Development of a Microcontroller-Based Relaying System for Grid-Connected Photovoltaic Systems for Small Appliance Loads

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***Abstract*—The use of photovoltaic (PV) cells to convert solar irradiation is one of the most popular forms of renewable energy utilization and improvements in the existing technologies has been one of the focus of various research studies. The implementation of photovoltaics for the study mainly focused on the use of PV system as a grid-tied element which served as the primary power supply for small appliance loads during loaded operation with the grid providing the backup supply in the case that the PV system failed to provide sufficient power. Such was the case when (a) sunlight is not sufficient to energize the load, (b) the energy storage unit, which is the battery, had insufficient charge, or (c) the current generated by the PV modules is less than the current through the load. These factors were monitored through the monitoring and control system elements of the design which also performed the necessary supply switching for the conditions of the system while also monitoring the energy consumed from the grid and energy delivered back to the grid. Through the system created, power generated by the PV modules was delivered to the load or fed to the grid, and load was shifted back to the grid, as necessary. The responses of the relay were the most suggestive of the effective implementation of the design. The responses recorded were of high accuracy and high precision in nature as tested for dependence through analysis of binary data by comparing the occurrence of expected outcome and actual observed outcome.**

***Index Terms*—Control System; Microcontroller; Photovoltaic System; Relaying System.**

I. INTRODUCTION

The degradation of the environment is one of the reasons why there had been an increased interest in clean energy sources. These clean energy sources are renewable, such as solar and wind and these sources would eventually play an important role in the power generation industry as other conventional sources diminish [1]. For this reason, a trend began which saw the inclination towards the use of environment friendly sources. These sources, aside from its harm free effects to the environment, significantly reduces the cost of operations because of its non-existent need to burn fuel. Though these renewable energy sources have high capital outlay, in the long run, the reduction of the operating costs more than makes up for the initial investment [2].

One of the most widely used, readily available, and recognizable example of a renewable source of energy is the sun which provides solar energy harvested through photovoltaics panels, hereafter referred to as PV panels. A specific parameter which is the foremost problem in the performance of PV systems is its complete dependence on solar radiation intensity and ambient air temperature. The output power of the photovoltaic cells sharply changes with these parameters. Aside from these, the time of day is also a problem since there is no solar irradiation available during the night. Also, in areas where a large amount of PV panels are connected, the voltage at load points may cause reverse power flows depending on the time of day because of the fluctuations in voltage of the PV panels. If the voltages produced stray away from the rated voltage of the system, there is a need for power conditioners which are also often called voltage regulators or charge controllers. Power conditioners improve the quality of power by acting in a variety of ways to provide voltage at the appropriate level to an electrical load [3]. Research on PV systems focuses on the improvement of its performance by conducting experiments to study the effects on the performance of the system by changing certain operating parameters [4]. On an economic standpoint, PV systems are currently experiencing a continuous cost reduction in the market. This leads to the growing support for PV systems in developed countries, especially as applied in PV grid-connected systems. This is compounded by the fact that the efficiency of PV modules has increased to 24-30% [5].

When people are presented with the idea of solar power and photovoltaic systems, the general idea is a large scale power plant covering a vast area to house the panels. However, the implementation of such a system for a household is a plausible concept and has even seen an increase in interest because of its simple concept and economic advantages, heedless of the high initial cost. It is even more advantageous to implement such systems for countries in the tropical region, like the Philippines, which are located near or at the equator because of the sheer amount of solar irradiation the lands receive especially during the summer.

II. LITERATURE REVIEW

A. Grid-Tied Systems in Renewable Energy Schemes

A system is said to be grid-tied when the power it produces or utilizes is synchronized with the immediate existing power grid in aspects of voltage, frequency, and phase. A large number of generating stations are grid-tied which already includes renewable energy plants the likes of wind power plants, hydrothermal plants, and many others.

Once these renewable energy systems generate power, there is a need to use power electronic converters which modifies the power quality to make it compatible to the grid to which it will be connected. These converters may either be rectifiers, inverters, buck boosters (DC-to-DC converter), or even transformers (AC-to-AC converters). Majority of the converter topologies, proposed or otherwise already implemented, are meant to incorporate renewable energy systems to three-phase power systems. However, recent developments in technology has led to the popularity of renewable energy systems implementation to single-phase power systems. This approach significantly reduces the cost and simplifies the power flow control. A consequent effect of these kinds of implementations leads to the reduction of electrical power demand in the affected microgrids [6].

B. Implementation of Grid-Tied Systems with Photovoltaics

This establishment of grid connections also extends towards PV systems. However, the stability of the entire power system must be considered if and when a PV system is to be connected to it. This is because the voltage fluctuations of PV systems may have adverse effects on the performance on the portion of the power system that it is connected to in that it may affect power flow, system voltages, and may even cause short circuit currents.

Having said that, advancements in technology has enabled the direct connection of photovoltaic systems to the power grid, either as part of the bulk power system or in micro grids. The most basic components needed for such an implementation are PV modules, wiring, inverters, and a racking system for structural support. Since it is part of the power system, there is a need to monitor the equipment and the performance. There are also predictive models which helps predict the output power of the installed PV system. These models take into account all the parameters affecting the performance of the PV system including a set of meteorological inputs [7].

For large-scale implementations, the generating stations of the PV system are often located far from heavily populated areas and take up large properties to take advantage of economies of scale. Also, because a lot of space is needed for the solar cells. Once generated, it undergoes standard voltage conversion to higher magnitudes for transmission. Subsequently, it undergoes down-conversion when it reaches the utility side and consumer voltages are required [8].

Grid-tied PV systems has had an increase in the capacity over the last few years. In 2012, the capacity of grid-connected PV systems was less than 1% of the peak load demand which is not much in retrospect. However, a PV system capacity of 5% to 10% may be less than 10 years from reality. Furthermore, the PV capacity has mostly been installed in the distribution grid. This connection, though minimal in voltage, raises the concern on system performance, operation, and stability. As the penetration level or the relative power delivered by the PV system rises, a number of challenges continue to arise which prompts researchers and engineers to further develop and improve the integration scheme and management practices of PV systems in the power grid [9].

C. System Controllers

For a system to function as it is expected to, the corresponding equipment and components must be considered. For grid-connected PV systems, a PV panel is needed, first and foremost, along with charge controllers, energy storage devices such as batteries or supercapacitors, inverters, and electrical relays which makes up most of the relaying system.

A control system is also needed. The controller may be a programmable logic controller (PLC), electronic equipment for solid-state switching, or a microcontroller such as Arduino. The latter one is the concern for this study.

A controller is designed as a control point and computing system for automated processes. Before advancements in the technology, these were made from very large logic components. Miniaturization and advancements in the production of solid state electronics and microelectronics led to the integration of most if not all of the components needed in a controller into a single chip. This is the advent of the microcontroller.

It became a highly integrated chip which includes the Central Processing Unit (CPU), Random Access Memory (RAM), Erasable Programmable Read Only Memory (EPROM), and input/output (I/O) terminals.

The CPU is the brain. It administers all the activities in the system and performs all operations on the data.

There are my models of single chip, integrated microcontrollers such as the 8048 and 8051 from Intel, the 6805 from Motorola, the PIC Micro Chip, and many others [10].

A popular microcontroller is the Arduino which incorporates hardware and software considerations and is a flexible, programmable device which can perform automation on a variety of applications.

This Arduino microcontroller and other similar devices are open source platforms which performs physical computing through the use of a simple input/output (I/O) board coupled with a Processing language for the development environment. It can be used to create a variety of prototypes with the aim of building it faster and more powerful [11].

For the relaying control of the PV system, the Arduino UNO is a sufficient microcontroller board. It uses the ATmega168P chip. It has 14 digital input/output pins (6 of these can be Pulse Width Modulated outputs), 6 analog inputs, a 16 MHz quartz crystal, a USB connection, power jack, an ICSP header and a reset button.

D. Control Systems in Power Grids and Microgrids

Research activities as of late has given significant focus to the development of automation systems of energy management. However, there is a need to increase efforts with regards to developing automatic systems for residential applications. Considerations for such a system includes the technical characteristics and constraints, particularly for innovative resources including but not limited to PV systems [12].

One of the main reasons as to why control systems are needed for renewable energy systems in general is that the power generation from these sources is intermittent and random. If the power is continuously injected without control, the power characteristic being fed to the grid will cease to be constant. This can cause fluctuations in voltage and frequency which can prove fatal to utility users. This also increases the vulnerability of the utility grid.

To address these problems and many others not mentioned, smart control systems are integrated. It incorporates two-way communication through sensors and smart meters which essentially adds intelligence and automation to the design. The integration of such a system to the electric power grid has generated the smart grid (SG). Because of the system-wide monitoring through such smart systems, certain problems such as continuous blackouts and increasing carbon emissions, has been significantly reduced [13].

Smart grids, especially those incorporating renewable energy systems such as photovoltaic systems, have the potential to increase the efficiency and reliability of the grid, and to reduce the economic and environmental issues caused by traditional fossil-fueled generation.

Two important features of a smart grid is that it has an efficient supply-demand management, and a great exploitation or effective usage of renewable energy. Due to an ineffective exchange of information, the conventional construction of the grid suffers inefficiencies in operation in both the supply and the demand sides. Due to the lack of continuous and real-time system monitoring, the traditional grid inadvertently provides low quality of service during peak hours and does not reap the benefits during valley-periods, or non-peak hours. Smart grid technology is able to provide the shortcomings of the traditional grid through its ability to correlate energy-provisioning and energy demand more closely which results to an effective supply-demand management [14].

E. Control of Demand Response

The electrical grid in its current technological status has minimal energy storage capacity. The consequence is that there is no buffer between the supplier and the consumer. This forces the supplier to match the energy demand at any time. Additionally, if and when the supplier generates in excess, the energy is wasted, returning to the fact that there is no energy storage capability. The demand for electricity is a highly dynamic parameter. However, over a specific region, it is predictable on an accurate and precise level which enables for proactive management [15].

This brings us to an important concept of load balancing for energy management. Load balancing has to do with how the power system responds to the demand of the load. Often, the implementation of this sort of technology is concerned with the smart grid. It is a method of managing customer loads. By design, it should be able to shift the power flow away from the load during non-peak hours or times when the load is off. This is called Demand Response (DR) and it can be designed such that load balancing occurs automatically via a controller or manually through a designed control mechanism software [16].

Demand response is any policy or procedure which influences the power flow in response to signals from the supplier of power. It is a crucial component of the smart grid initiative as it helps improve the reliability and efficiency of the power grid.

III. OBJECTIVES

This paper was focused on the development of a control system for a grid-tied photovoltaic system which seeks to make the PV panels the primary source of energy for the loads with the grid providing backup supply to maintain supply continuity during low-sunlight conditions. The system switched to the backup whenever (a) there was insufficient light, (b) the battery had insufficient charge, and (c) the generated power from the panel was less than the power demanded by the load. The PV system is composed of the solar panel, a charge controller which maintains the charging voltage for the energy storage unit, a 70 Ah deep-cycle battery, and an inverter for converting the DC power to AC power to make the grid connection possible. The two power supplies are electrically interlocked through relays and therefore cannot supply the load simultaneously

IV. RESEARCH METHODOLOGY

To achieve the objectives of this project, there were two main components that were needed to be completed: the control system and the overall circuitry. The control system was programmed based on the process flow of the system. On the other hand, the circuitry was dependent on how the control system was developed.

The microcontroller was the center of the design of the prototype which served as the brain which performed the analysis of the data gathered from the field devices. The parameters it monitored included the output voltage of the solar panel before entering the charge controller. This determined the presence or absence of light. It also monitored the charging current and the load current at the PV system. This served to compare the energy consumption rate of the load relative to the generation rate of the panel. Lastly, it monitored the voltage level of the battery which assisted in determining the charge level of the battery. These parameters were continuously monitored so that the supply switching or load shifting was done based on real-time conditions of the system. These were all possible through the development of an effective algorithm for the microcontroller which addressed all of the parameters. Figure 1 shows the system process flow in block diagram form.

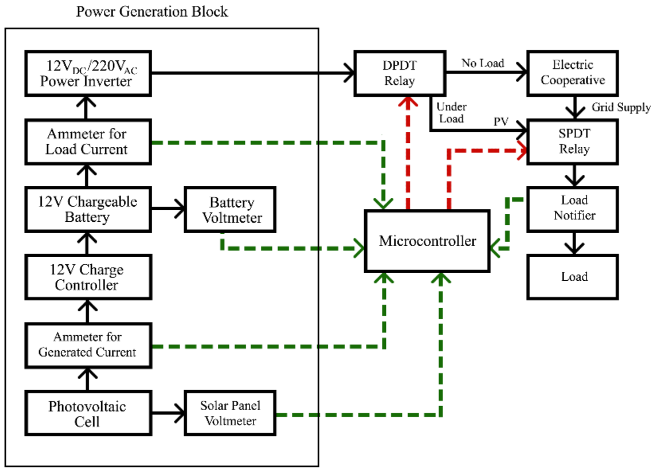

Figure 1: Block Diagram of Control System

The actuation of the relay was facilitated by the microcontroller through the relaying system shown in Figure 2. This was done after the microcontroller has assessed the condition of the system and has determined whether the PV system can maintain operation as the supply or if there was a need to shift the load to the grid.

The control system monitors the conditions of the different components of the system and determined whether the PV system can maintain the operation as the supply. Mainly, the control system determined the presence or absence of light, the demand of the load relative to the generated power of the panels, and the charge level of the battery. Three conditions exist which shifted the load from the PV system to the grid, namely: there is no light, the load demands energy at a rate greater than the panel can generate, and the battery has insufficient charge to maintain operation. The load shifting is facilitated through the relaying system (Figure 2).

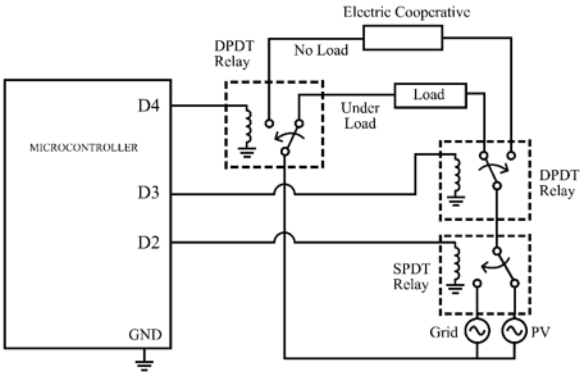

Figure 2: Relaying Circuit Design

However, it was designed so that the system still operates and the panels still generates power when there is no load connected. Unless circulated, the energy generated when there is no load is wasted. This is why this study seeks to sell the generated power at no load to the electric cooperatives so that the energy is not wasted.
The selection of the microcontroller was part practicality and part functionality. This means that the selection of the microcontroller depended on its ability to perform all the functions of the system while still being economically acceptable.

V. TESTING AND ANALYSIS

Most of the tests done included the observation of relay responses to the conditions which the system was being exposed to. Individual parameters were first tested which includes the presence of light, the battery voltage, and the comparison between generated current and the load current. The presence of light and the battery voltage parameters both had to do with voltage variations and were measured using the Arduino built-in voltmeter. The voltage variations were simulated by using variable direct current (DC) supplies from the laboratory. This was done because it would have been difficult to attain such varying voltage variations from (a) the solar panel because the voltage was wholly dependent on the intermittency of light which cannot be reliably controlled, and (b) the battery because voltage variations are obtained by charging or discharging the battery to a point which would have been time consuming had this route been taken. The load current was varied by connecting an array of light bulbs which can be switched on and off individually for load current variations. Full system tests were done by varying the three mentioned parameters which resulted to eight (8) possible combinations.

VI. RESULTS AND DISCUSSIONS

The system was designed such that there are specific relay states for the varying conditions that the system is exposed to. Since there are expected states for the relays, a test of accuracy and precision was done to compare the observed responses with the expected responses. To do this, a contingency table was created with the format shown in Table 1. A table similar to this was constructed for all the tests.

Table 1
Contingency Table

	Test: Hypothesized HIT	Test: Hypothesized MISS
Reality: HIT	TP	FN
Reality: MISS	FP	TN

TP stands for True Positive which corresponds to actual hits which are hypothesized to be hits while TN stands for True Negative which corresponds to actual misses originally hypothesized to be misses. FP is the Type II error or False Positives which corresponds to erroneous actual misses. Similarly, FN is the Type I error or False Negatives which corresponds to erroneous actual hits. These are needed to quantify the accuracy and precision of the relay actuation for every test by using the following equations.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100\% \quad (1)$$

$$Precision = \frac{TP}{TP + FP} \times 100\% \quad (2)$$

A summary of the test results for the full system tests are shown in Table 2. The individual tests are not shown since the full system test can account for the type of responses being simulated in the individual parameters test.

Table 2
Contingency Table

Sufficient Sunlight	Sufficient Battery Charge	Generated current greater than load current	Expected SPDT state	Actual SPDT state
Yes	Yes	Yes	LOW	LOW
Yes	Yes	No	HIGH	HIGH
Yes	No	Yes	HIGH	HIGH
Yes	No	No	HIGH	HIGH
No	Yes	Yes	HIGH	HIGH
No	Yes	No	HIGH	HIGH
No	No	Yes	HIGH	HIGH
No	No	No	HIGH	HIGH

The performance of the full system test above considered the amount of sunlight, the charge of the battery, and the generated current compared to the load current.

For the presence of light, it was listed ‘Yes’ if the amount of sunlight produced a corresponding voltage of at least 13.6 V from the solar panel. This was the set point value to determine the presence of sufficient sunlight to charge the battery. When listed ‘No’, the test performed was conducted with a solar panel voltage of less than 13.6 V.

For the parameter regarding battery voltage, it was listed ‘Yes’ whenever the test conducted had a battery voltage of greater than 11.8 V. Any voltage less than 11.8 V was listed as ‘No’. This was the set point value of a significantly discharged battery which needs to be charged first.

Lastly, the full system test also compared the generated current and the load current. Whenever the generated current was greater than the load current, it was listed as ‘Yes’, otherwise, it was listed ‘No’.

From observation, the actuation of the SPDT relay is determined by using the AND logic on the three parameters listed.

The tests shown were performed with each condition being tested for 30 trials. The relays responded accordingly in all of the trials performed which resulted to an accuracy of 1 and a precision of 1 expressed as proportions instead of percentages. Note that 30 trials were performed to ensure the statistical significance of the data.

The previous test details the operation of the system under loaded conditions. However, the system designed had a separate function for when no load was connected. Once the system had determined that no load was connected, it actuated the DPDT relay such that the generated energy was directed to the electric cooperative represented by a light bulb. This was tested and the responses of the DPDT relay was recorded as shown in Tables 3 and 4.

Table 3
Load Connection System Response

Trial	Load Connection Response (Expected=HIGH)			Relay Response (Expected=LOW)		
	Actual	HIT	MISS	Actual	HIT	MISS
1	HIGH	X		LOW	X	
2	HIGH	X		LOW	X	
3	HIGH	X		LOW	X	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	HIGH	X		LOW	X	

Table 4
Load Disconnection System Response

Trial	Load Disconnection Response (Expected=LOW)			Relay Response (Expected=HIGH)		
	Actual	HIT	MISS	Actual	HIT	MISS
1	LOW	X		HIGH	X	
2	LOW	X		HIGH	X	
3	LOW	X		HIGH	X	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	LOW	X		HIGH	X	

This test was also performed using 30 trials to ensure statistical significance. It can be observed that the relay responded accordingly in all of the performed trials resulting to an accuracy and a precision of 100%. This ensured that the system was functioning as expected

VII. CONCLUSION

Based on the results, the developed control system was able to control the relaying system effectively and according to the function specified in the design. During loaded operation, the system was able to transfer the load to the grid and away from the photovoltaic system whenever one or more of the following conditions occur: (a) there was insufficient light to drive the charge controller as determined through the voltage reading; (b) the battery had insufficient charge as determined through the voltage reading; and (c) the generated current of the solar panel was less than the load current. This was determined by observing the response of the single-pole single-throw (SPDT) relay which was responsible for supply switching.

The system was also able to perform its intended function under no load conditions. Specifically, a double-pole double-throw (DPDT) relay disconnected the photovoltaic system from the loaded circuit and transferred it to the electric cooperative represented by a light bulb. This mitigated the waste of generated energy whenever no load was connected since generation continues regardless of the load connection.

It can be noted that the intermittency of sunlight causes the generated current to be less than the load current when a significant load wattage was connected and this happened more frequently than expected. It is recommended to use an array of solar panels to increase the generated current capacity of the photovoltaic system.

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