Advanced Materials Research Vols. 805-806 (2013) pp 93-98
© (2013) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.805-806.93

Fault Diagnosis for Building Grid-Connected Photovoltaic System Based on Analysis of Energy Loss

Peng Xu[1, a], Jinming Hou[1,b] and Dengkuo Yuan[1,c]

[1] School of Mechanical Engineering, Tongji University, Shanghai 201804, P. R. China

[a] xupengwb@gmail.com, [b]1130998@tongji.edu.cn, [c]yuandengkuo@126.com

Keywords: PV system; Simulation model; Fault diagnosis; Supervision.

Abstract. The photovoltaic (PV) systems are the most promising options to meet the rapidly increasing energy demand for renewable energy resources development. A simple and well fault diagnosis system can guarantee the normal operation of photovoltaic systems. This paper proposes a simple diagnostic method to tell the operating status of the PV systems by contrasting the simulation parameters and the measured parameters. The diagnostic algorithm uses the irradiance level, the PV modules temperature, the number of PV modules and its output power as the inputs. So, just temperature and irradiance sensors, as well as several power meters are needed in the monitoring system forming part of the fault diagnostic system. The proposed fault detection method has been successfully validated in simulation and experiment.

Introduction

In the new century, as a renewable energy source, the solar photovoltaic (PV) power generation has been researched as a popular topic in the trend of low carbon economy. Large and small scale PV systems have been regarded as one of most promising renewable energy [1]. In the future, more and more PV system will be used in buildings and the application will not be limited to roof but expanded to anywhere expose to sunshine in buildings [2]. In the process of operation, many factors have adverse effect on PV system and result in output value lower than normal, such as degradation of system component, fault of component, dust gathering, sheltering, etc. The diagnosis and alarm corresponding with operation conditions above can decrease the energy loss of abnormal operation; thus decrease the input-output ratio in full life circle of PV system in another way.

Until now, a few researchers have come up with some fault diagnosis methods for PV components and system. For PV components, some researchers made a study of fault diagnosis for PV modules [3], inverter [4], maximum power point tracking [5], etc. For the system, S. K. Firth et al proposed seven faults of PV system and divided them into four categories to diagnose, considering those seven faults can't be fully distinguished by test data [6]. T. Takashima used ground capacity method to diagnose faults of parallel connection module in PV array [7]. A. Choude et al proposed a method of fault diagnosis based on the energy loss of PV array [8]. Y. Yagi et al developed a PV diagnosis method based on data analysis [9]. N. Gokmen proposed a method for diagnosing open circuit and short circuit of a string of PV panels in array [10].

The fault detection and diagnosis (FDD) system can keep the PV system in normal operation. This paper presented a FDD system based on environmental parameters and electric power parameters, which needs less parameters and easy to obtain. The corresponding test bed was established to test and verify this system.

Grid-connected PV System and Data Acquisition System

In the grid-connected PV system, the power generated by PV array was transferred to grid-connected PV inverter, which inverts the direct current (DC) received to alternating current (AC), and provides to the electric equipment or power grid. When the power generated by PV array is not enough, inverter will get the power from grid for itself. And it will transfer redundant electric energy to grid if the power generated is sufficient. The data collection system will collect the environmental parameters (e.g., irradiance, ambient temperature, the temperature of photovoltaic cell) and electric parameters of PV system (e.g., output direct current and voltage of PV array, output alternating current and voltage of inverter). The hardware schematic diagram of whole system is shown in Fig. 1.

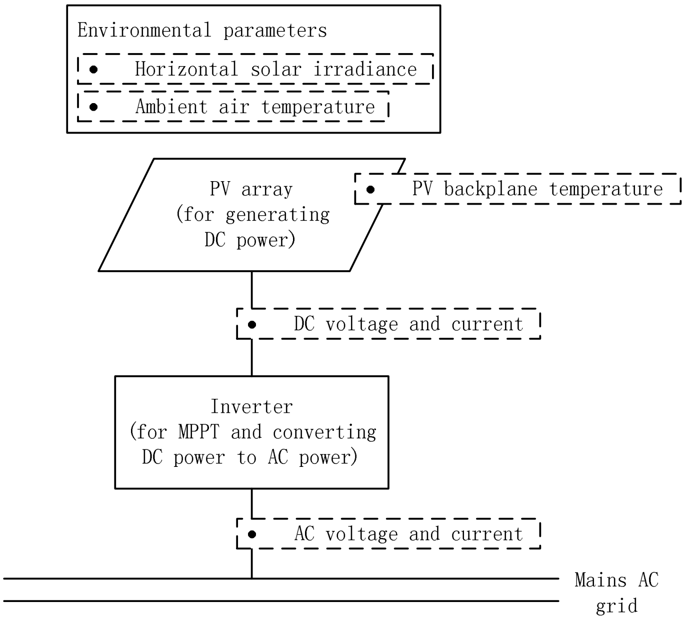

Fig. 1 The hardware schematic diagram of whole PV system

Simulation Model of PV System

Simulation model of PV system consists of model of PV cell, MPPT model, model of inverter and other simulation models, which represents the process of electric power transformation (the power is generated by photovoltaic cells and transferred to alternating current by inverter then accesses the power grid). The simulation model of this system is shown in Fig. 2.

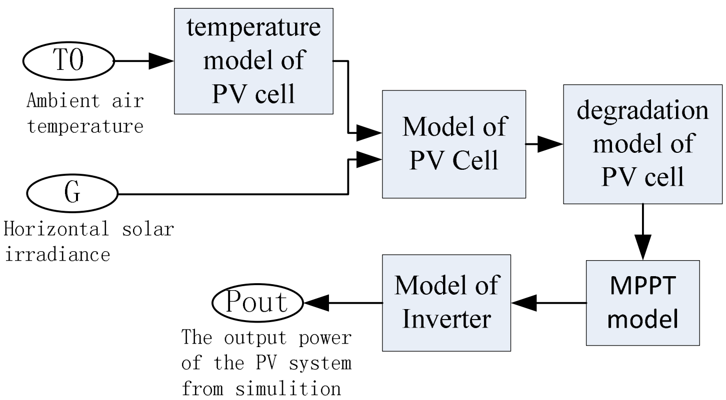

Fig. 2 The simulation model of the whole PV system

Model of PV Cell. The model of PV cell can be established by equivalent circuit based on the physical property of the cell. The common photovoltaic cell equivalent circuits are four-parameter single diode model (low degree of accuracy) [11, 12], five-parameter single diode model (complicated equation and long time for solving) [12, 13] and two-diode model (solution procedure is very difficult and normally needs necessary assumptions to solve) [14]. In this paper, two correction factors are added to traditional four-parameter single diode model, which can obtain output curve of PV cell in specified conditions accurately and quickly.

The mathematical expression of the traditional four-parameter single diode model is

$$I = I_{ph} - I_D = I_{ph} - I_0(\exp(\frac{V + IR_s}{nV_t}) - 1) \quad . \tag{1}$$

Where, I_{ph} is photo-generated current (A), I_o is dark saturation current of diode (A), R_s is module internal series resistance (Ω), n is ideality factor of diode, V_t = k*q/T is thermal voltage of photovoltaic cell (V), where k = 1.381×10^{-23}J/K is Boltzmann's constant, q = 1.602×10^{-19}C is charge of an electron, T is temperature of PV cell (K), N = n*V_t.

In this paper, two correction factors are added to traditional four-parameter single diode model, which can obtain output curve of PV cell in specified conditions accurately and quickly. The difference between model output and measured output could be controlled to be less than 1%. The mathematical expression of four-parameter single diode model with correction factors is

$$I = I_{ph} - I_o(\exp(\frac{V + K \cdot I + I \cdot R_s}{N}) - 1) \quad . \tag{2}$$

where, $K = \frac{V_{mp,348} - V'_{mp,348}}{I_{mp,348} \cdot (348 - 298)} \cdot (T - T_{ref}) \cdot \frac{G}{G_{ref}} = \frac{V_{mp,ref} + 50 \cdot b - V'_{mp,348}}{50 \cdot (I_{mp,ref} - 50 \cdot a)} \cdot (T - T_{ref}) \cdot \frac{G}{G_{ref}}$ is the correction factor for maximum power point; $V'_{mp,348}$ is the measured voltage on the maximum power point when the temperature of photovoltaic module is 348K; the subscript "ref" means the parameter is under the reference state and "mp" means the parameter is on the maximum power point; a is temperature coefficient of short-circuit current, A/K; b is temperature coefficient of open circuit voltage, V/K. Generally, we take the standard test condition as the reference condition, i.e. G_{ref} = 1000W/m^2, T_{ref} = 298K. In this paper, we chose 348K as the benchmark to calculate K, because the maximum test temperature provided by manufacturer of photovoltaic is 348K. And this equation can be revised according to specific circumstances.

In reference condition, relevant data in technical documentation provided by manufactures can be used to calculate parameters of model, such as the open circuit voltage V_{oc}, short-circuit current I_{sc}, voltage and current of maximum power point V_{mp}, I_{mp}, in standard test condition.

When the PV cell doesn't operate in reference condition, the equation below can be used to calculate as an extension of model parameters:

$$I_{sc} = I_{sc,ref} \cdot \frac{G}{G_{ref}} + a(T - T_{ref}) \quad ; \tag{3}$$

$$I_{mp} = I_{mp,ref} \cdot \frac{G}{G_{ref}} - a(T - T_{ref}) \quad ; \tag{4}$$

$$V_{oc} = V_{oc,ref} + b(T - T_{ref}) + M \ln(\frac{G}{G_{ref}}) \quad ; \tag{5}$$

$$V_{mp} = V_{mp,ref} + b(T - T_{ref}) + M \ln(\frac{G}{G_{ref}}) \quad . \tag{6}$$

Where $M = (V_{oc,200} - V_{oc,ref}) / \ln(\frac{G_{200}}{G_{ref}})$ is the correction factor of voltage when the irradiance is changing, $V_{oc,200}$ is the open circuit voltage of PV array when G = 200W/m^2, T=298K.

This extension can be used from PV cell to module and then to array, thus the simulation model of PV array in whole working condition is got and the form of its equation will stay the same.

MPPT model. From the output curve of PV characteristics, we can get the output curve of PV cell in particular environmental condition. There is a maximum output point here, i.e. maximum power point (MPP). The most commonly used algorithms of searching maximum power point are perturbation and observation method and conductance increment method. Perturbation and observation method is used to search the maximum power point in particular environmental condition in this paper.

Model of Inverter. Inverter consumes some power when it works, and the output efficiency will change according to different input power. In this paper, the relationship between output power and input power of inverter is fitted based on efficiency curve provided by manufacturer, which is used to simulate its theoretical output power.

Other Models. Other models are based on other limitation and physical laws of PV components and aim at obtaining more precise simulation. The examples are degradation model of PV cell (represents the influence of degradation in output property of cell), temperature model of PV cell (uses heat transfer method to get more accurate temperature of cell), etc.

Classification and Diagnostic Method for Faults

In this paper, nine common kinds of faults and their diagnostic method are listed here, as shown in Table 1.

Table 1 The faults of PV system and their diagnostic method

Defective parts	Type	Result	Reason	Diagnostic method and its requirement
PV array	1.Short time open circuit	No output in branch or system in short time	system maintenance, transient poor contact in line	Under the condition that the illumination meets the requirement of normal operation ($G>200W/m^2$), when the number of panels out of work, N_{ma} is equal to the number of panels connected in series in the array, ns, the "Fault 1" alarm will be released and recorded from that moment. If the output power is larger than the defined value above, quit this fault and record the starting and ending time of this kind of fault. When the output power sustained almost zero longer than 1 hour, the fault transferred to long time open circuit.
	2. Long time open circuit	No output in branch or system in long time	Component damage, open circuit of branch or line in whole photovoltaic side	When the short time open circuit transfers to long time open circuit, the "Fault 2" alarm will be released and recorded. If the output power is larger than the defined value above, quit this fault and record the starting and ending time of this kind of fault.
	3. Short circuit	Output of branch reduce integral multiples of module or array	Breakdown diode in module or array level, short circuit	Under the condition that the illumination meets the requirement of normal operation ($G>200W/m^2$), when the output power DP is smaller than theoretical value calculated by model, calculate N_{ma} by $PR1=DP/DP0=1-(1/N)*N_{ma}$. If $N_{ma}>0.5$, near a integer(±0.2) but unequal to ns, and values of N calculated during a period of time (5 calculate points) are stabilized near the integer above, the "Fault 3" alarm will be released and recorded.
	4. Periodic Sheltering	Output value lower than theoretical value in the same time domain, Multi MPP	Photovoltaic array self-sheltering or fixed time sheltering by surrounding	Calculate the value of PR1 of whole monitoring time, screen numerical points whose PR1<0.9 in several days (3 days). If the points whose PR1<0.9 in these days is more than setting number (90%), the "Fault 4" alarm will be released and recorded.
	5.Degradation, dust, soiling	Output value lower than ideal value for a long time	Natural aging and dust gathering of PV panel	Calculate the value of PR1 of whole monitoring time, if the values of PR1 are lower than limited scope of normal value (〈0.9) for a long time (1 day), the "Fault 5" alarm will be released and recorded.

Inverter	6.MPPT	Operation point is under the output curve in S,G, but not the MPP	Inverter's MPPT section failure	Calculate the value of PR1, when the values of PR1 are lower than limited scope of normal value (〈0.9), bring output direct voltage value into the photovoltaic model then obtain the output direct voltage value. If the direct output voltage value from calculation and measurement are approximate (±5%), time of duration is beyond the defined scope (5 testing points), the "Fault 6" alarm will be released and recorded.
	7. Energy imbalance	Energy of inverter ends is not balanced	Inverter's inverting section failure	Bring the output power of photovoltaic array into inverter model to get the theoretical value of output power, and calculate PR2, the ratio between AP (measured value of output power) and AP0 (theoretical value of output power). If the value of PR2 is lower than the limited scope of normal value (〈0.9), the "Fault 7" alarm will be released and recorded.
	8.Shut down	Having voltage in DC but no output power in AC	Inverter opened in incorrect time or closed by fault	If the direct voltage can be measured in photovoltaic array, the output power of inverter is almost zero (the measured value of output power AP<=1W), and the time of duration is beyond the defined scope (5 testing points), the "Fault 7" alarm will be released and recorded.
Other	9.Other fault	System output value lower than expectation	Other faults cause the system output value lower than expectation	No faults above can be diagnosed but the system output is lower than expectation

On the basis of type and diagnostic method above, we divided them into time sequence fault and non-time sequence fault, according to the duration of each fault. The time sequence fault includes fault 1, 2, 3, 6, 7, 8 and 9, which uses real time data to diagnose. Fault 4 and 5 belong to non-time sequence fault, which can use historical data to diagnose.

Application and Verification of the Fault Diagnostic Method

We developed a fault diagnostic system based on the fault diagnostic method above in Matlab/Simulink. Tests for proposed fault diagnosis system were conducted in simulation conditions and experimental conditions respectively.

The test in simulation used a PV system combined with a PV array which has 4*2 KC175GHT-2 PV panels and a Sunny Boy 1200 inverter. We tested the 9 faults by giving the diagnostic system the prepared data and the result is that the system can distinguish and show the corresponding fault correctly.

And using the PV test bench we built, we done the experimental test. But we could not do all the 9 fault types, so we tested the fault types from 1 to 5. The result shows that the system can distinguish and show the corresponding fault correctly in the experimental conditions. And the PV test bench we built is combined with a PV array which has 4*2 ENN PV panels, a Sunny Boy 1200 inverter and a data acquisition system.

Acknowledgements

This work was financially supported by the Shanghai Science and Technology Committee, Research project (11PJ1409600) of real-time performance of PV power generation fault diagnostic system (10002360122) and Shanghai ENN Solar Energy Company, project of real-time monitoring of PV power generation facilities and fault diagnosis system (10002450433).

References

[1] McHenry, P. Mark: Energy Policy. Vol. 45 (2012), p. 64

[2] E. Karatepe, T. Hiyama, M. Boztepe, M. Colak: Energy Conversion and Management. Vol. 49 (2008), p. 2037

[3] M.A. Munoz , M.C. Alonso-García, N. Vela, F. Chenlo: Solar Energy. Vol. 85 (2011), p. 2264

[4] T. Sugiura, T. Yamada, H. Nakamura, M. Umeya, K. Sakuta, K. Kurokawa: Solar Energy Materials and Solar Cells. Vol. 75 (2003), p. 767

[5] G. Petrone, G. Spagnuolo, R. Teodorescu, M. Veerachary, M. Vitelli: IEEE Transaction on Industrial Electronics. Vol. 55 (2008), p. 2569

[6] S.K. Firth, K.J. Lomas, S.J. Rees: Solar Energy. Vol. 84 (2010), p. 624

[7] T. Takashima, J. Yamaguchi, M. Ishida: Photovoltaic: Research and Applications. Vol. 16 (2008), p. 669

[8] A. Chouder, S. Silvestre: Energy Conversion and Management. Vol. 51 (2010), p. 1929

[9] Y. Yagi, H. Kishi, R. Hagihara, et al: Solar Energy Materials & Solar Cells. Vol. 75 (2003), p.655

[10] N. Gokmen, E. Karatepe, B. Celik, S. Silvestre: Solar Energy. Vol. 86 (2012), p. 3364

[11] R.P. Vengatesh, S.E. Rajan: Solar Energy. Vol. 85 (2011), p. 1727

[12] A.N. Celik, N. Acikgoz: Applied Energy. Vol. 84 (2007), p. 1

[13] V.L. Brano, A. Orioli, G. Ciulla: Solar Energy Materials and Solar Cells. Vol. 94 (2010), p. 1358

[14] K. Ishaque, Z. Salam, H. Taheri: Solar Energy Materials and Solar Cells. Vol. 95 (2011), p. 586