Simulation of synchronization photovoltaic system and low voltage grid

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Abstract. In this research, the synchronization between the PV system and grid designed with synchronization parameters are voltage, frequency, and phase angle difference. As a result, by using a synchronization system, the PV system and grid could be parallelized and supplying power into the load at the same time. The synchronization method used is zero-crossing detection because it is simple than the other method. The synchronization system consists of several components; voltage detector, frequency detector, phase angle detector, and switch controller which all of them are controlled using the Arduino board. The switch controller will be functioned based on input from the detector to do synchronization or parallelize the PV system and grid. Testing is done by simulating running in Proteus. Based on the result of the simulation, the system is successful to do synchronization between the PV system and grid, it can be observed from the grid and PV inverter voltage graph and current which is measured from load, grid, and inverter.

1. Introduction

The Photovoltaic system (PV system) consists of a solar module to convert solar energy to electrical energy then saved into the battery. To serve the alternating current (AC) load, electrical energy saved in a battery (DC supply) is frequently converted into electrical energy using the inverter device. The PV system produces fluctuating electrical power influenced by solar radiation hit the solar module. When the intensity of solar radiation is high, the PV system produces more maximum electrical energy, meanwhile, when the intensity of radiation is low, so electrical energy produced is decreasing, moreover, in the dark, the PV system does not produce electrical energy at all. The utilization of the PV system is expected to make loads such as lighting, water pump, and other electrical devices not only served by the electrical energy sources by the state electric company but also from the PV system so that the cost of electricity is cheaper. Therefore, a synchronization system to make the PV system work together with the state electrical company grid (hybrid) is needed. Hybrid power generation systems consist of two or more different electrical energy sources, whether connected to the grid or not, however when it connects into the grid, it will be more reliable because the grid can supply electrical energy into load when the PV system is disconnected from the system. As a result, the synchronization system is required so that electrical energy from the PV system and grid can supply and serve the load. Therefore, in this research, the synchronization system for the PV system and grid with synchronization parameters; voltage, frequency, and phase angle differences are designed.

Many previous kinds of research conduct synchronization between the PV system and grid by using different synchronization methods. In this research, synchronization done uses the Arduino controller and zero-crossing detection to detect phase angle differences between the PV system and the grid. In this research, advantages of synchronization system are more simple system because inverter used is a pure sine wave so that synchronization system is only handling switch controller...
when voltage and frequency between the PV system and grid are same, and different of the voltage phase angle between both of them is not more than accepted maximum limit.

Testing of the system is conducted by doing the simulation of the synchronization process between the PV system and grid, by observing the condition of inverter voltage and grid voltage while synchronous or not synchronous. Moreover, it is also reviewed the current of each grid, inverter, and current at load. Simulation is run by using Proteus, an inverter is assumed presenting the PV on this research.

2. Grid synchronization

Synchronization means to minimize the differences in voltage, frequency, and phase angle between generator output and grid [1]. The necessity of synchronization and electric generator parallel is often based on the following things [2]:

1) The capacity of generator owned by existed system has been exceeded by new burden
2) The increasing of reliability (several generators vs single generator unit) must be considered
3) The efficiency of the generator

There are several electric generators that can be connected into a grid such as hydro, thermal, solar, etc, to supply power into the load. This generator unit can supply power if it has fulfilled rules. Intended rules are the variation or the change of voltage and frequency must on the limit of value, which have been determined, such as what has been explained in section 2.1 [2]. Before connecting the PV system to the grid, it must be synchronized with the parameter of the grid. Improper synchronization can influence power systems and produce electrical and mechanical transients that can ruin the prime mover, generator, transformer, and other system components [1].

The following is ideal synchronization [3]:
1) Able to detect the phase angles very well
2) Detect the varying frequencies efficiently
3) Reduce harmonic interference efficiently
4) Respond to the change on grid side well

2.1 Synchronization Parameters

The first problem on the synchronization process is equalizing the synchronization parameter, which the magnitude of voltage, frequency, phase, and phase angle between the grid and PV system must be matched. Table 1 showing several standards for interconnection between the PV system and the grid [4].

| Table 1. Standards of PV system-grid connected |
|------------------------------------------------|
| Voltage parameter | Standard |
|-------------------|----------|
| Magnitude         | ANSI C84.1 |
| Frequency         | IEEE 929  |
| Phase Angle       | IEEE 929  |
| Synchronization   | ANSI 25   |

| Aggregate rating of DG units (kVA) | Frequency Difference (Δf, Hz) | Voltage difference (ΔV, %) | Phase angle difference (ΔΦ, °) |
|-----------------------------------|-------------------------------|---------------------------|-------------------------------|
| 0-500                             | 0,3                           | 10                        | 20                            |
| >500-1500                         | 0,2                           | 5                         | 15                            |
| >1500-10000                       | 0,1                           | 3                         | 10                            |

Moreover, another standard is IEEE Std. 1547, IEEE Std. 1588-2008, IEC Std. 1727, IEEE Std. 929-2000 [3]. The synchronization parameter is voltage fluctuation, the magnitude of voltage, the sequences of phase, frequency, and phase [2]. Table 2 presents the synchronization parameter, however, the synchronization parameter allows little differences based on the standard used in every country [5].
2.2 Synchronization Schematic
Phase, frequency, and voltage are parameters and input on the synchronization system. Generally, the synchronization schematic is shown in Figure 1. After synchronization is done, power from the PV system will be connected to the grid on the PCC point [6].

![Figure 1. General Synchronization Schematic](image)

3. Zero-crossing detection
The Zero-crossing detection method is measurement of voltage and detects zero points of voltage when voltage changes from negative value (-Ve) into positive value (+Ve) as shown in Figure 2. Because used for switching, then there must be such a thing as harmonic or noise [7]. Zero-crossing detection is also stated as a comparison, as shown in Figure 3, where zero-crossing detection uses a basic operational amplifier (Op-Amp) to compare two voltages simultaneously and change output according to the result of the comparison. Zero-crossing detection can be applied to the phase meter and time marker generator.

![Figure 2. Zero crossing detection on AC voltage](image)

![Figure 3. Basic circuit Op-amp](image)

4. Configuration of system
The system proposed shown in Figure 4. This synchronization system integrated voltage detector, frequency detector, phase angle detector, and Arduino as the controller.
4.1 PV module configuration
The PV module used in this research is the polycrystalline solar cell with more complete specification as shown in Table 3.

| Model          | BP350U          |
|----------------|-----------------|
| Serial         | C1051213 4439776|
| Electrical Ratings | (At STC 1000 W/m², AM 1.5 spectrum, cell temperature 25°) |
| Peak Power (Pmax) | 50 W            |
| Warranted Minimum Pmax | 45 W            |
| Voltage (Vmp)     | 17.5 V          |
| Current (Imp)     | 2.9 A           |
| Open Circuit Voltage (Voc) | 21.8 V        |
| Short Circuit Current (Isc) | 3.17 A          |
| Minimum Bypass Diode | 9 A             |
| Maximum Series Fuse | 20 A            |

4.2 Design of inverter
Inverter design has voltage output 220 V and frequency 50 Hz. The inverter circuit diagram used in this research is shown in Figure 5. Voltage waves produced by the inverter are pure sine waves as shown in Figure 6.
4.3 Voltage detector
The voltage detector is used to read the voltage of the grid and inverter. The measurement of AC voltage is conducted by decreasing voltage because Arduino is only able to measure the voltage between 0V-5V and it is not able to read negative voltage value. Source voltage can be decreased with the transformer and voltage divider circuit as shown in Figure 7. The resistor on the voltage detector circuit diagram is a voltage divider series and a capacitor as a filter.

Figure 7. Voltage detector circuit diagram

The voltage detector design, which is designed on Proteus is shown in Figure 8. The result of voltage reading from the grid and inverter is illustrated on the LCD.

Figure 8. Design voltage detector
4.4 Frequency detector

Frequency on AC voltage can be calculated by measuring the time of the AC voltage wave. Time is the full-time wave, which means a half positive wave and a half of negative wave. To make it easier to detect and measure frequency, the diode rectifier is used as shown in Figure 9. Series to measure the AC frequency magnitude is shown in Figure 10, Optocoupler component is used as isolation for high voltage and low voltage from Arduino.

![Figure 9. Period of sinewave](image1)

![Figure 10. Frequency detector circuit diagram](image2)

4.5 Phase angle detector

Phase angle detector is a circuit diagram to know the differences of the phase angle. Measurement of the difference of the phase angle between grid and inverter is the same with the measurement of power factor, but the difference is only on implementation. To measure phase angle, first decreasing voltage from both sources using a transformer, then utilizing Op-Amp to detect zero points of grid voltage wave and inverter. Op-Amp convert sinusoidal wave signal becomes square wave with 4V amplitude, which is then linked into XOR gate input and processed by Arduino, shown in Figure 11. Moreover, the output of the XOR gate is shown in Figure 12. For example, the calculating of phase angle difference is shown in Figure 13. The simulation result of zero-crossing detection with several delay time values regulated is illustrated in Table 4.

![Figure 11. Phase angle detector circuit diagram](image3)
Figure 12. Gate XOR output

Figure 13. Example measure phase angle difference

Table 4. Phase angle simulation

| No | Time Delay Setting between the grid and the inverter output | Zero-Crossing Detection | Cos $\theta$ (p.f) |
|----|-------------------------------------------------|----------------------|-----------------|
| 1  | 1 ms                                           | 18,15                | 0,95            |
| 2  | 2 ms                                           | 35,84                | 0,81            |
| 3  | 3 ms                                           | 54,96                | 0,58            |
| 4  | 4 ms                                           | 78,23                | 0,32            |
| 5  | 5 ms                                           | 90,67                | 0,01            |

5. Simulation and results

Voltage detector, frequency detector, and phase angle detector which have been designed before will be integrated becoming a system to do synchronization testing between the PV system and grid. Figure 14 is the display of LCD when synchronization between PV inverter and grid is successfully done.
5.1 Result of simulation test

The test is not only to know the result of synchronization but also simulation done to know how the relay responds work properly, whether when all of the synchronization parameters are fulfilled or not. Table 5 informs the work of the relay which success to work is stimulated based on parameter value with 9 different possible conditions.

| No | Parameter | Status | Inverter Relay | Grid Relay |
|----|-----------|--------|----------------|-----------|
| 1  | 1         | 1      | 1              | 1         |
| 2  | 1         | 1      | 0              | 1         |
| 3  | 1         | 1      | 1              | 0         |
| 4  | 0         | 1      | 1              | 1         |
| 5  | 1         | 0      | 1              | 1         |
| 6  | 1         | 0      | 1              | 0         |
| 7  | 0         | 1      | 0              | 1         |
| 8  | 1         | 1      | 1              | 0         |
| 9  | 0         | 0      | 0              | 0         |

5.2 Phase synchronization

To be parallelized between the PV system and grid, both phases should be the same and not allowed to have phase angle different exceed the parameter limit determined. As a result, before synchronization of phase between PV inverter and grid must be conducted. The blue wave is grid voltage, red is inverter voltage, and green is PWM inverter wave. The yellow graph is the output of the zero-crossing detection series, which can be seen as yellow graph remarks zero points of grid voltage wave. Figure 15 shows the condition when the phase between grid voltage and inverter is not synchronous, meanwhile, Figure 16 shows the condition when the phase between grid voltage and inverter is synchronous.

![Figure 15. Vgrid and Vinv when asynchronous](image-url)
5.3 Grid and inverter voltage
When the simulation process is conducted, delaying happens several seconds until the voltage produced by the inverter has stabilized and steady-state so that it can be synchronized with the grid as shown in Figure 17. From those graphs, it can be seen that grid voltage and inverter are synchronous when it is 160ms, it can be seen voltage is synchronous although there are little differences in phase angle. The graph illustrated in Figure 17 is the inverter voltage and grid graph, which red graph is the grid voltage graph, meanwhile yellow is inverter voltage graph.

5.4 Grid and inverter current
To ensure the inverter helps to supply electrical energy to the load, so current measurement of the inverter, grid, and load is conducted. The result of current measurement when it is synchronous between inverter and grid is illustrated in Table 6. Based on Table 7, it remarks the current percentage supplied from the inverter is not constant, it caused inverter only supply current to support grid in serving the same load, or known as load sharing, the condition of two or more generators operates in parallel to supply the same load.

| No. | Resistive load | Grid current | Inverter current | Load current |
|-----|----------------|--------------|------------------|--------------|
| 1   | 100 Ω          | 1,1 A        | 1,1 A            | 2,2 A        |
| 2   | 120 Ω          | 1,375 A      | 0,45 A           | 1,83 A       |
| 3   | 240 Ω          | 0,77 A       | 0,13 A           | 0,91 A       |
| 4   | 360 Ω          | 0,61 A       | 0,114 A          | 0,88 A       |
Table 7. Current supply percentage

| No. | Load  | Grid current | Inverter current | Load current (A) |
|-----|-------|--------------|------------------|------------------|
| 1   | 100 Ω | 50 %         | 50 %             | 2.2 A            |
| 2   | 120 Ω | 75.72 %      | 24.27 %          | 1.83 A           |
| 3   | 240 Ω | 85.71 %      | 14.28 %          | 0.91 A           |
| 4   | 300 Ω | 84 %         | 15.90 %          | 0.73 A           |

6. Conclusion
The synchronization system designed in this research is successful to do synchronization between the PV system and the grid, simulated in Proteus. Based on the result of the simulation, the zero-crossing detection method can do synchronization with a very simple scheme, and the synchronization process can be done with Arduino control. The success of synchronization can be observed that PV inverter and grid can supply current to load simultaneously although the amount of current supplied from the inverter/PV system to load is not consistent or change depending on the load used. Arduino controls the synchronization process and switches the controller as the interconnection point between the PV inverter and grid. The system design also shows the value of voltage, frequency, and phase angle difference on the grid and inverter side in real-time that is illustrated in the LCD.

7. References
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