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An Iot Based Monitoring System For Single Phase Grid Connected Photovoltaic System

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Abstract:
The increasing adoption of photovoltaic (PV) systems for clean and renewable energy generation necessitates effective monitoring and control solutions. In this paper, we propose an Internet of Things (IoT) based monitoring system specifically designed for single-phase grid-connected PV systems. Here a low cost simple IoT based monitoring system using Arduino Mega 2560 controller and ESP8266 Wi-Fi Module along with various sensors is designed and the parameters is monitored on IoT Cloud platform ThingSpeak. The system uses IoT technologies to collect real-time data from PV panels, inverters, and grid interfaces, enabling comprehensive performance analysis, fault detection, and energy optimization. The remote monitoring and control capabilities of the system enhance maintenance efficiency and overall energy yield. Through case studies and performance evaluations, we demonstrate the system's effectiveness in improving PV system performance and fault detection accuracy. The proposed IoT-based monitoring system contributes to the efficient management and maintenance of single-phase grid-connected PV systems, paving the way for enhanced energy efficiency and cost savings.

Keywords: Internet of Things (IoT), Photovoltaic System, Maximum Power Point Tracking, Sensors.

1. Introduction

The global demand for clean and sustainable energy sources has led to a significant increase in the deployment of PV systems. These systems harness solar energy and convert it into electricity, reducing dependence on fossil fuels and mitigating environmental impact. However, ensuring the optimal performance, fault detection, and energy optimization of PV systems present ongoing challenges for system operators and maintenance personnel. To address these challenges, this paper introduces an IoT based monitoring system specifically designed for single-phase grid-connected PV systems.

PV systems are widely recognized as a reliable and environmentally friendly solution for renewable energy generation. They are commonly integrated with the electrical grid, allowing excess energy to be fed back into the grid and minimizing reliance on non-renewable energy sources. Monitoring and controlling these grid-connected PV systems are critical to ensure their efficiency, productivity, and longevity. Traditional monitoring approaches often involve manual inspections or periodic data logging, which may be time-consuming and inefficient. Moreover, these methods do not provide real-time insights into system performance, limiting the ability to promptly detect faults and optimize energy generation.

The emergence of IoT technologies offers new possibilities for monitoring and controlling PV systems in a more efficient and intelligent manner. IoT allows for the seamless integration of various components and devices, enabling real-time data collection, analysis, and remote monitoring. By implementing an IoT-based monitoring system, operators can gain insights into the performance of PV panels, inverters, and grid interfaces, facilitating proactive maintenance and optimizing energy generation. This system aims to enhance the overall operational efficiency, fault detection accuracy, and energy yield of single-phase grid-connected PV systems.

In the following sections, we will delve into the architecture, data acquisition and analysis, performance evaluation, and implementation considerations of the proposed IoT-based monitoring system for single-phase grid-connected PV systems. The ultimate aim is to demonstrate the system's effectiveness in improving performance, fault detection, and energy optimization, thereby enabling efficient management and maintenance of PV installations.

2. Literature Review

Previous work on IoT-based monitoring systems for single-phase grid-connected PV systems has focused on improving the efficiency, fault detection, and energy optimization of these systems. These previous works highlight the potential of IoT-based monitoring systems and the effectiveness of real-time data collection, advanced analytics, and remote control capabilities in enhancing system efficiency, reducing downtime, and maximizing energy yield. Building upon these contributions, the present study aims to further advance the field by proposing a comprehensive IoT-based monitoring system specifically tailored for single-phase grid-connected PV systems. Here, we discuss some notable prior work in this domain:

Hamied et al. designed and developed a low-cost monitoring system with fault diagnosis for an off-grid photovoltaic system for greenhouse farm at remote location. A real time implementation is done using various sensors and microcontroller Arduino Mega2560 board and ESP8266 Wi-Fi module. The IoT monitoring technique is strongly recommended to remotely monitor the PV data [1]. Md. Ikramul Islam Nuhin et al. simulated an IoT-based monitoring system of a grid-connected solar PV system. The monitoring of PV parameters is done using IoT and implemented through the “ThingSpeak Read” block of Matlab/Simulink and its simulated results is promising [2]. M Rumbayan designed a system for recording of off-grid solar PV data at remote locations and real time monitoring of data is achieved using IoT and solar panels performance is observed [3]. Ghedhan Boubakr et al. presented an IoT-based real-time monitoring system for solar PV system using maximum power point tracking controller for improving system reliability and efficiency. The proposed system using various sensors and wi-fi communication module is validated for different PV panel shading conditions and accurate real-time monitoring results for diagnosing the system condition is achieved [4-5]. Guillermo Almonacid et al. developed IoT based monitoring system using Arduino along with low-cost sensors and predicted the behaviour of the PV system using several machine learning approaches using the data available from IoT module [6]. Soham Adhya developed an low cost IoT-based monitoring system to analyse the performance of grid-connected PV systems in real-time. The system collected data from PV panels and utilized cloud-based analytics to monitor energy generation and system efficiency. The study demonstrated the effectiveness of the IoT-based approach in optimizing energy yield and identifying performance issues for prompt maintenance [8]. Author presented IoT and LabVIEW-based automatic monitoring system for fault detection and shading effect of PV solar array [9]. The authors [7],[10] presented an IoT-based energy management system for grid-connected PV systems. The system collected real-time data from PV panels, inverters, and grid interfaces and utilized cloud-based analytics to optimize energy generation and consumption. The study showed that the IoT-based energy management system effectively improved the self-consumption ratio and reduced reliance on the grid, resulting in enhanced energy efficiency and cost savings. The authors proposed a low cost monitoring system using sensors, Raspberry and Arduino providing a flexible and wireless architecture capable of being implemented in most PV installations [21]. In this paper [23] author presented a system to monitor the performance of photovoltaic power supply from sensor node in a WSN system. The observed parameters are temperature, irradiance, current, and voltage. The system divided into 3 main blocks as client, server, and communication system. The communication devices are radio-frequency module, Xbee. The server is a PC software developed using LabView software.

Here [24] proposed system gives the solar panel wireless monitoring and the controlling system from remote location with ZigBee and RF module providing reliable and secure communication even when supporting 65000 nodes at a time. The design of a low complexity fuzzy logic controller-based energy management system for a residential grid-connected microgrid is presented and predicted upcoming outputs based on Fuzzy logic and Adaptive neuro fuzzy inference system [28]. López-Vargas et al. [19] in 2018 developed an low-cost datalogger for standalone PV system for remote areas to overcome shortcomings of the solar Arduino^{TM} datalogger, the power consumption was minimized and the number of meteorological parameters measured was increased and a user-friendly interface was integrated. The results indicated that the datalogger provided high accuracy, and it was autonomous, low-cost and robust in harsh environments. In this minimal maintenance is a manual procedure requiring human operator intervention for collecting data, which can be an inconvenient at locations that are difficult to access as well as it increases the maintenance costs and operation [29]. Balakrishnan D. et al. proposed Fuzzy logic-based fault detection algorithms to improve the performance and reliability of solar PV panels affected by shading, soiling, degradation, and electrical faults. The system includes wireless sensors to collect the electrical and environmental parameters which is processed and analysed using machine learning algorithms. The system can detect and diagnose faults in real-time, and provide alerts and recommendations to maintenance personnel to take appropriate actions to prevent further damage or downtime.

3. Research Methodology

In this paper a single-phase grid tied solar PV system and its parameters monitoring through IoT has been implemented, which enables real-time monitoring, data analysis, and remote management, ultimately improving the efficiency, reliability, and maintenance of the PV installation while providing valuable insights to users for its fault diagnosis and schedule maintenance. Here IoT technology is used to monitor parameters both environmental and electrical data through internet connection and using the microcontroller the data captured from the sensors is analysed, processed, and communicated to cloud server through a Wi-Fi module.

Figure 1 shows the block diagram of the overall system.

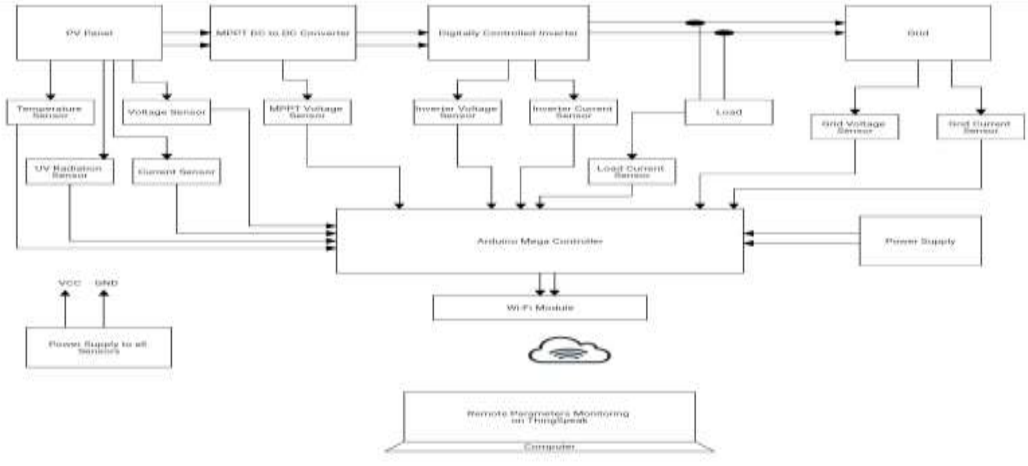


Figure 1. Block diagram of the overall system

This block diagram as shown in Figure 1. illustrates the components and interactions within an IoT-based monitoring system for a photovoltaic system. This solar PV monitoring system has two parts: the single-phase grid connected solar PV system (power generation) and IoT monitoring system (data collection). The power system part consists of a solar panel, a MPPT based DC to DC converter, digitally controlled inverter, nonlinear load, and single-phase grid. The solar panel capture sunlight and convert it into electrical energy which is step up using MPPT based boost converter which continuously track the Maximum Power Point (MPP) of the solar panel's voltage-current curve and adjust the voltage and current to maximize the power output from the solar panel, even under varying environmental conditions like changes in sunlight intensity, temperature, or shading and harvesting more energy from the solar panels, increasing the overall system efficiency [11]. This DC power is converted to AC power using digitally controlled inverter using MPPT control and grid connected converter control adjusting parameters like voltage, current, and switching frequency to maximize conversion efficiency and reducing harmonics in the output current improving power quality for the non-linear load and then the excess power is fed to the grid. The power supply section supplies power to the hardware including sensors and microcontroller. The data acquisition part of the system consists of the sensors and the controller. The sensors used here are solar panel temperature sensor, solar radiation sensor, various voltage sensors and current sensors. The Arduino mega controller is the central processing unit in the system which collects and process the data from all sensors installed in our system and communicates data to the Wi-Fi module using serial communication. The Wi-Fi module establish a Wi-Fi connection to the internet and sends this data to ThingSpeak, where it can be stored, visualized, and analysed. This integration enables real-time monitoring and data logging of our system. ThingSpeak is an open source IoT platform and user-friendly interface for sensors logging for data monitoring, collection, and visualization providing real time notifications and alerts.

4. System Design and Implementation

The designed and developed experimental prototype system consists of two main parts: 1. The single-phase grid connected solar PV system consists of 160W UTL solar panel, MPPT based DC to DC boost converter, Digitally Controlled Solar Inverter, Linear load (lamp), Nonlinear load (AC motor), Grid and 2. Data acquisition system consisting of various sensors, Arduino Mega controller and Wi-Fi module forming IoT based monitoring system.

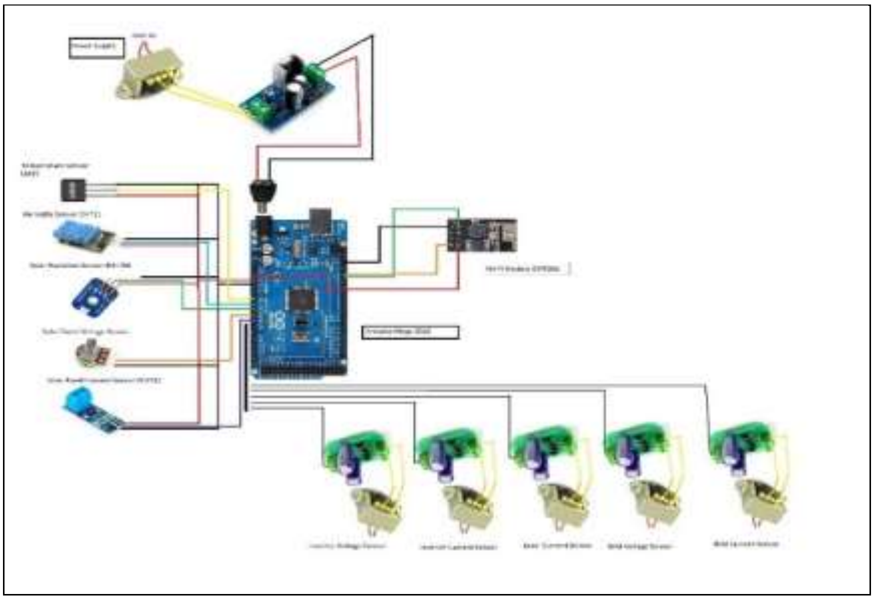


Figure 2. Schematic Diagram of the Monitoring and Data Collection System

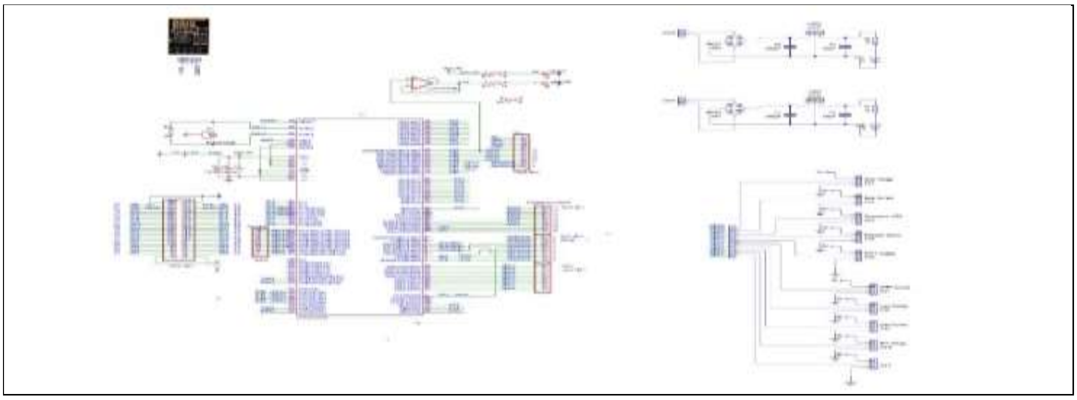


Figure 3. Wiring and PIN Diagram of the Microcontroller and Sensors

4.1 Hardware Design

Figure 2. shows the schematic diagram of the monitoring and data collection system consisting of the various measurement sensors along with microcontroller Arduino mega 2560 and Wi-Fi module ESP8266 whose details is discussed below. The connections along with its pin configuration is as shown in Figure 3.

4.1.1 Current Sensor ACS712

The ACS712 20A is a Hall effect-based current sensor that can be used to measure both DC and AC current. It is a linear sensor, whose output voltage is directly proportional to the current flowing through it used with an Arduino Mega to measure solar panel current. It operates on the principle of the Hall effect, detecting incoming current by generating a magnetic field and produces analog output voltage proportional that is read by the Arduino Mega [17], [18]. The ACS712 has a sensitivity of 66 to 185 mV/A and bandwidth of 80 kHz and is calibrated by determining the offset and gain of the sensor to ensure accurate current measurements.

4.1.2 Voltage sensor

This voltage sensor is basically a voltage divider circuit created for an Arduino to read the voltage of a solar panel using two resistors which divide the input DC voltage into a smaller output DC voltage, which reads the PV panel output voltage and provides the sensor output voltage Vout = (R2 / (R1 + R2)) * Vin. The solar panel voltage value is obtained by the analog pin of Arduino mega controller by Vread = ($\mathbf{5}/\mathbf{1}$023) ×sensor voltage Vout × (R1+R2)/R2. [19]

4.1.3 Temperature sensor LM 35

The LM35 precision analog linear temperature sensor whose outputs voltage is proportional to the temperature in degrees Celsius having a temperature range of -55 to 150 degrees Celsius and an output voltage of 10 mV/°C is used to measure the solar panel temperature connected to the Arduino with a pull-up resistor to ensure that the output voltage of the sensor is always positive. The arduino mega controller reads the temperature value from Vout of LM35 sensor connected to its analog input pin and converts it to temperature in degrees Celsius using the LM35's sensitivity (10 mV/°C). As analog inputs on the microcontroller have a 10-bit resolution, which can provide output 2^10 = 1024 discrete values. The solar panel temperature obtained from LM35 is read by Arduino controller using formula Temperature = reading from ADC * (5/1023) *100 [19].

4.1.5 Humidity Sensor DHT11

The DHT11 is a low-cost, basic digital humidity and temperature sensor provides digital output for the humidity that is connected to Arduino mega. This sensor has humidity range 20% to 80% RH (Relative Humidity) with accuracy: ±5% RH, ±2°C and resolution: 1% RH, 1°C. This sensor includes a resistive assembly of wet components and NTC temperature measurement devices, the DATA pin of the DHT11 sensor is connected to a digital pin of your Arduino Mega for data communication between the sensor and the Arduino. Humidity is measured with the electrodes having moisture holding substrate between them. Hence, the value of humidity is inversely proportional to the resistance of substrate [24].

4.1.5 Solar Radiation Sensor BH1750

The BH1750 is a 16 bit digital light sensor that measures ambient light levels and measures the intensity of sunlight across various wavelengths having operating voltage = 2.4V to 3.6V, light Intensity Range = 1 to 65535 LUX (small variation of +/- 20%) and built-in illuminance to digital converter. This sensor uses an I2C interface to interface with Arduino mega microcontroller and gives an output in LUX providing an accurate value and high resolution [20]. To measure solar radiation accurately, typically pyranometer or a solar radiometer is used but as this are very costly and to designed the monitoring system at low cost here BH1750 sensor is used in continuous measurement mode and the flux value received by the sensor is converted to the irradiance using Arduino programming to the approximate W/m^2 using a multiplication of 0.079 that is a very close approximation with the data obtained from pyranometer.

4.1.5. Current Transformer and potential transformer for current and voltage measurement.

A current transformer (CT) and potential transformers (PT) are interfaced with Arduino mega microcontroller and used as sensors for measuring alternating current (AC) current and voltage such as inverter output voltage, inverter output current, grid voltage, grid current and load current. The CT primary winding is connected in series with the inverter and grid output through which the measured current flows and secondary winding having large number of turns is connected to the analog input pin of Arduino mega through the rectifier. It works by inducing a current in its secondary winding that is proportional to the current flowing through the primary winding but reduced in magnitude. The PT is a step-down transformer which step down the AC voltage to a level that can be safely and accurately measured by the Arduino. The primary winding of the PT is connected across the inverter output or grid whose AC voltage is to measure and secondary winding of the PT is connected to a diode bridge rectifier circuit to convert AC to DC and ensures that the polarity of the voltage is always positive, and the output of the diode bridge rectifier is connected to Arduino mega microcotroller analog input pins and the GND of the diode bridge rectifier to the GND of the Arduino properly measuring the high value of AC voltage and current [25].

4.1.6. Arduino Mega 2560 microcontroller

The Arduino mega 2560 microcontroller board is the main attraction and heart of this system It is an open-source single-board microcontroller is the ATmega2560 microcontroller, which is an 8-bit AVR microcontroller with 256KB of flash memory, 8KB of SRAM, and 4KB of EEPROM and operates at a clock speed of 16 MHz. The Mega 2560 board features a total of 54 digital input/output pins. There are 16 analog inputs on the Mega 2560 which are used to read analog signal values. This board has 4 hardware UART (hardware serial ports) along with USB connection and ICSP header [14]. It is compatible with the Arduino IDE, making it easy to write, compile, and upload code to the board and thus a versatile and powerful microcontroller board as a choice for this research project [26]. All the sensors used here such as temperature, humidity, solar radiation, DC voltage, DC Current sensor along with AC voltage and current sensor are interfaced to the Arduino mega 2560 microcontroller to its analog and digital pins through which it acquires, processes, and manages data from all sensors and processes this raw sensor data, performing calculations, filtering, data manipulation and perform statistical analysis, and execute control algorithms based on sensor inputs and improves the accuracy and reliability of measurements.

The Arduino Mega 2560 communicates with other devices in the system using Wi-Fi, connections through ESP8266 and transmit data to a server and display information on a web interface and send alerts and notifications. Overall, the Arduino Mega 2560 microcontroller serves as a flexible and powerful central processing unit enabling data collection, analysis, communication, and control of sensors used.

4.1.7 ESP8266 Wi-Fi Module

The ESP8266 Wi-Fi Module is a cost-effective and highly integrated Wi-Fi MCU with built-in TCP/IP networking software, and microcontroller capability providing Arduino mega 2560 microcontroller access to any Wi-Fi network. It is small in size having low power consumption with excellent Wi-Fi capabilities. It supports UART communication due to which it communicates with Arduino mega 2560 microcontroller, sensors, and other devices. The ESP8266 module is connected to an Arduino Mega 2560 by establishing a serial communication link between the two, which allows the Arduino Mega to send commands and data to the ESP8266 module, which can then handle Wi-Fi communication. The ESP8266's TX (Transmit) pin is connected to Arduino mega 2560 RX1 (Receive) pin for the ESP8266 to send data to the Mega & ESP8266 RX (Receive) pin is connected to one of the Mega TX1 (Transmit) pin for the ESP8266 to receive data from the Mega. Thus, this ESP8266 module functions as a supporting device for the Arduino mega 2560 microcontroller to connect to an internet connection and make connections based on IP addresses [14]. Wireless local area networks (WLANs) are based on the 802.11 family of standards. Wireless monitoring relies on an ESP8266-based Wi-Fi module to transmit data. The ESP8266 module is programmed using the Arduino IDE so that ESP8266 module provide Wi-Fi connectivity to send all the data from Arduino mega 2560 microcontroller data to ThingSpeak's servers using the ThingSpeak API.

4.2 Software Design

4.2.1 ThingSpeak

ThingSpeak is an open-source Internet of Things (IoT) platform and data analytics service provided by MathWorks. It is an API for storing and retrieving data from things that use HTTP over the internet or a local area network (LAN) designed to collect, analyze, and visualize data from various IoT devices and sensors offering a user-friendly and web-based interface to create IoT applications. In this research project through ThingSpeak, the sensor logging and location tracking is done and the data is collected from Arduino mega 2560 microcontroller through ESP8266 and loaded it into the software environment for historical data analysis and parameters monitoring of the system in real time.

ThingSpeak features includes: i) open API, ii) real-time data collection, iii) geolocation data, iv) data processing, v) data visualizations, vi) device status messages, and vii) plugins. ThingSpeak provides APIs and libraries for a variety of IoT platforms and microcontrollers, such as Arduino, ESP8266, Raspberry Pi, and more. Users can send data from their IoT devices to ThingSpeak using HTTP, MQTT, or other supported protocols. Data sent to ThingSpeak is automatically logged with a timestamp in the specified Field. It offers built-in tools for creating interactive charts, graphs, and maps to visualize the data collected in your Channels.

4.2.2. Monitoring Algorithm

The flowchart of single-phase grid connected photovoltaic monitoring system algorithm is as shown in Figure 4. The developed monitoring system start with the library definitions, variable parameters, and board setup. Then the system checks the availability of Wi-Fi connectivity. If the connection is accessible, it connects Wi-Fi module with the available internet and ThingSpeak login. Then the controller start reading all the system sensors data do the necessary calibration and using the built-in Wi-Fi gateway on the ESP8266, the ESP8266 sends various sensor data to the ThingSpeak server various fields [27]. Also, if the data such as inverter current exceeds the limit it alerts and turn off the system through relay. The developed system continuously monitor and update the data in real time and thus the user can then monitor PV parameters sensor data remotely from any location through the internet.

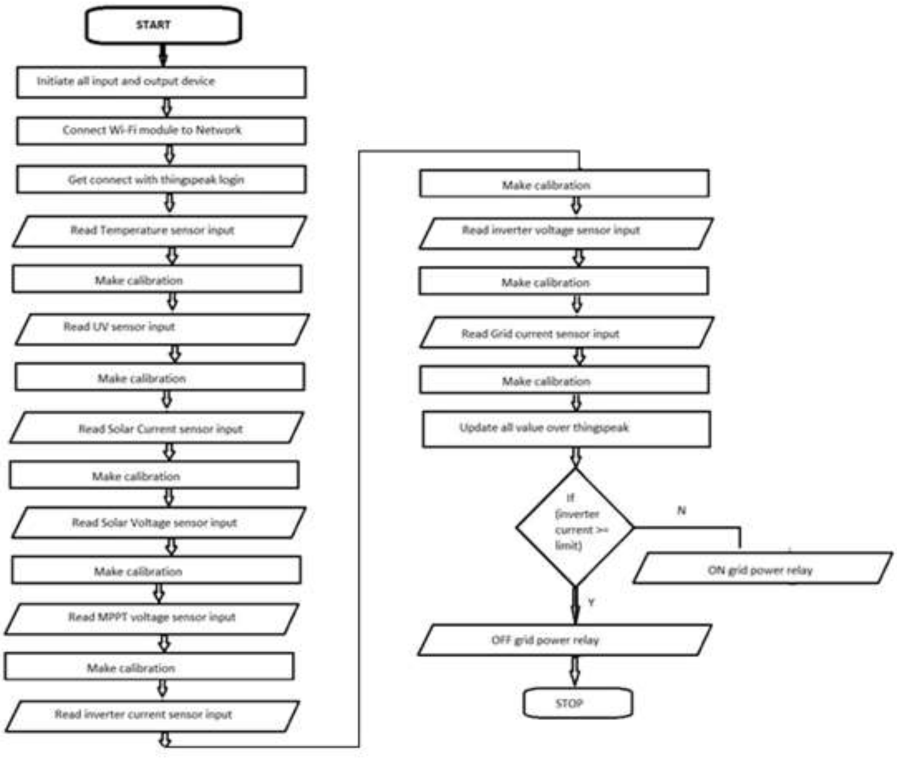


Figure 4. Operation Process Flowchart

4.3 Implementation Setup.

The experimental implemented setup of the developed system is shown in Figure 5. This setup consists of UTL 160W solar panel whose specifications is given in Table 1, MPPT based DC to DC boost Converter, digitally controlled inverter, Load (linear and nonlinear) and a grid along with filter forming a solar PV single phase grid connected system and various sensors along with Arduino mega 2560 microcontroller and ESP8266 building a wireless sensor network and IoT environment whose details is tabulated in Table 2. The sensors are connected to the microcontroller is powered by an external power supply. The Arduino mega sends the sensor data to the ThingSpeak server via the ESP8266 Wi-Fi module. Thus, the single-phase grid connected photovoltaic system parameters is monitored on open-source IoT platform ThingSpeak which is used as a database and to visualise the remotely acquired data with an interactive graph and dashboard in order to keep the system low-cost and easy to access and create [18].

PV Parameters	Information
Module Type	UTL160W
Maximum power	160W
Voltage at Pmax (Vmp)	19.08V
Current at Pmax (Imp)	8.42A
Tolerance	± 3%
Open circuit voltage (Voc)	22.68V
Short circuit current (Isc)	8.87A

Table 1. PV Module Specifications

Hardware and Software	Specification
Main microcontroller	Arduino Mega 2560
Wi-Fi module	ESP8266
Current sensor module	ACS712 30 A
Voltage sensor module	Voltage divider circuit
Temperature sensor	LM35
Humidity sensor	DHT11
Solar radiation sensor	BH1750
AC current and voltage sensor	CT and PT
IoT platform	ThingSpeak

Table 2. IoT System Information

Figure 5. Implemented Setup of the System.

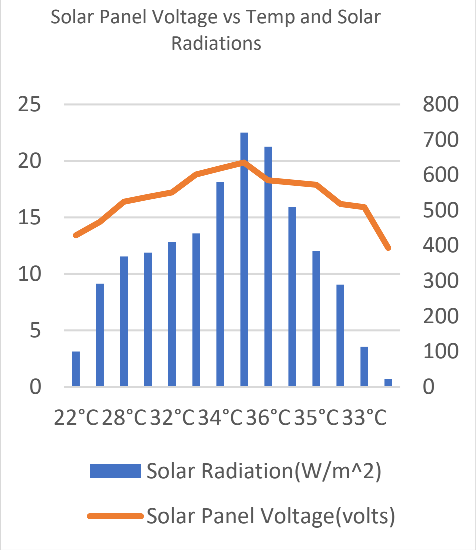
5. Results and Discussions

The developed system as shown in Figure 5. is tested to evaluate its performance under nonlinear conditions (using non linear load as AC motor) and its parameters is monitored using IoT on ThingSpeak channel through laptop to view graphic data obtained via the ThingSpeak platform. The testing was done from 12 June to 26 June 2023 at the home terrace in Jalgaon, Mahrashtra State, India. The full day monitoring is done on 26 June 2023 from morning 6 am to evening 7 pm with the system connected to the Wi-Fi network and the collected data were uploaded to the ThingSpeak platform for every 30 s interval throughout the day and then downloaded for analysis. Table 3. Shows the data collected through IoT monitoring to analyse the sysem performance to gain insight about the relationship between the environmental conditions and the power generated by the solar PV system. Figure 6. shows the graphical data obtained from the ThingSpeak platform. Moreover, Figures 5(a) to (i) depict the PV parameter measurements, which include solar panel temperature, solar radiations level, panel voltage, panel current, MPPT based DC to DC converter output voltage, inverter output voltage, load current, grid current along with monitoring system channel placement is shown in Figure 6(i). The linear relationship between solar irradiation, PV output current, and PV output voltage values indicates that the sensor readings and data collecting system are working appropriately. In around 30 seconds, the sensor collects, analyses, transmits, and stores the data into cloud server. It is observed from the collected data readings that the temperature value is the inverse of the humidity value. If the temperature is high, the relative humidity will be low, and vice versa. In the meantime, the irradiance varies according to the sun's movement and the shadows that prevent sunlight from reaching the solar panel's surface. The value of solar radiation is low due to the cloudy atmosphere of June month so it is observed that the the radiation value falls if there are shadows preventing the sun rays from the surface of the PV and will return to its maximum if there are no shadows blocking the sun rays.

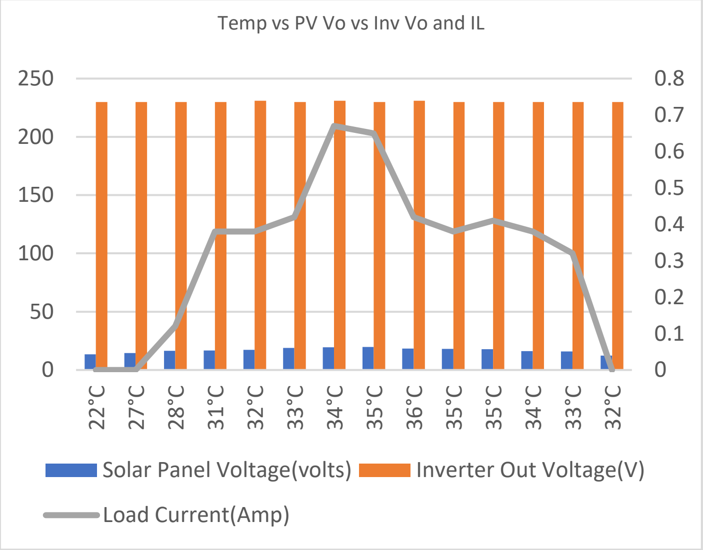
Time	Solar Panel Temp(°C)	Solar Radiation (W/m^2)	Humidity	Solar Panel Voltage (volts)	Solar Panel Current (Amp)	MPPT Voltage (Volts)	Inverter Out Voltage (Volts)	Load Current (Amp)	Grid Current (Amp)
06:00	22°C	100	76%	13.4	0	12	230	0	0
07:00	27°C	292	72%	14.6	0.02	12	230	0	0
08:00	28°C	369	69%	16.4	0.8	12	230	0.12	0
09:00	31°C	380	65%	16.8	5.47	12	230	0.38	0.12
10:00	32°C	410	60%	17.2	5.34	12.2	231	0.38	0.09
11:00	33°C	435	54%	18.8	5.38	12	230	0.42	0.12
12:00	34°C	580	50%	19.34	8.17	12.1	231	0.67	0.22
13:00	35°C	720	45%	19.86	7.95	12	230	0.65	0.2
14:00	36°C	680	42%	18.3	5.46	12.1	231	0.42	0.22
15:00	35°C	510	45%	18.1	5.32	12	230	0.38	0.16
16:00	35°C	385	46%	17.9	5.56	12	230	0.41	0
17:00	34°C	290	49%	16.2	4.86	12	230	0.38	0
18:00	33°C	114	52%	15.9	5.1	12	230	0.32	0
19:00	32°C	22	55%	12.3	0	12	230	0	0

Table 3. Data collected with IoT monitoring

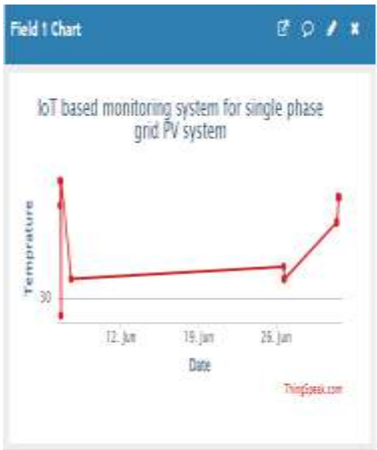
The data collected readings of Table 3. and Graph 1. shows that as temperature and solar radiations level increases the DC voltage of the solar panel also increases thus increasing the solr energy generation and the inverter output voltage and load current also increases as shown in Graph 2. Increasing the generated AC power thus the system operates with maximum efficency and this low cost IoT based parameter monitoring technique developed for the single phase grid connected system efficiently monitor the performance in real time.



Graph 1. UV radiations vs PV voltage variation

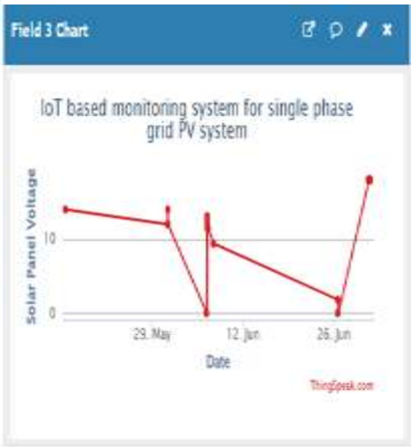


Graph 2. Inverter voltage and Load current

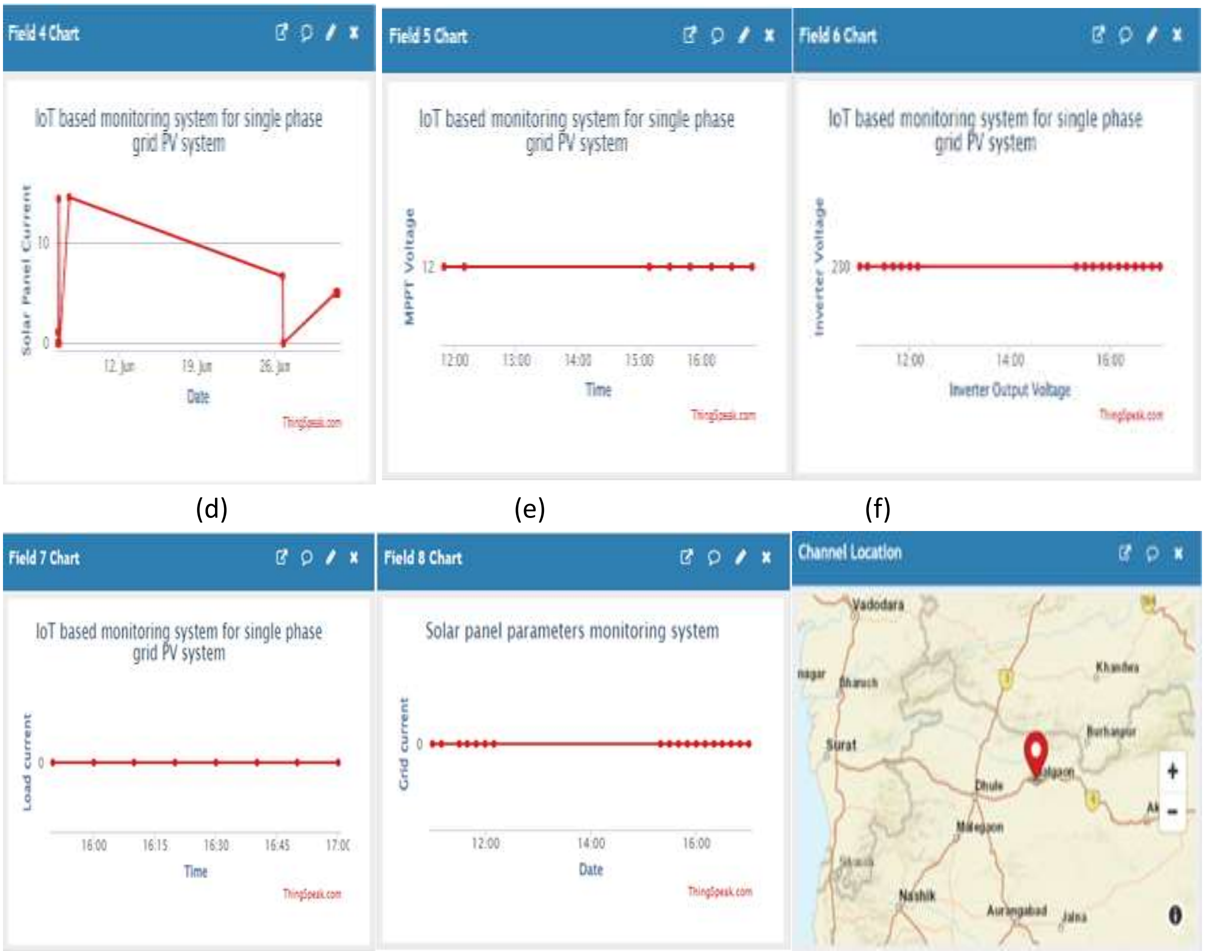


(a)

(b)



(c)



(d) (e) (f)

(g) (h) (i)

Figure 6. Captured visual data from ThingSpeak platform; (a) Temperature, (b) Solar UV Radiation, (c) Panel voltage, (d) Panel current, (e) MPPT output voltage, (f) Inverter output voltage, (g) Load current, (h) Grid current, (i) channel location.

6. Conclusion

The development and implementation of an IoT-based monitoring system for single-phase grid-connected photovoltaic systems presented in this paper represent a significant advancement in the field of renewable energy management and sustainability. This IoT based real-time monitoring system has successfully measured various parameters like temperature, humidity, solar radiation, DC/AC voltage and current values of the system using low cost sensors and the main controller of the system Arduino mega 2560 processed and transmitted this values with ESP8266 to the cloud server and monitored remotely from anywhere on open source IoT platform ThingSpeak. The testing of the developed system provided accurate results which is validated using standard measurement instruments with low mean square error.

This technology presented in this paper has explored the key aspects and contributions enabling real-time data collection, analysis, and remote monitoring helpful for fault detection and predictive maintenance improving system performance and efficiency significantly to the reliability of grid-connected PV systems ensuring consistent energy production. As the global transition to clean energy sources continues, the insights of transformative potential of IoT-based monitoring systems for single-phase grid-connected PV systems in this paper hold great promise for a more sustainable and energy-efficient future.

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