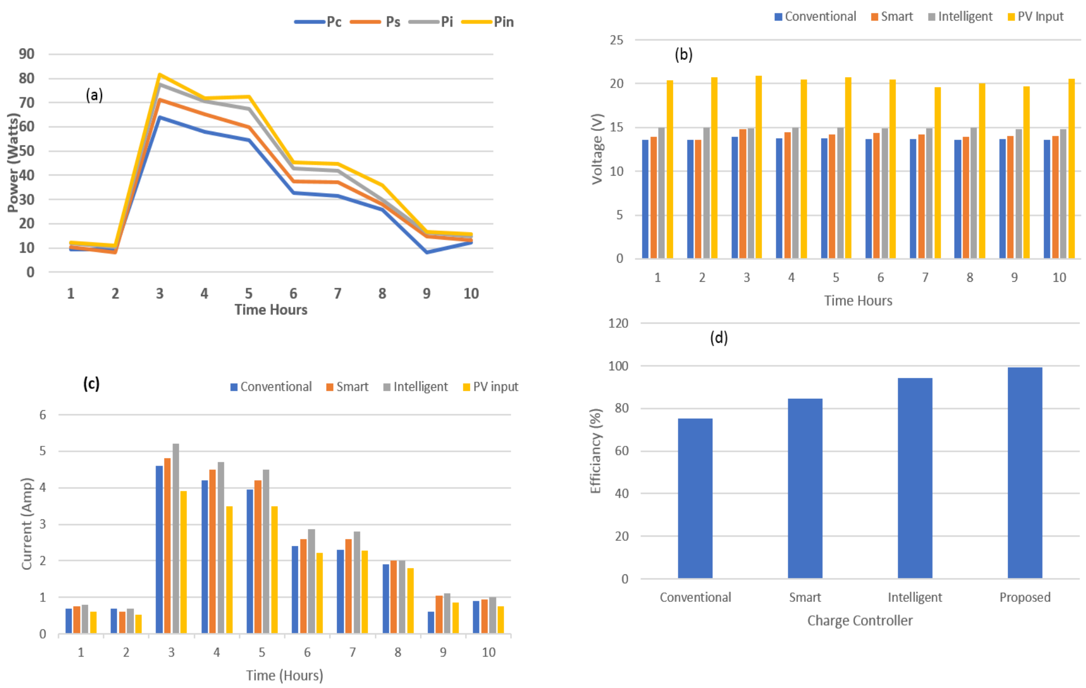

Figure 6. Visualization of experimental output (a) Power, (b) Voltage, (c) Current and (d) Efficiency of Charge Controllers

The highest average efficiency recorded 95.65% during time slot 1.00 p.m. to 3.00 p.m. which is the PV generation 81.48 W and the extracted power by the charge controller to the load is 77.48W. This data support that the integration of IoT with MPPT technique to extract the maximum power from the solar panel is working efficiently. Figure 6 depicts the value of output (a) power, (b) voltage, (c) current and (d) efficiency graphically.

6.1 Simulation Result (MATLAB)

In flow chart Figure 4 shows the proposed intelligent solar MPPT charge controller, which is simulated using MATLAB/SIMULINK. In MATLAB simulation Solar irradiance is considered according to experimental. Output power and battery state of charge of standard, smart and intelligent controller in respect of PV input power shown in shown in Table 5.

Table 5: MATLAB simulation results

Time	Irradiance	P_c	P_s	P_i	SoC_c	SoC_s	SoC_i
0	257	41.91	54.98	67.82	70	75	78
1	443	49.91	65.46	80.51	70.2	75.3	78.4
2	603	57.32	75.18	92.24	70.4	75.6	78.9
3	714	62.78	82.33	100.86	70.7	76	79.4
4	756	64.65	85.18	104.3	70.9	76.3	79.9
5	733	63.78	83.64	102.44	71.1	76.6	80.4
6	657	59.96	78.63	96.4	71.4	77	80.9
7	519	53.39	70.02	86.01	71.6	77.3	81.3
8	227	40.69	53.37	65.88	71.7	77.5	81.7
9	114	36.23	47.54	58.81	71.9	77.8	82.1

*$P_{\_c}$, $P_{\_s}$, $P_{\_i}$, $SoC_{\_c}$, $SoC_{\_s}$, $SoC_{\_i}$ power extracted by conventional, smart and intelligent charge controller and state of charge of battery.

Visualization of MATLAB simulink data shown in Figure 7 (a) & (b) for output power of controllers and the comparative analysis of battery State of Charge (SoC) shown in figure 7 (b).

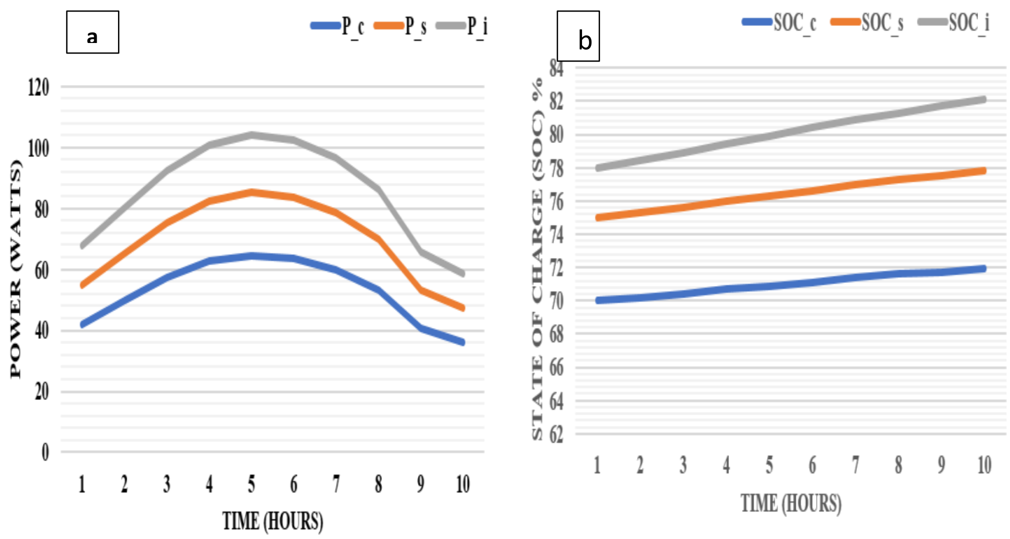

Figure 7. (a) Power output, (b) Battery SoC comparison

The PV system installation and performance evaluation depends on meteorological factors like solar isolation pattern, wind pattern, ambient temperature and site geographical factors like longitude, latitude, orientation, shade, dust particles and pollution type. The temperature variation directly influences the power output of the standalone photovoltaic system then battery charging shown in figure 8(a) & (b). The solar PV system has more irradiation in month of May and June with suitable temperature range which support to power generation. The data of temperature daily and monthly shown in figure 3(a) and 3(b) respectively, data of temperature daily and monthly shown in figure 3(c) and 3(d) which obtained from PVGIS.

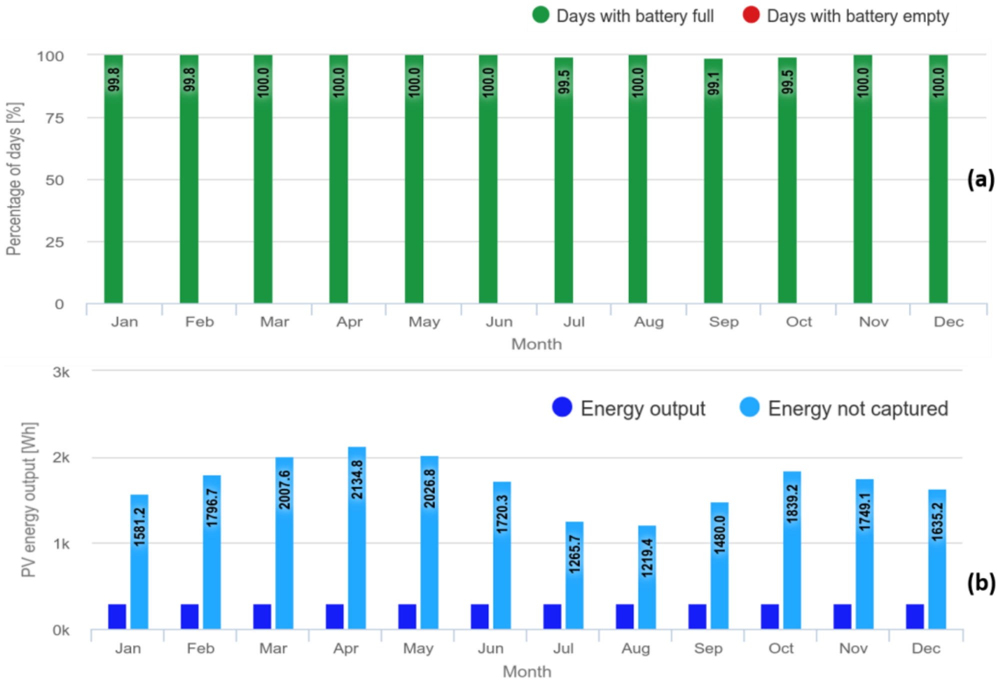

Figure 8. (a) Battery performance, (b) Power production estimation of islanded mode PV system by PVGIS

Comparative analysis of experimental and simulink data of islanded mode PV system charge controllers is shown in table 6 in terms of maximum efficiency.

Table 6: Charge controllers' efficiency comparison

Conventional	Smart	Intelligent	Proposed
75.16%	84.7%	94.2%	99.2%

Table 7: Comparative analysis of charge controllers

Parameters	Conventional Charge Controller	Smart MPPT	IoT based Charge Controller	Intelligent Charge controller
Rated Voltage	12V/24 V	12V/24 V	12V/24 V	12V/24 /48V
Rated Current	10 A	20 A	20 A	20A
Tubular Battery	Yes	By default,	12V/24/48V	12V/24/48V
Lead Acid Battery	×	×	12V/24/48V	12V/24/48V
Temary Lithium Battery	×	×	12 V3/24V7/48V13	✔
Lithium iron phosplate Battery	×	×	12V4/ 24V8/48V16	✔
Wi-fi Connectivity	×	×	Yes	✔
Stage Charging	×	×	3-stage charging	✔
Battery Temperature Monitoring	×	×	Yes	✔
Charging Protection	×	✔	6-charging protections	✔

Parameters	Conventional Charge Controller	Smart MPPT	IoT based Charge Controller	Intelligent Charge controller
Load Shading	×	×	×	✓
Monitoring	×	×	×	✓

6.2 Discussion

Comparative analysis shown that proposed IoT-integrated intelligent charge controller significantly outperforms conventional and basic smart systems in terms of efficiency, adaptability, and monitoring. The integration of IoT tools real-time data visualization and remote control, which traditional systems lack. Adaptive load management and SoC-based decision-making improve battery life and overall system reliability. These results confirm the effectiveness of combining intelligent algorithms with IoT platforms in advancing islanded mode PV system.

7. Conclusion and Future Work

An intelligent IoT-integrated MPPT charge controller significantly improves islanded mode PV system efficiency and reliability. Real-time monitoring, adaptive control, and smart decision-making make it superior to conventional systems. Future scope several enhancements can be pursued a complete hardware implementation of the intelligent MPPT controller integrated with IoT dashboards for real-time field deployment. This will help assess system performance under real environmental conditions and actual load variability.

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