

Detection and control of power loss due to soiling and faults in photovoltaic solar farms via wireless sensor network

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Abstract

Solar photovoltaic (PV) farm output power is highly related to the panel conditions. Soiling causes faults in the PV panels leading to a drastic reduction in the system efficiency. In vast solar PV farms, the detection of faults in an individual PV panel is a difficult task since it is usually done manually. In this research, a new design is proposed to detect the production of individual PV panel automatically and periodically to evaluate the condition of each panel in the farm no matter how it is connected in the array. The proposed design allows the user to measure the open circuit voltage (VOC), the short circuit current (ISC) and the delivered power for each PV panel in the farm. It is also capable of controlling each panel to work at the maximum power point using a built in Maximum Power Point Tracking (MPPT) sub-circuit on each solar panel. The presented system depicts a complete wireless sensor network, which does not need any extra wiring and is characterized by being of low cost, reliable and efficient.

Keywords: Photovoltaic Solar Farms; Fault Detection; Fault Control; Arduino Applications; WSN; MPPT.

1. Introduction

There is no doubt that the solar energy is an indispensable source of energy for many reasons, including development of material science, cost increase of the bio-fuel, global warming and more. The establishment of a productive PV solar farm needs a vast open land area to install. This area could be on mountain slopes, floated on the lakes, or any odd land, but even with a flat land, it needs a hard work for monitoring and controlling the performance of all these very large numbers of individual panels. Checking of each PV panel in the farm will be a major problem, especially in areas that are hardly affected by soiling. Soiling could affect all the panels in the solar farm or could affect some individual once, but in both cases the power production capability will certainly be decreased [one]-[4] even if the PV panels are connected in series, in parallel, or in array [5], [6].

The dust constitute one of the major problems among all other soiling factors especially in the Middle East and North Africa [7]–[10]. Researchers in [11] proposed using the PV power-line with transceiver to control and monitor the movement of a solar tracker, however this paper suggests a system for monitoring and control the faults for the fixed solar panels. Wi-Fi network investment in managing and monitoring the power consumption for indoor usage was discussed briefly in [12], [13].

This paper will adopt a similar strategy for an outdoor vast network. It is also feasible to use the same network to adopt the algorithms presented in [14], [15] in case the solar panels are using trackers and that may be accomplished easily since all calculations are carried out in the main computer and the data of the tilt and elevation angles are sent using the adopted network.

The proposed system of this paper suggests the addition of a low cost electronic circuit attached to each solar panel (module). This circuit can control and measure the produced power in each panel, then broadcast the data via Wi-Fi to the Main Control and Monitoring Unit (MCMU). This MCMU consists of a computer and a dedicated HTML website designed for this purpose. The user can monitor wirelessly individual solar panels in the farm to have a complete view about the open circuit voltage, the short circuit current, and the produced power to be compared with the ideal values. It is also possible to disconnect any bad PV panel from the string or boost it voltage to match the other panel in the string. Additionally, the proposed system has its own built in MPPT circuit to keep each single solar panel at the maximum power point.

The proposed system takes into consideration that all panels are identical when installed, so external effects may cause any mismatching. The research work in [16], [17] offered detecting system faults from monitoring the main load then using some algorithms to find the exact location of the faulty PV panels. However, this is different from the proposed system in this paper, which is able to detect faults directly since it gathers all data directly from each solar module. Other researchers in [18] suggested an artificial neural network to detect the faults caused by partial shading only. The use of ZigBee as a transceiver with Arduino Mega was suggested in [19], but such design has many disadvantages being of a large size of the Arduino Mega compared to Node MCU, cost of around 40 USD only for ZigBee, and it requires a special receiver to read the ZigBee signal.

The rest of this paper is organized as follows: Section 2 gives a brief description of the soiling accumulation as one major cause of faults. In Section 3, the system design of the proposed model is introduced. Results and discussion are presented in Section 4, and finally Section 5 concludes the paper.

2. Soiling accumulation

The Photovoltaic Soiling Index (PVSI) is an indicator for the performance of PV panels under exposure to dust at the Standard Test Conditions (STC) [20]. Soiling is described as the dirt accumulation on the solar panel modules and is an important loss factor particularly in locations when there are very dry conditions, scarce rain, and even frequent dust or sand storms [21]. Two independent parameters; the local environment and the dust properties, which consist of shape, component, weight and size [22], affect the characteristics of soiling accumulation on solar panels. These properties play important role in dust scattering and result some different problems that cause a soil accumulation on solar panels. Below is a list of some of these factors and types, which may affect each other as described by [23] [26]:

- 1) Environment factors: irradiation, wind movement, wind direction, dust storm, temperature, air pollution, air pressure, volcano and snow.
- 2) Dust Type: carbon, soil and sand, clay, bacteria.
- 3) Location and Insulation: sandy area, industrial area, latitude and longitude, glass material, orientation, height, tilt angle and flat surface.

There are many dust-accumulation mitigation strategies discussed by researcher such as [27], but dust-accumulation is still one of the major problems that face the efficiency of the vast solar farms.

3. Mismatching effects

The mismatching in solar modules or solar cells may be due to many factors, one of them is to use not identical solar modules or solar cells. Every type of PV module has a variable specification

caused by processing characteristics. Even the response to the variation of the solar irradiation may be different, since it depends on the manufacturer characteristics and material like the reflection of the protection glass, heat dissipation of the panel, rated voltage and current [28]. For these reasons, it is recommended to use the same type of the PV panel in the solar array. Another important factor causing the mismatch losses in PV modules and arrays is the partial shading of the solar array because the solar cell with the lowest output will control the output of the entire PV module. This article considers that all the PV panels are identical and there is no row-to-row collector shading as depicted in Figure 1, so if any mismatching occurs it will be due to soiling, or a fault in the wiring connections.

4. System design

In General, the system consists of server controller and client controller. The server controller is software designed for this purpose, but the client controller consists of software and hardware parts. Figure 2 shows the system modules but as a communication topology, the solar panels can be connected according to power requirement (in series, in parallel, or combined).

These controllers are connected via Wi-Fi network with a star topology as in Figure 3. Star topology is a topology for a Local Area Network (LAN) in which all nodes are individually connected to a central connection point, like a hub or a switch. In this design, a main computer will do the server duties. Static Internet Protocol (IP) will be given for each PV panel. The server controller sends a request to individual client controllers to read the supplied power, the short circuit current ISC, and the open circuit voltage VOC, so the user can figure out if there is any solar panel or string of panels being shaded or partially shaded [30] or dusty [31], [32].

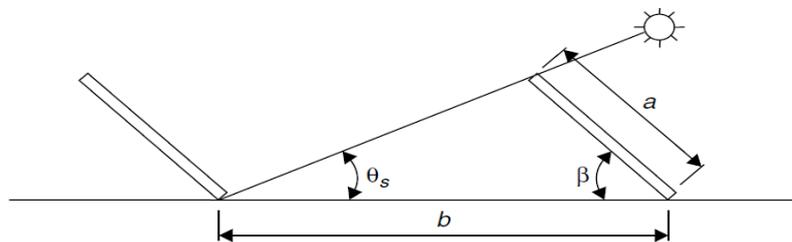


Fig. 1: Row-to-Row Collector Shading [29].

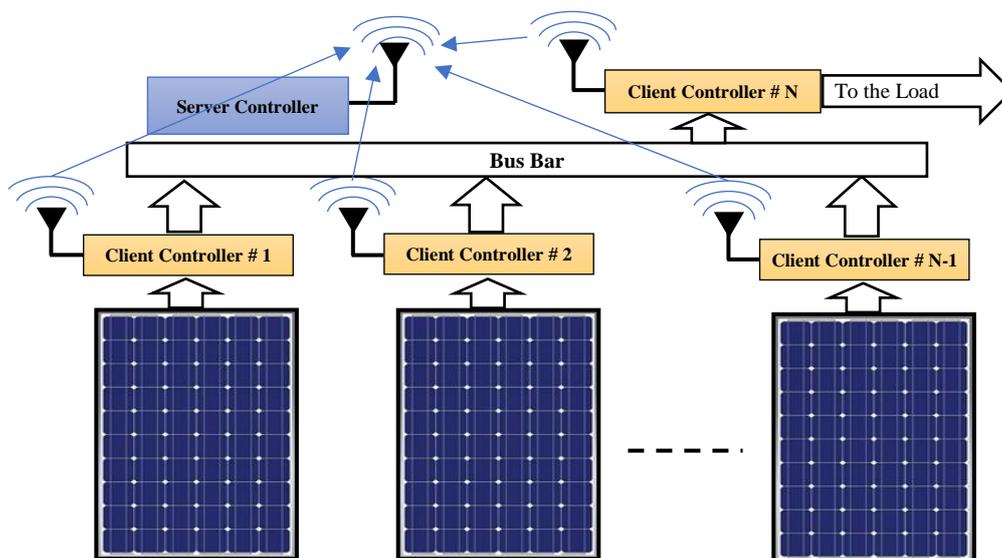


Fig. 2: System Module.

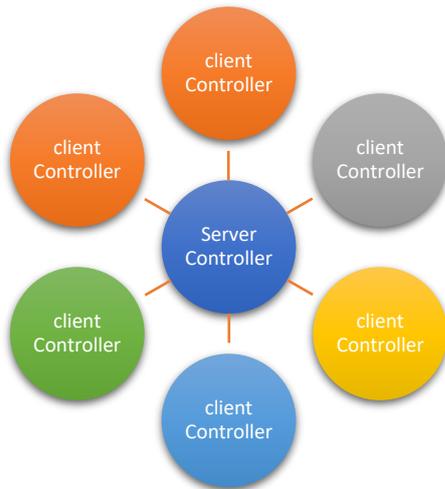


Fig. 3: System Star Topology.

4.1. Server controller

The server software can be installed on any personal computer, laptop, or even a smart phone. It communicates with the client controllers via Wi-Fi to gather and control the data. Figure 4 shows the designed website that displays the total power, rated voltage, total current, the V_{oc} and I_{sc} for each PV panel, PV panel condition (by comparing the measured voltage and current with manufactured values), button to forced test the V_{oc} and I_{sc} (since the system does that periodically), time and date to save the data with time stamp, and a login data (user name and password). The system adopts many software languages, see Table.1, to design the web site establish connections with clients and to support the client controller.

Table 1: List of the Adopted Languages

Abbr.	Meaning	Purpose
HTML	Hyper Text Markup Language	HTML documents, the foundation of all content appearing on the World Wide Web[1].
Ajax	Asynchronous JavaScript and XML	Encompasses much more than the technologies that make up this catchy acronym [2]
jQuery	JavaScript library	Designed to simplify the client-side scripting of HTML[3], [4].
CSS	cascading style sheets	To take control of the style of your pages, including the color and size of fonts [5].
Bootstrap	open-source front-end web framework	Designing websites and web applications[6]–[8].
Arduino IDE	Open-source makes it easy to write code and upload it to the Arduino boards.	This software is used to program the NodeMCU and ESP8266[9].

4.2. Client controller

The client controller consists of software and hardware parts. The software part includes the programming of NodeMCU using Arduino IDE software. NodeMCU has a built in Wi-Fi module and is programmed to be a client that receives requests from the server controller.

The flowchart of Figure 5 shows how the client controller reads voltage and current periodically and replays these to the server. In case the server requests the V_{oc} and I_{sc} , the server client will disconnect the PV Model from the string to calculate the V_{oc} and apply a short circuit to measure I_{sc} . The hardware electronic circuit is displayed in Figure 6, which consists of the following sub-circuits:

Panel Number	Check	Voc	Check	Isc	Panel Condition	MPPT Duty Cycle %
1	Check Voltage	23.43 V	Check Current	4.88 A	Good	51.21%
2	Check Voltage	22.10 V	Check Current	4.09 A	Average	54.29%
3	Check Voltage	23.66 V	Check Current	4.92 A	Good	50.71%
4	Check Voltage	20.86 V	Check Current	3.96 A	Bad	57.52%

Fig. 4: Server Website.

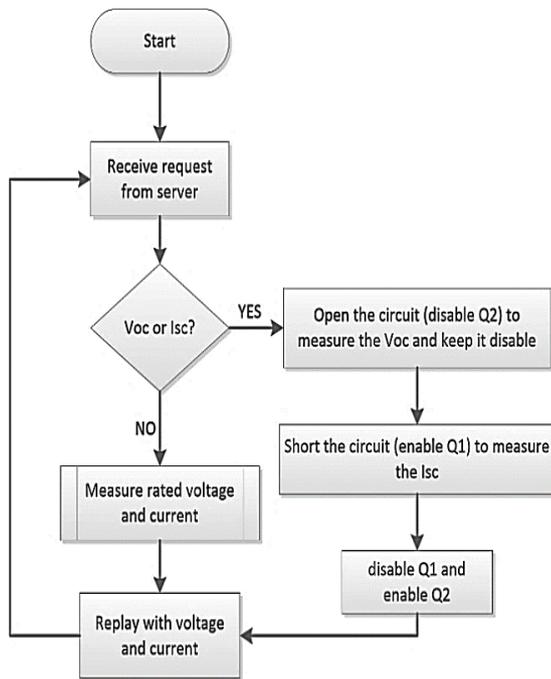


Fig.5: Flowchart for the Client Controller Software.

4.2.1. Current measurement and control

This sub circuit consists of a Power MOSFET (IRLZ44N) as switch, which is responsible for shorting the circuit of the PV panel to measure the ISC. The used current sensor (ACS712) is fully integrated, hall effect-based linear current sensor IC with 2.1 kVRMS isolation and a low-resistance current conductor. The design adopts ACS712ELCTR-30A-T which has a sensitivity equal to 66mV/A. This sensor is supplied from the main bus bar via a voltage regulator (7805) so when the PV panel voltage is equal to zero, it will keep running and this is accomplished by synchronizing the Q2 to cut the solar panel from the string. The Zener diode D2 and R6 have been added to protect the Power MOSFET from the high voltage since this type can handle maximum gate-source voltage $V_{GS\ MAX} \pm 16V$.

4.2.2. Voltage measurement and control

This sub circuit is responsible for measuring the output voltage of the solar panel with or without load. Normally the circuit reads the load voltage (Rated Voltage), but when the Q2 Power MOSFET is disconnected then the reading corresponds to the open circuit voltage V_{oc} . Q2 gate is protected as for Q1 using the Zener diode. The voltage divider which consists of R1 and R2 is responsible for scaling the voltage down since the ESP8266 ADC can handle maximum voltage of 5V. LED D1 gives an indication that the system is powered.

4.2.3. Maximum power point tracking

The sub-circuit for the MPPT is responsible for tracking the maximum power point. The solar panels exhibit nonlinear relationship between the current and voltage characteristics which will produce a maximum power at only one particular operating point. Many researchers discussed this matter in detail like [10]–[12]. In this paper, we contemplate employing a separate MPPT sub-circuit for every single panel. This circuit is linked as part of the system circuitry shown in Figure 6. Its function is to keep the system at maximum power point and measure the bus bar voltage to match the produced voltage by this particular panel with bus the bar voltage. Table 2: shows the power MOSFET states of operation.

4.2.4. Node MCU ESP-32S board

The main controller for this system is ESP8266-12 NodeMCU, which is considered as a client. The main computer/controller will work as a server and collect data from the solar farm clients. Only the server has the ability to request from the clients to measure and evaluate the ISC or V_{oc} for each solar panel. This survey is made once a day or periodically according to system setting to give the user a complete picture about each panel in the farm. A solar panel with low readings of I_{sc} or V_{oc} needs to be checked. In case all the panels are suffering from a low voltage, this gives an indication for cleaning the panel front glass from heavy dust. In case of soft shadow that is caused by tree branches or small clouds, these panels will be disconnected if the MPPT is failed to keep the statuses of voltage and current matching the other PV panels in the farm.

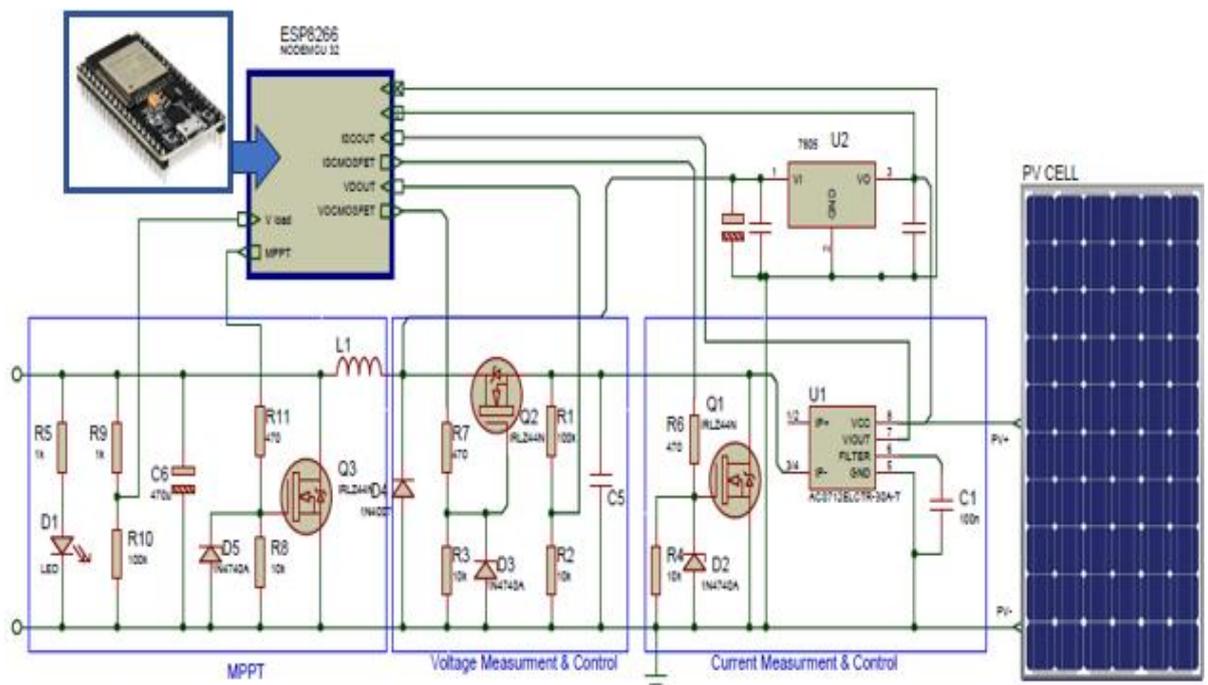


Fig.6: System Circuitry.

Table 2: Power MOSFET States of Operation

Status of operation	Q1	Q2	Q3
Measure ISC	OFF	ON	OFF
Measure VOC	OFF	OFF	OFF
Normal	OFF	ON	OFF
MPPT	OFF	PWM	PWM

5. Results and discussion

To validate the proposed system, an array of 12 PV modules is proposed with [4] strings in parallel, and each string has three PV modules. The used PV Module produces 24 VDC, 5A (120 W) (ideally), which means that every string should have 72V/5A, and in total (72V/20A/1440W). Then, the server is used to scan all the client controllers to check the readings of the test results for the open circuit voltage VOC and the short circuit current ISC for each PV panel and display these data as shown in Figure 7 and Figure 8 respectively.

Generally, the faults in the PV system are classified into two types [45], [46]: (i) irreversible error caused by mechanical or electrical problems, such as open circuit, short circuits and PV panel aging; and (ii) temporary power loss faults that are caused by sheltering, such as cloud shadows. Figure 9 gives a brief description of these faults in a PV system. All these faults can be diagnosed from the given data in Figure 9 according to following steps:

- 1) Open Circuit: this fault in the given connection affects the main supplied current, and any measured rated current gives a zero-ampere meaning there is such fault. Normally all the modules in the same string will give zero ampere.
- 2) Short Circuit: this fault is easily to diagnose by reading the rated
- 3) Voltage. If it is equal to zero it means there is a short circuit on the PV panel, also the rated measured current will be high since it means the ISC and not rated current.
- 4) Mismatching: this fault can be diagnosed from the mitigation in VOC or ISC.
- 5) Grounding: this fault causes a sudden high drop in the main voltage and current.
- 6) The cost of the proposed design is an important factor. Table.3 shows a list of the quantities, estimated unit cost and total cost for the system client controller only, since the server controller will entail no extra cost, as it could be the PC, laptop, or your smart phone, which are parts of the existing system. A pictorial representation of the proposed circuit is small in size (10cm x 6cm) and can fit inside the solar panel in a plastic box and it is of a plug and play type as shown in Figure 10 and Figure11 for the printed circuit and the three-dimensional module respectively.

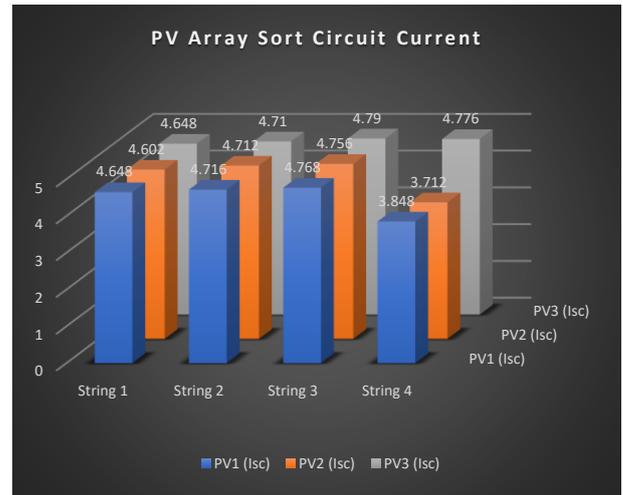


Fig.8: Short Circuit Current Test Results.

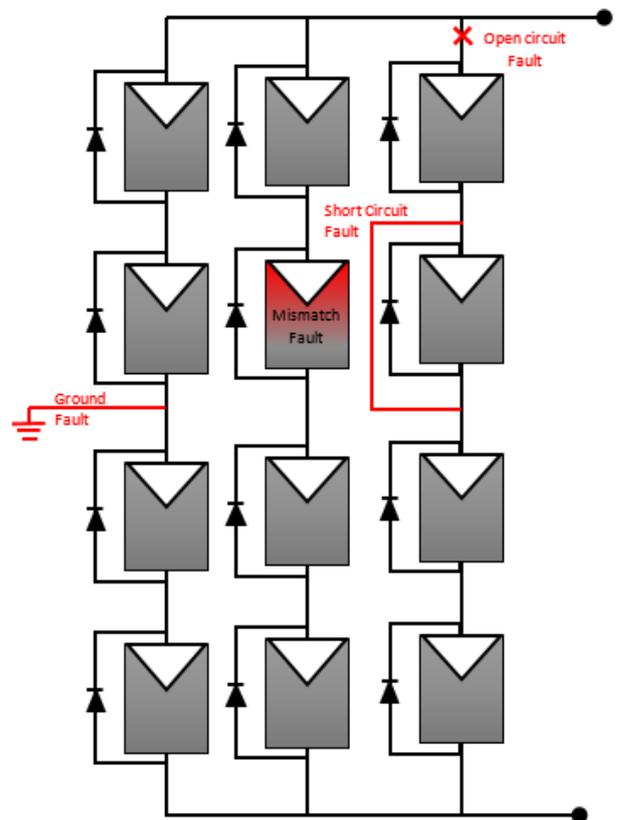


Fig.9: Faults in the PV Panel.

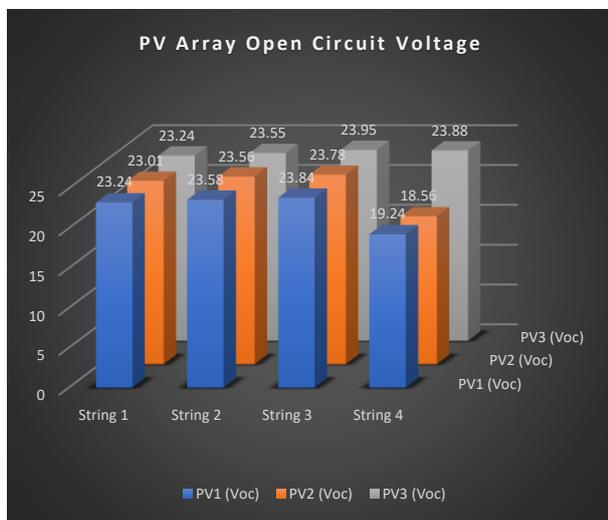


Fig.7: Open Circuit Voltage Test Results.

6. Conclusion

In order to keep the running of a vast PV solar systems reliable, safe and productive, it is envisaged to design and implement a system that detects faults automatically and classify them and this is in no doubt is a major challenge to the designer. In this paper, a fault detection system is proposed to monitor each individual PV panel in vast solar farm wirelessly. The offered system is cost effective, reliable and is capable of locating and detecting all types of faults. The main contribution of this paper is not only the detection and location of faults but it also saves the time and cost in comparison with the traditional laborious manual methods.

Table 3: Bill of Quantities and the Estimated Cost

Category	Qty	Refs	Value	Unit Cost (USD)	Cost (USD)
Capacitors	3	C1-C3	100nF	0.1	0.3
Capacitors	3	C4-C6	470uF	0.2	0.2
Resistors	2	R1, R10	100kΩ	0.1	0.1
Resistors	4	R2-R4, R8	10kΩ	0.2	0.6
Resistors	2	R5, R9	1kΩ	0.3	0.3
Resistors	3	R6-R7, R11	470Ω	0.4	0.8
Integrated Circuits	1	U1	ACS712	3.95	3.95
Integrated Circuits	1	U2	7805	0.8	0.8
Transistors with heatsink	3	Q1-Q3	IRLZ44N	1	3
Diodes	1	D1	LED	0.1	0.1
Diodes	2	D2-D3, D5	1N4740A	1.15	2.3
Diodes	1	D4	1N4007	0.1	0.1
Inductor	1	L1		0.2	0.2
Connector	1	J1		0.2	0.2
Connector	2	J3, J5		0.3	0.6
Connector	1	J4		0.2	0.2
NodeMCU	1	ESP8266	32b	8.45	8.45
PCB Board	1	Two layers		5	5
Soldering Cost	1			5	5
Total Cost					≈31.73 USD

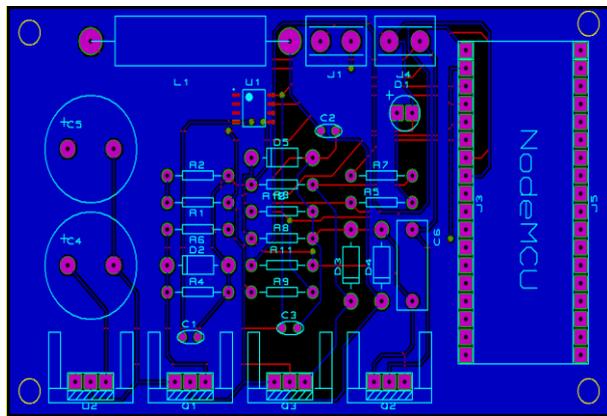


Fig.10: Printed Circuit Board.



Fig. 11: Three-Dimensional Module of the Client Controller.

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