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Research paper

Online Monitoring on a PV-based Smart Grid System

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Abstract

Optimizing the use of energy in a PV-based smart grid system using an online monitoring is described in this paper. This technique is based on the power monitoring using the client server experimental verification. Sensors are used to monitor the load voltage and current giving the power value. This kind of monitoring system can be done via online system based on web server and ubiquitous access. In this research, the mechanism of monitoring has been carried out through the wireless communication system. An internet Wi-Fi module has been made accessible through website to effectuate this kind of monitoring mechanism. Such monitoring system is prospective to be used in Internet of Things (IoT)-based smart grid networks in the future. The proposed system in this study results in a current reading range up to 30A, and voltage up to 30V. The read data have been stored in a memory card of microcontroller system, producing a data logging system and supporting the data sending through the web service for real-time monitoring system wirelessly.

Keywords: *Online monitoring system; PV smart grid; IoT (Internet of Things).*

1. Introduction

Development of smart grid technology has experienced a rapid expansion and pervasive growth [1-2]. In order to optimize the benefit of renewable energy resources, the implementation of smart grid system can be highly interesting, since it allows their integration into a traditional electric system domain, and enables the interconnection among components in the traditional system like bulk generation, markets and transmission system [3-6]. The need for electricity supply in Indonesia has been continuously rising along with the rapid progress in national commercial, industrial, information and technology developments. However, the electricity supply provided by PLN as the only national electricity company in the country cannot fulfill the total need.

Being located along the equator line, Indonesia is endowed with large solar energy potential. From around 4.8 kWh/m2/day, it is only about 10 megawatts peak out of the total equivalent potential of 112 terawatts peak which has been utilized. It is included in the roadmap of national energy development that around 0.87 GW or equivalent to 50 MW/year of solar power capacity to be installed by 2025.

A smart-grid system development can also be accomplished by building micro-scale systems taking the benefit of wind turbines equipped with the appropriate converter systems. Due to the allowance of real-time monitoring of smart grid power system components, operators can easily make an appropriate decision in order to increase the system performance [7]. The system performance may degrade because of the change in the utilization level of electrical energy as well as inefficient use of electrical equipments.

The smart-grids are mandatorily equipped with an adequate protection system involving various components specially designed to monitor the power condition in the systems. Such monitoring method can be operated based on the sensing results of electrical parameters like voltage and current [8].

This paper proposes an experimental approach for an online monitoring system in a PV-based smart grid system, which may become a part of a microgrid system. The microgrid has been recently introduced for managing the distributed generations in a power distribution network including renewable energy resources. It can work by either being connected to the grid (distribution network) or by itself which both of them can be monitored remotely [9-12]. In the system considered in this paper, the measured data from PV are logged and transmitted to a server using an internet connection to enable accessible information wirelessly.

2. Theoretical Review

The experimental approach taken in this study is supported with some basic theoretical understanding on the production of current and voltage in a PV solar cell and how it is characterized, how the cell responds to light spectrum, its dependence on temperature as well as the influence of its inherent parasitic resistance.

2.1. Generation of Voltage and Current

A silicon solar cell is typically fabricated by joining boron doped p-type and phosphorous doped n-type silicon diode. Considering the behaviour of the light shining on the cell, the generated power can be maximised by its photons absorption. The influence of electric field at the *p-n* junction will act to separate electrons and holes to the oppositely located *n* side and *p* side. Possible recombination of electrons and holes reduces the chance of carriers collection, and consequently the generation of a finite current when V = 0. The greatest chance for carriers collection is achieved when the pair of electrons and holes are generated within a diffusion length of the junction.

The generated power is characterized by the plots of current I against voltage V (I-V curves), as expressed using equation (1). The current I_0 represents the condition when there is no light exposed on the cell, whereas I_L is the current generated by the light.

It means that illumination of a cell is like adding the current in the diode law equation with the current due to the light.

$$I = I_0 \left[\exp(\frac{qV}{nkT}) - 1 \right] - I_L \quad (1)$$

By observing the equation (1), it is well understood that the addition of current due to the falling light will just shift down the I-V curve. The extracted power from the cell is represented by the rectangular area of the quadrant. Commonly the curve is reversed, giving the equation as expressed in (2).

$$I = I_L - I_0 \left[\exp(\frac{qV}{nkT}) - 1 \right] \quad (2)$$

For certain values of irradiance condition, temperature of operation, and area, the solar cell output is characterized using two kinds of limiting parameters, which are:

a) The current at short-circuit condition (I_{sc}), being the maximum current when the voltage is zero. Ideally, if V = 0, I_{sc} = I_L. The current I_{sc} is proportional to the coming sunlight.
b) The voltage at open circuit condition (V_{oc}), being the maximum voltage when the current is zero. V_{oc} values increase logarithmically when the sunlight increases. This parameter is formulated as (3)

$$V_{oc} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_o} + 1 \right) \quad (3)$$

Each point along the I-V curve, represents the values of voltage and current giving the output power at certain operating condition. The maximum power point characteristic of a solar cell is produced when the result of V_{mp}×I_{mp} gives their maximum value. It is graphically given by the largest rectangle obtained under the I-V curve. It can be calculated by setting the differential $d(IV)/dV$=0, giving the V_{mp} as expressed in (4):

$$V_{mp} = V_{oc} - \frac{nkT}{q} \ln\left(\frac{V_{mp}}{(nkT/q)} + 1 \right) \quad (4)$$

2.2. Spectral Response

Solar cell responds to photons from a coming light in a way to absorb it to produce electron-hole pairs, as long as the energy of the photon (E_{ph}) is larger than the energy of the bandgap (E_g). The energy of the photon which exceeds the bandgap energy will be dissipated fast as heat. The efficiency of quantum (QE) in a solar cell is defined as the number of electrons deplacing from the valence band to the conduction band for each (per) photon dealing with the solar cell. The quantum efficiency depends on the bandgap. The bandgap limits the possible longest wavelength in this case. The spectral response of the solar cell is resulted by the current production per watt of the coming light to the cell. Ideally, this increases with wavelength. However, short wavelengths have a drawback as cells are not able to utilize all the available photon energy. Meanwhile, when the wave is long, the absorption of weak light indicates that most of the photons are chased away from the junction collection and the limited length of diffusion in the cell material limits the response cell. The responsiveness spectrum (SR) can be calculated using (5),

$$SR = \frac{I_{SC}}{P_{in}(\lambda)} = \frac{q \cdot n_e}{\left(\frac{hc}{\lambda}\right) n_{ph}} = \frac{q\lambda}{hc} \quad (5)$$

where n_e indicates the flux of electrons per unit time, which flows in the external part of the circuit in a short-circuit connected condition, and I_{sc} is the short-circuit current, n_{ph} is the flux of photons for a given wavelength λ coming on the cell per unit time, P_{in} is the power of incoming light and $EQE=(1-R)$. IQE is the external efficiency, which is different from the internal quantum efficiency (IQE), R is the light being reflected from the upper surface. SR to be 0 due to λ=0. This phenomenon occurs with several photons in each power of incoming light. Wavelengths have a strong influence on responsiveness, consequently it makes the cell performance dependent greatly on the content of solar spectrum. In addition, optical loss and recombination loss mean that in reality the cell can only be approached with ideal condition.

2.3. Temperature Dependence

The working temperature of solar cells depends on the surrounding air temperature, the characteristics of the encapsulating module, the intensity of the coming sunlight on the module, and other variables like wind speed. The saturation current in dark condition I_0 increases when the temperature increases, as given by equation (6)

$$I_0 = BT^{\chi} \exp\left(\frac{E_{g0}}{kT} \right) \quad (6)$$

where B does not depend on temperature, E_{g0} is the zero extrapolated linear bandgap of a semiconductor that composes the cell whereas γ covers the temperature dependence of other parameters which determine I_0. Short circuit current (I_{sc}) increases when the temperature increases, because the energy of bandgap (E_g) lowers and more photons reach enough energy to make the *e-h* pair. Nevertheless, it is a small effect, and for silicon it can be formulated with (7)

$$\frac{I}{I_{sc}} \frac{dI_{sc}}{dT} \approx +0.0006°C^{-1} \quad (7)$$

The principal effect of the increase in temperature for silicon solar cells is the reduction of the values of open voltage *Voc*, the fill factor (FF) and consequently affects the cell output. The higher the *Voc* value, the smaller the expected temperature dependence. The temperature dependence of *Voc* and FF for silicon is estimated by equation (8)

$$\frac{dV_{oc}}{dT} = \frac{-\left[V_{go} - V_{oc} + (kT/q) \right]}{T} \approx -2mV/°C \quad (8)$$

2.4. Parasitic Resistance

Solar cells inherently have parasitic series and shunt resistances related to them, as given in Figure 1. Both parasitic resistances act to reduce the fill factor (FF).

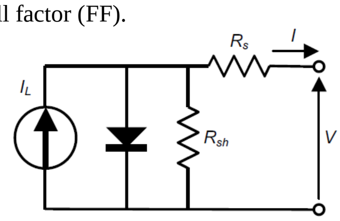


Fig. 1: Parasitic series and shunt resistance in solar cell

The series resistance (R_s) is mainly composed of resistances coming mostly from semiconductor materials, metal connections and interconnections, transport of carriers through the top of the diffused layer, and contact resistance between metal and semiconductor contacts. Shunt resistance (R_{sh}) is caused by a non-ideal pn connection and impurity near the junction, which causes the connection to be shortened from a junction, especially near the edge of the cell. Because the fill factor (*FF*) determines the output power of the cell, the maximum output power and current associated with the series resistance, can be estimated approximatively through the equation (9) and (10).

$$P_m = P_{mp}\left[1 - \frac{I_{sc}}{V_{oc}} R_S\right] \quad (9)$$

$$I = I_L - I_0\left[\exp\left(\frac{V + IR_S}{nkT/q}\right) - 1\right] - \frac{V + IR_S}{R_{sh}} \quad (10)$$

3. Experimental Method

The method used in this research is composed of hardware and software designs. The design of PV system construction includes the measurement node, internet connection with web server and client as typical access user. The systems have also been measured and validated with experimental verification using data logger and web service application.

3.1. System Design

The block diagram of the system is presented in Figure 2. In general, it consists of more than one node. Each node comprises a PV set, energy storage, solar charge control, wireless sensor module, data monitoring and electrical load. The coordination of the system includin the related mechanism of control at node are monitored via internet connection. Basic online monitoring client-server web service is shown in Figure 3. Each node sends the measurement results containing the data of time, date, voltage, current, power, temperature and humidity from node client to the server. The web server was constructed using PHP web-based programming and MySQL database to accommodate the request and response from client and server.

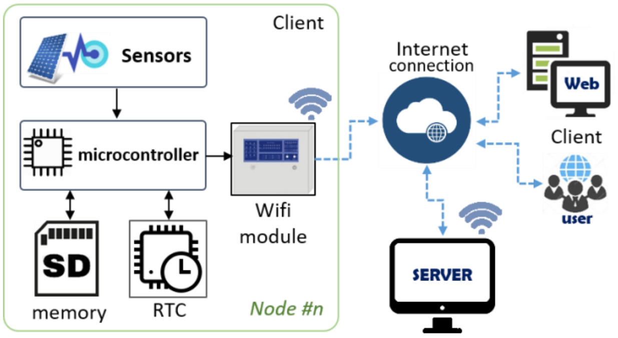


Fig. 2: Design of the online monitoring system

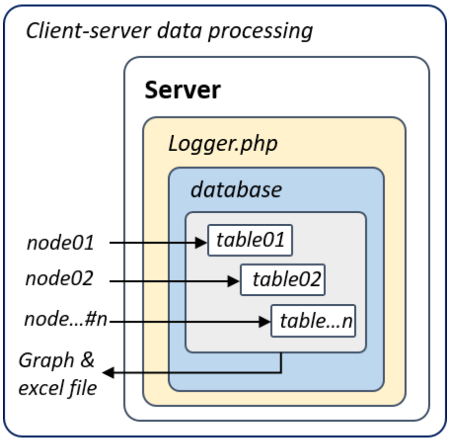


Fig. 3: Design of client-server data processing

3.2. Experimental Setup

The experiment has been carried out by measuring current, voltage and power based on the data of the sensors being resulted from the change in voltage source under light solar illumination. The stored data in SD card memory are reached eacht time the measurement process was conducted, and they were used to validate the resulted data on the web report. The measurement test has been conducted using a PV panel of 200 Wp and a sol gel VRLA battery of 100 Ah, respectively. PV monitoring measurement devices are shown in Figure 4 and Figure 5.

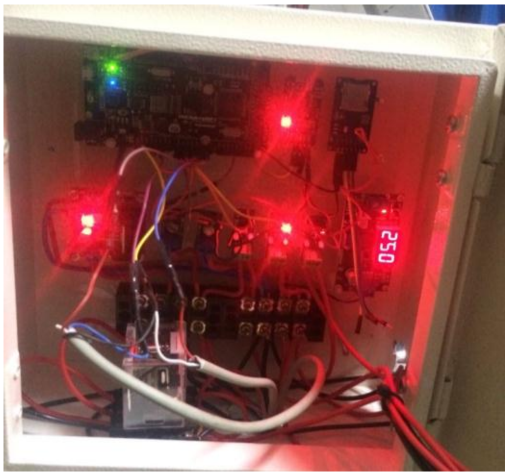


Fig. 4: Sensing and measurement devices inside the box

Fig. 5: Measurement setup of direct light PV conversion

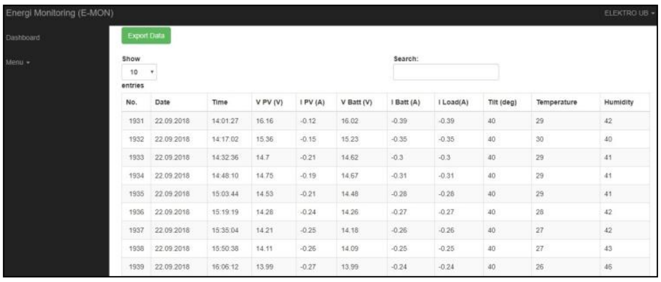
4. Results

The experiment results comprise the measured data from the voltage and current sensors installed in the smart grid system. The data of flowing current from the PV panel, battery and electrical load have been obtained using the current sensor. The measurement has been repeated ten times with the voltage provided from a supplying source up to 30 A. The measurement of load current has been undertaken using a sensor and the load has been represented by a resistive load. The measurement of voltage generated by PV module and battery has been done using a voltage sensor. The power voltage has been limited to a voltage range of 0-30 volts and regarded as a voltage sensor circuit with the input voltage is converted into the ADC input voltage in order to be able for processing by a microcontroller. Interval time for data processing was varying from each minute, 5, 10 and 15 minutes during the recording into the internal memory of SD card and the sending wirelessly to the server.

4.1. Online web monitoring

Web observation has been prepared by reading the electrical parameters of PV through an internet connection with a bandwidth of 2-10 Mbps through the public domain. The measured data over internet wirelessly using Chrome and Safari web browser are shown in Figure 6 and Figure 7, respectively. The data represented in these table indicate that the electrical and physical phenomena have been recorded. The parameters represent the voltage, current and power from PV, battery and electrical load, respectively. The temperature, relative humidity and PV tilt angle were also measured and monitored wirelessly. There were no different values between the results of direct measurement and monitoring wirelessly through online system. The measured data were monitored on the web service according to the specific url of:

http://devel.elektro.ub.ac.id/logging.



No.	Date	Time	V PV (V)	I PV (A)	V Batt (V)	I Batt (A)	I Load(A)	Tilt (deg)	Temperature	Humidity
1931	22.09.2018	14:01:27	16.16	-0.12	16.02	-0.39	-0.39	40	29	42
1932	22.09.2018	14:17:02	15.36	-0.15	15.23	-0.35	-0.35	40	30	40
1933	22.09.2018	14:32:36	14.7	-0.21	14.62	-0.3	-0.3	40	29	41
1934	22.09.2018	14:48:10	14.75	-0.19	14.67	-0.31	-0.31	40	29	41
1935	22.09.2018	15:03:44	14.53	-0.21	14.48	-0.28	-0.28	40	29	41
1936	22.09.2018	15:19:19	14.28	-0.24	14.26	-0.27	-0.27	40	28	42
1937	22.09.2018	15:35:04	14.21	-0.25	14.18	-0.26	-0.26	40	27	42
1938	22.09.2018	15:50:38	14.11	-0.26	14.09	-0.25	-0.25	40	27	43
1939	22.09.2018	16:06:12	13.99	-0.27	13.99	-0.24	-0.24	40	26	46

Fig. 6: Monitoring view from PC using Chrome web browser

No.	Date	Time	V PV (V)	I P\ (A)
1931	22.09.2018	14:01:27	16.16	-0.
1932	22.09.2018	14:17:02	15.36	-0.
1933	22.09.2018	14:32:36	14.7	-0.
1934	22.09.2018	14:48:10	14.75	-0.
1935	22.09.2018	15:03:44	14.53	-0.
1936	22.09.2018	15:19:19	14.28	-0.
1937	22.09.2018	15:35:04	14.21	-0.
1938	22.09.2018	15:50:38	14.11	-0.
1939	22.09.2018	16:06:12	13.99	-0.
1940	22.09.2018	16:21:47	13.89	-0.

Showing 1,931 to 1,940 of 1,940 entries

Fig. 7: Monitoring view from iPhone using Safari web browser

4.2. Data Analysis

The measured data from online monitoring system have been recorded and characterized to produce the PV profile during measurement. The profile of generated voltage and power from PV indicates the increasing light radiation at midday. This value is also followed by a temperature increase in these conditions. However, the increasing tenndecy occurs at an earlier voltage than the increase in ambient temperature. During the day the relative humidity (RH) decreases from morning to evening. Analysis of spectral scattering against changes in this phenomenon is still needed to support the existing theories. The influence of temperature and humidity can indicate the change in power which occurs in the measured PV. The voltage, current, temperature and relative humidity measurement profiles are shown in Figure 8 and Figure 9.

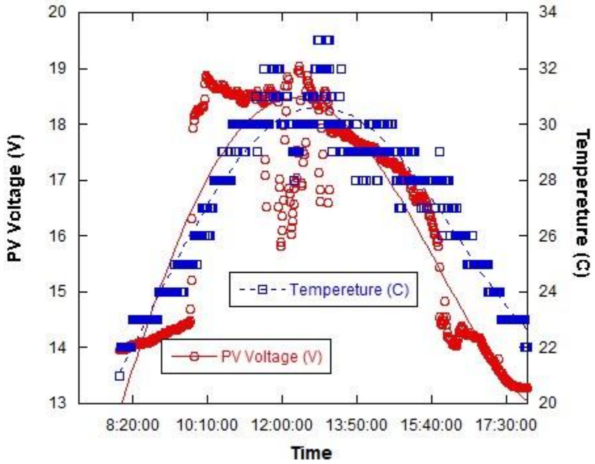


Fig. 8: Profile of measured voltage and temperature

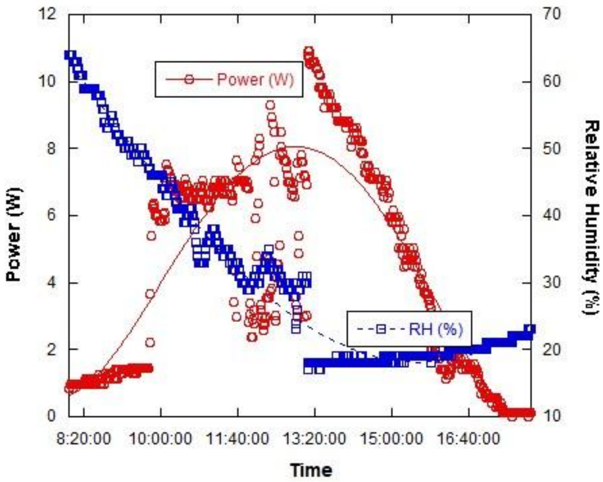


Fig. 9: Profile of measured power and humidity

5. Conclusions

The design of online monitoring system on a PV-based smart grid in this research has been successfully implemented and verified experimentally. The assigned server could successfully obtain the data from the sensor module and store it into the table of each node in the MySQL database. The reading of MySQL database through PHP program connection worked well. The database reading includes 3 tables of 10 columns each. Smart grid monitoring graphs could successfully display the data which were in accordance with the data stored in the database. The downloadable file of *.xls and *.csv were working with 100% success rate.

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