Fault Condition Analysis in a Grid Connected PV Energy System

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Abstract. One of the most popular issues in the future power generation is the renewable energy and the development of Micro-grid (MG) energy system. Different types of renewable energies are harnessed and integrated into the MG energy system formed a hybrid MG energy system, which can enhance the stability and flexibility of the entire energy system. This paper focus on fault condition analysis in a grid connected Photo-voltaic (PV) energy system. The grid connected PV energy system is operated under different level of solar irradiation, corresponding to the different Direct Current (DC) voltage level. The output current of the Voltage Source Inverter (VSI) at different level of solar irradiation are monitored and analyzed. The result shows the impact of various solar irradiations on the system stability and the necessity of fast and flexible control system.

Keywords: Photo-Voltaic, Voltage Source Inverter, Micro-grid.

1. Introduction

Solar energy is one of the most commonly used Renewable Energy Sources (RES) in the MG energy system. It is the second fastest developed energy source which has attracted many attentions. Solar energy system is growing 15% per year during last two decades and it’s developing even faster recent years, the speed is up to 30% per year [1]. But unfortunately solar energy system has two major problems; the conversion efficiency is low especially under low irradiation conditions and the electric power generated by solar arrays changes continuously with weather conditions [2]. Moreover, the Voltage-Current (V-I) characteristic is nonlinear and varies with irradiation and temperature. Therefore a flexible control system is needed to regulate the operation of MG. The conversion system are a vital component in the MG energy system, it can properly control the operation of the MG energy system either interconnected to the low voltage network or islanded from the utility grid working in stand-alone mode. In the grid connected mode, the inverter system in the MG usually works in the constant current control mode to provide pre-set power to the utility of power system. When the MG is disconnected from the main grid, the inverter system switch to the voltage control mode to provide a constant voltage to the local loads [4].

The fault condition in the PV-grid connected energy system happens when the voltage level of the DC side is lower than the required DC input value. When the fault happens in a inverter connected energy system, the output current of the inverter becomes asymmetrical. The asymmetrical current waveform raises above the horizontal axis considerably more than it goes below for the first few cycles. This wave is offset from or asymmetrical with respect to the horizontal axis. This condition happens in circuits containing reactance which are short-circuited at some time other than when the current is passing through the zero point on the cycle. It occurs in one or more phases in all 3-phase circuits. When this happens, a DC current is superimposed on top of the AC current causing asymmetry. The DC component actually decays to zero within a short time after the fault occurs. The final decay of the DC component signifies a change from asymmetrical to symmetrical [5].

2. PV Energy System Description
The hybrid MG as a combination of different sources can decrease the impact of the varying weather conditions. PV array, wind turbine, fuel cell, energy storage devices, data acquisition devices, power conversion system are considered as the main structure of hybrid MG energy system. In this work the hybrid MG energy system are consists of different types of RES, such as PV array, wind turbine generation and energy storage device).

2.1 PV array
Solar energy is one of the fastest developed RES [1]. Because of its environmental and economical benefits, solar energy has been widely utilized in many fields. But unfortunately the PV energy system also has its own drawbacks, the conversion efficiency of the converter and inverter is low under low irradiation conditions and the power generated by PV array changed continuously with the weather conditions, the V-I characteristic is nonlinear and varies with irradiation and temperature [2].

The output current of the PV array can be calculated as,

\[
I = n_p I_{ph} - n_p I_{rs} \left[ \exp \left( \frac{q}{kT_A} \right) - 1 \right]
\]  

Where,
- \( I_{ph} \): PV current
- \( n_s \): Number of cells connected in series
- \( n_p \): Number of modules connected in parallel
- \( q \): Charge of an electron
- \( k \): Boltzmann’s constant
- \( A \): Diode ideality factor
- \( T \): Cell temperature
- \( I_{rs} \): Cell reverse saturation current

The PV current \( I_{ph} \) depends on the solar radiation and the cell temperature and can be found by,

\[
I_{ph} = [I_{scr} + k_i (T - T_r)] \frac{S}{100}
\]

Where,
- \( I_{scr} \): Short-circuit current of the cell at reference temperature and irradiation
- \( k_i \): Short circuit current temperature coefficient
- \( S \): Solar irradiation in W/m²

The PV array power \( P \) can be calculated using the following equation,

\[
P = IV = n_p I_{ph} V - n_p I_{rs} V \left[ \exp \left( \frac{q}{kT_A} \right) - 1 \right]
\]

Where \( V \) is the output voltage of the PV array, from (8) it is obvious that in order to gain the maximum available power, the PV array should be operated at its MPP. The instantaneous output power generated by the PV array at the MPP can be calculated by [7]:

\[
P_{mp} = I_{mp} V_{mp}
\]

2.2 Conversion system
The converter and inverter are normally called conversion system. The conversion system together with a control system are employed to allow the entire hybrid MG energy system operate either in islanded mode or in grid-connected mode. When the hybrid MG energy system works in islanded mode, the inverter controller will be switched to voltage control mode to provide a constant voltage to the local loads. While the energy system works in grid connected mode, the inverter controller will be switched to a current controlled mode to provide a preset power to the local loads as well as utility grid if there is extra power [3-4].
An inverter is an electrical device that inverts a sufficient high DC to a desired alternating current (AC), the inverted AC can be at any required voltage level and frequency with the use of appropriate transformers, switching, and control circuits. Three phase DC/AC VSI is a vital components for the hybrid MG energy system. As shown in Fig. 1 the switch is in position 1 during D and in 2 during 1-D, by controlling the duty ratio D it is possible to generate a sinusoidal current in phase with grid line voltage, as long as the input DC voltage sufficiently high [2].

![Three-phase dc/ac voltage source inverter](image1)

In order to simplify the simulation system, the PV array and the boost converter are replaced by a 600V DC voltage source. As shown in Fig. 2 is the Simulink model of PV energy system, implementing the fast monitoring and telecommunication technology.

![Simulink model of the grid connected PV energy system](image2)

3. **Fault current**

Fig. 3 is a demonstration of asymmetrical current becoming symmetrical represents an offset fault current wave [6]. It raises above the horizontal axis considerably more than it goes below for the first few cycles. This wave is offset from or asymmetrical with respect to the horizontal axis. This condition happens in circuits containing reactance which are short-circuited at some time other than when the current is passing through the zero point on cycle. It occurs in one or more phases in all 3-phase circuits. When this happens

![Components of an asymmetrical current waveform](image3)

a DC current is superimposed on top of the AC current causing asymmetry. The DC component actually decays to zero within a short time after the fault occurs. The final decay of the DC component signifies a change from asymmetrical to symmetrical. [5].
This phenomenon can be described by a series connected RL circuit, when the switch is closed, the inductor L will prevent an instantaneous change in current through the circuit. The voltage across the inductor will then be determined by Kirchhoff’s voltage law, or $V=I\cdot R=0V$. The current across the resistor will then begin to increase, while the voltage across the inductor decreases [5].

Therefore, the voltage according to Kirchhoff’s voltage law is

$$v = V_m \sin(\alpha t + \theta) = iR + L \frac{di}{dt}$$  \hspace{1cm} (5)

Solving the first-order differential for $i$ gives

$$i = \frac{V_m}{R} \sin(\alpha t - \tan^{-1} \frac{X}{R}) - \frac{V_m}{R} \sin(\theta - \tan^{-1} \frac{X}{R}) e^{-\frac{tR}{L}} = \frac{V_m}{R}[1 - e^{-\frac{tR}{L}}]$$  \hspace{1cm} (6)

Equation above can be further defined as

$$i_{ac} = i = i_{ac} + i_{dc}$$  \hspace{1cm} (7)

Where

$$i_{ac} = \frac{V_m}{R} \sin(\alpha t - \tan^{-1} \frac{X}{R})$$  \hspace{1cm} (8)

$$i_{dc} = -\frac{V_m}{R} \sin(\theta - \tan^{-1} \frac{X}{R})$$  \hspace{1cm} (9)

In a highly inductive circuit where L is much larger than R, the current is at or near its maximum value when the voltage is zero. Therefore, if the applied voltage waveform is at or near zero when switch is closed, the circuit is required to provide an instantaneous change in current. To provide this instantaneous AC change, a DC of equal and opposite magnitude is produced to maintain the total initial current $I$ at zero, as required by (6). The DC part will decay to zero as a function of the time constant of the circuit, given by $e^{-\frac{tR}{L}}$. The more inductive the circuit, the longer the decay period will be. The components of this current waveform are shown above.

4. Result and Discussion

The simulation was conducted under different solar irradiances. Different battery voltage levels are simulated to test the stability of the system. When the solar irradiation is 400 W/m$^2$, the output power of the PV array is 4.47KW, the output voltage is 223V. If we consider the output current from the battery is 20A, the output voltage will be 223V. The battery is connected to the grid through the inverter, the VSI output current curve is shown in Fig. 4. The phase of the VSI output current is 180 degree with the VSI output voltage, the direction of the current is opposite with inverter voltage, current is back feed from the grid to inverter side.

Fig. 4: VSI output current when battery voltage is223V, 296V, 389V and 595V
When the solar irradiation is 500 W/m² the output power of the PV array is 5.93 KW, the output voltage is 296V, and the output current curve is shown below. When the solar irradiation is 650 W/m² the output power of the PV array is 7.79 KW, the output voltage is 389V, the VSI output current starts flow from the inverter side to the utility grid. The fault current phenomenon gradually vanish, the simulated current curve becoming a sinusoidal waveform. When the solar irradiation is 800 W/m² the output power of the PV array is 9.6 KW, the output voltage is 480V, the simulated current curve is become common as sinusoidal waveform.

5. Conclusion

The grid connect PV energy system was simulated using Matlab Simulink. The input energy is replaced by battery. The inverter output current is monitored, the curve above shows that if the voltage level higher than 400 or equal to 400V, the inverter output current is stable, but if the voltage level is lower than 400V the inverter output current curve shows the unbalance among the three phases. This is mainly caused by the load characteristic of the inverter. When the voltage level is lower than 400V, the grid current will flow back to the inverter side. The PV energy system works as a load, it consumes energy from the utility grid. So it is significant to make sure the PV energy system absorb as much energy as possible from sun irradiation to ensure the sufficient high voltage level of the battery so as to get a stable AC output power. Meanwhile, it is necessary to cut it off from the main grid when PV energy system doesn’t produce sufficient energy and the battery voltage level is lower than the threshold.

6. Acknowledgements

The author would like to acknowledge, with gratitude for the support provided by University Malaysia Pahang.

7. References


