## Dynamic Characteristics and Graphic Monitoring Design of Photovoltaic Energy Conversion System

KUO-HUA LIU Department of Electrical Engineering Hsiuping Institute of Technology No.11, Gongye Rd., Dali District, Taichung City 41280 TAIWAN ee.kuohua@gmail.com

*Abstract:* - This study explored the dynamic characteristics and monitoring design of the photovoltaic energy conversion system, which is a system model of an independent power supply. This study first established the non-linear differential equation of the system model, linearized the model, and analyzed the eigenvalues and dynamic response of the system using the MATLAB program. The dynamic characteristics of the photovoltaic energy conversion system were obtained from systematic analysis. In addition, this study used the main controller in industrial automation, programmable logic controller (PLC), to monitor the overall system and the electric energy of solar cells. It employed the man-machine interface application program to construct a PLC monitoring system of network graphic monitoring. The personal computer (PC) was connected to the PLC through the RS232 port, and the changes in voltage and current were monitored on the PC display. Finally, the accuracy of the model was verified by the operating points, eigenvalues, and dynamic response.

*Key-Words:* - Dynamic Characteristics, Programmable Logic Controller, Monitoring System, Photovoltaic, Solar Cell, Eigenvalue.

## **1** Introduction

As energy sources become exhausted, society must discover an alternative energy, which must be inexhaustible. At present, the possible practical renewable energy sources include solar power, wind power, fuel cells, geothermal power generation, etc., among which, photovoltaic energy is the most promising. Solar heat and light are the prime power for the diversified ecology of our planet. As the sun continuously transfers energy to the earth, the solar cell power generation is definitely one of the new energy sources with most development potential to achieve pollution-free energy, protect the existing natural environment of the earth, and provide an adequate energy source. The solar power generation has advantages of environmental protection and sustainable resource, as it discharges less of the pollutants of traditional thermal power generation, such as carbon dioxide oxysulfides, nitrogen oxides, and suspended particles. It also protects regional air, water, and soil quality. Moreover, it is almost a zero-pollution energy asset, and has indexed sightseeing economic benefit. As semiconductor manufacturing, electric, and electronic technologies change quickly, the manufacturing cost of solar cells decreases continuously, and its economic value will increase in the future [1-3]. Therefore, how to

develop the photovoltaic energy conversion system at a period lacking new energy is an important topic.

The solar cells have the following advantages: (1) quiet energy converter; (2) structure modularization, easy expansion; (3) efficiency-rated power generation; and (4) low pollution power generation. As solar cells are actively developed in recent years, a high efficiency has been attained, and European countries, the U.S., and Japan have gradually paid attention to them and made policies to promote their applications. At present, there have been many favorable research findings of solar energy, such as the simulation research on the effect of solar cells connected to power grid in parallel [4-6], to PLCbased electric energy management control systems [7-9], and the design and realization of remote control of distributed control systems [10-11].

This study proposes an independent power supply system based on a photovoltaic energy conversion system, as shown in Fig.1. The photovoltaic energy is stored in an battery and converted by a inverter into AC in order to supply power for the load. A PLC electric energy monitoring system of network graphic monitoring is constructed using the PLC and a man-machine interface application program for efficient utilization.



Fig.1 Photovoltaic energy conversion system.

## 2 System Model Configuration

The complete hardware connection of the studied photovoltaic energy conversion containing a photovoltaic battery system, a battery unit, and a DC-to-AC inverter is shown in Fig. 1. The battery unit may store or release the generated renewable energy. An industrial PLC with the RS485/RS422 port combines with multi-functional digital power meter is also shown in Fig. 1. The digital power meters are employed for accessing the measured electrical data of the photovoltaic energy conversion systems. The proposed PLC also connects to a remote personal computer through the RS232 port. The remote computer also uses WPLSoft software to graph the monitoring program and achieve the goal of monitoring reliability and stability. The PLC employed in this paper is DVP16ES2 series of DELTA Company [21-22]. The hardware photo of the PLC is shown in Fig. 2. Fig. 3 shows the framework of the employed system software in this The framework includes data area. paper. foreground program, background program, and application program.



Fig. 2 Hardware photo of the employed PLC.

The main software for the proposed real-time monitoring and control system in this paper includes timely voltage and current monitoring, event detection, information collection, and setup of security system. Associated important functions of the employed software are listed as follows.

- (1) Identification system: This system uses security codes to identify the duty privilege of a user or users.
- (2) Dynamic state of link and real-time data: This function is through monitoring the computer screen. If either user ID or password is wrong or incorrect, the warning page will be displayed on the screen.



Fig. 3 Framework of the employed PLC's system software

The decision-making hardware framework is shown in Fig. 4. The arrangement of the implemented complete hardware is shown in Fig. 5.



Fig. 4 Photo of hardware framework for decisionmaking control.

## **3** System Model

This section introduces the model of a photovoltaic energy conversion system, where the system model is of independent power supply. It deduces the linear and nonlinear mathematical equations of this system model in order to complete the dynamic characteristics of the system.

#### 3.1 Mathematical model of solar cell

The solar cell is a photoelectric semiconductor device that uses sunlight to directly generate power. A semiconductor containing an electric field generates electric power when there is a light source, and the potential difference occurs in the interface by means of such characteristics. The principle of solar power generation is that, when the sunlight irradiates the solar panel, the positively charged holes move towards the p-type region, and the negatively charged electrons move towards the ntype region, thus, electric power is generated. A solar panel is composed of many solar cells, and each solar cell consists of a P-N junction semiconductor that directly converts light energy into electric energy. It is assumed that the solar panel generates an independent current source for a load in sunlight. Fig. 6 shows the equivalent circuit of a solar cell [12], where the is the current of solar energy, junction diode, equivalent series resistance inside material , and parallel resistance , and and are the output current and voltage of solar cell, respectively.



Fig. 5 Photo of the arrangement of the studied complete system.



Fig. 6 Equivalent circuit of solar cell.

The mathematical equation of output current of solar cell is

$$I_{pv} = I_{ph} - I_{sat} \left( e^{\left(\frac{qV_{pv}}{AK_bT}\right)} - 1 \right)$$
(1)

where, q denotes the electronic charge,  $q = 1.602 \times 10^{-19} C$ ,  $K_b$  is Boltzmann's constant,  $K_b = 1.38 \times 10^{-23} J/k$ , T is the solar cell module surface temperature, A is the solar cell module ideal factor, where the range of A is between 1 and 2. The reverse saturation current  $I_{sat}$  of solar cell module is

$$I_{sat} = I_{rr} \left(\frac{T}{T_r}\right)^3 e^{\frac{qE_s}{AK_Q} \left(\frac{1}{T_r} - \frac{1}{T}\right)}$$
(2)

where,  $T_r$  is the reference temperature of the solar cell,  $I_{rr}$  is the reverse saturation current at temperature  $T_r({}^{0}K)$ , and  $E_g$  is the band-gap energy. The photoelectric conversion current  $I_{ph}$  is

$$I_{ph} = GI_{scr} \left( 1 + K_0 \left( T - T_r \right) \right)$$
(3)

where, G is the sunshine intensity  $(kW/m^2)$ ,  $I_{scr}$  is the short-circuit current measured at the baseline value of sunshine amount  $1kW/m^2$ . The mathematical equation of output power can be obtained from Eq. (1)

$$P_{pv} = I_{pv} V_{pv} = I_{ph} V_{pv} - I_{sat} V_{pv} \left( e^{\left(\frac{qV_{pv}}{AK_b T}\right)} - 1 \right)$$
(4)

Kuo-Hua Liu

The graph of the relation between the voltage, current, and power of solar cells and sunshine intensity and temperature changes can be clearly plotted using a mathematical analysis method, which combines Eq.  $(1)\sim(4)$  and changes the sunshine intensity and atmospheric temperature.

#### 3.2 Mathematical model of DC-AC inverter

Fig. 7 shows the equivalent circuit of a DC-AC inverter module, which inverts DC into AC.  $V_I$  is the input voltage of the DC-AC inverter,  $I_I$  is the current of the DC transmission line passing through the inductor. The Input/Output transformation equation of DC-AC inverter is [13-15]:

$$V_I = V_{qi} \cos \gamma_I - \frac{\pi}{6} X_{CI} I_I \tag{5}$$

where,  $V_{qI}$  is the voltage of the AC side of a inverter, and  $\gamma_I$  is the extinction angle of the inverter.



Fig. 7. Equivalent circuit of DC-AC inverter module.

#### **3.3 Mathematical model of battery**

Fig. 8 shows the model of a DC transmission line and battery, the battery model is simulated by connecting a DC voltage source to a small resistance in series.  $V_{DC}$  is the voltage at both ends of an battery,  $r_s$  is the equivalent resistance in series of battery,  $R_R$  and  $R_E$  are the equivalent resistance of the transmission line, and  $L_R$  and  $L_E$  are the equivalent inductance of the transmission line [14-15].



Fig. 8 Equivalent circuit of transmission line and battery

# **3.4 Mathematical model of independent** power supply system

The block diagram of this system model is shown in Fig. 1, which consists of a solar cell, an accumulator, a DC-AC inverter, and loads. The solar cell in this model supplies load power and charges the accumulator, and the loads are resistive loads and inductive loads. According to the aforesaid equivalent circuit diagrams of various models, the nonlinear equations of the overall system can be obtained, as follows.

$$L_R I_R = V_{PV} - R_R I_R - E_D \tag{6}$$

$$C_{DC}E_{D}=I_{R}-I_{I}$$
(7)

$$L_E I_I = E_D - R_E I_I - V_I \tag{8}$$

$$C_L V_L = I_I - I_L \tag{9}$$

$$L_L I_L = V_L - R_L I_L \tag{10}$$

Eqs. (6)~(10) are the nonlinear differential equations of this model, and the state vector in this model is  $X = [I_R, E_D, I_I, I_L, V_L]^T$ .

The equations of linearized photovoltaic cell model can be determined from the linearization procedure of the aforesaid nonlinear equations.

$$L_{R}\hat{I}_{R} = \hat{V}_{R} - R_{R}\hat{I}_{R} - \hat{E}_{D}$$
(11)

$$C_{DC}\hat{E}_{D} = \hat{I}_{R} - \hat{I}_{I}$$
(12)

$$L_{E}\hat{I}_{I} = \hat{E}_{D} - (R_{E} - \frac{\pi}{6}X_{CI})\hat{I}_{I} - V_{L0}\cos\hat{\gamma}_{I} - \cos\gamma_{I0}\hat{V}_{L}$$
(13)

$$C_L \dot{\hat{V}_L} = \hat{I}_I - \hat{I}_L \tag{14}$$

$$L_L \dot{\hat{I}}_L = \hat{V}_L - R_L \hat{I}_L \tag{15}$$

Eqs. (11)~(15) are the equations after system linearization, the state vector  $X_{\Delta} = [\hat{I}_R, \hat{E}_D, \hat{I}_I, \hat{I}_L, \hat{V}_L]^T$ .

## 4 Dynamic Characteristics and Graphic Monitoring Design

According to the results in Table 1, the eigenvalues of the independent power supply circuit of a photovoltaic energy conversion system are in good condition, are in the left half plane, and the system is stable. According to the results in Table 2, the larger the solar cell short-circuit current  $I_{sc}$  is, the larger the output power is, but the smaller the efficiency ( $\eta$ ) is. According to Table 3, the voltage and current at the load end increase as the extinction angle of inverter  $\gamma_I$  increases, thus, the output power increases as angle  $\gamma_I$  is increased. Since the input power is a fixed value, the efficiency increases as angle  $\gamma_I$  is increased.

Once the program in remote computer enters monitoring mode of operation, the user must enter his/her user name (or user ID), password. Fig. 9 shows the security page for user input his/her identification. If either user ID or password is wrong or incorrect, the warning page will be displayed on the screen as shown in Fig. 10. When user's ID and password are both correct, the program will enter main monitoring menu as shown in Fig. 11. The voltage of accumulator, magnitude of current, realtime power of photovoltaic energy can be known, as shown in Fig. 11.

Table 1 System eigenvalues (rad/s)

$\lambda_{1,2}$	-5.89±j206.88
λ <sub>3,4</sub>	-200.22±j45.23
$\lambda_5$	-26.17

I <sub>SC</sub>	1.0	2.0	3.0
I <sub>R</sub>	0.168	0.174	0.182
E <sub>D</sub>	1.123	1.138	1.141
$I_{I}$	0.161	0.163	0.164
$V_{L}$	1.091	1.098	1.106
$I_L$	0.182	0.185	0.189
P <sub>in</sub>	0.831	1.231	1.624
Pout	0.196	0.198	0.199
η	0.152	0.146	0.135

Table 2 Operating point analysis when solar cell short-circuit current  $I_{SC(p,u)}$  changes

Table 3	Operating point analysis when extinction
	angle of inverter $\gamma_{I}$ changes

•		• 1	•
$\gamma_{\rm I}$	12°	15°	18°
I <sub>R</sub>	0.163	0.167	0.171
E <sub>D</sub>	1.154	1.143	1.138
$I_{I}$	0.161	0.165	0.168
$V_{\rm L}$	1.083	1.091	1.211
$I_{L}$	0.181	0.184	0.188
P <sub>in</sub>	0.913	1.241	1.589
Pout	0.197	0.199	0.211
η	0.177	0.182	0.189

Photovoltaic Energy Conversion System
User Name:
Password
The get my pressured

Fig. 9 Password page for user identification.



Fig. 10 Warning page for wrong user input data.

America	
Photovoltaic Energy Conve Storage Battery Voltage 12.08 Photovoltaic Current : 0.48 Photovoltaic Power : 5.64	ersion System (*) [7] [4] (4) (5) (5) (5) (5) (7) (5) (6) (7) (5) (6) (7) (6) (7) (6) (7) (6) (7) (7) (7) (7) (7) (7) (7) (7

Fig. 11 Real-time voltage, current, power diagram.

The dynamic response of an operating point variation, when the system is added with a small interference, is discussed using the deduced nonlinear model. If the system can revert to the original operating point, or reach a new stable operating point when it receives the interference, then it is a stable system. On the contrary, if the system cannot revert to a stable operating point, or diverges when it is added with a small interference, the system is unstable. Fig. 12 shows when t=0.5 s, the instantaneous step will increase the dynamic response simulated by the amount of short-circuit current  $I_{sc}$  1.0 pu of solar cell. It is observed that the system can revert to a new steady-state operating point when it receives a step interference. When  $I_{SC}$  increases instantaneously,  $I_R$ ,  $E_D$ ,  $I_I$ ,  $V_L$  and  $I_L$  will increase to a new steady-state operating point, as shown in Fig. 13-17. Whereas  $\gamma_1$  will decrease to a new steady-state operating point, as shown in Fig. 18. The input power and output power will increase as the  $I_{sc}$  increases, as shown in Fig. 19-20. The efficiency ( $\eta$ ) decreases to a new steady-state value when the interference is added at t=0.5s, as shown in Fig. 21.



Fig. 12 Dynamic response of solar cell short-circuit current.



Fig. 13 Dynamic response of solar cell output current.







Fig. 15 Dynamic response of output current of DC-AC inverter.





Fig. 17 Dynamic response of load current.



Kuo-Hua Liu



Fig. 18 Dynamic response of extinction angle.





Fig. 19 Dynamic response of input power.

Fig. 20 Dynamic response of output power.



## 4 Conclusion

This study discussed the dynamic characteristics of a photovoltaic energy conversion system, which is a system model with an independent power supply type. The conclusions of this paper are as follows.

- (3) Operating points and eigenvalues: The voltage and current values of all nodes of the system, input and output power, and efficiency can be obtained from the analysis of operating points. It is observed from the eigenvalue analysis that all system eigenvalues are in the left half plane, proving that this system is a stable system.
- (4) Graphic monitoring: This study used PLC control to monitor the load system; the changes in the load voltage and current can be clearly observed from a PC in order to timely know the state, power, and total kwh of the accumulator.
- (5) Dynamic response: According to the results of dynamic response, the system can revert to a new steady-state operating point when it receives step interference, further showing that this system is a stable system.

References:

- P. Benner, L. Kazmerski, Photovoltaics Gaining GreaterVisibility, *IEEE Spectrum*, vol. 26, Sep 1999, pp. 34-42.
- [2] D. E. Carlson, Resent Advances in Photovoltaics, Proceedings of the Intersonciety Engineering Conference on Energy Conversion, 1995.
- [3] M. P. Choi, A. Tan, Photovoltaics Demonstration Projects, *Proceedings of EMPD* 98, Vol. 2, 1998, pp. 637-643.
- [4] G. Vachtsevanos and H. Kang, Simulation studies of islanded behavior of grid-connected

photovoltaic systems, *IEEE Transactions on Energy Conversion*, vol. 4, No. 2, June 1989, pp. 177-183.

- [5] S. J. Ranade, N. R. Prasad, S. Omick, and L. F. Kazda, A study of islanding in utility-connected residential photovoltaic systems Part I Models and analytical methods, *IEEE Transactions on Energy Conversion*, Vol. 4, No. 3, September 1989, pp. 436-445.
- [6] G. A. Smith, P. A. Onions, and D. G. Infield, Predicting islanding operation of grid connected PV inverters, *IEE Proceedings*, *Electric Power Applications*, vol. 147, no. 1, 2000, pp. 1-6.
- [7] S. Hughes, PLC control systems for the remote control of cranes and manipulators, *IEE Colloquium on Advances in Programmable Logic Controllers*, 1992, pp. 5/1 -5/4.
- [8] M. Y. Cho and C. W. Huang, Development of PC based energy management system for electrical energy saving of high voltage customer, *Industrial and Commercial Power Systems Technical Conference*, 2001, pp. 7-12.
- [9] A. M. Graham and M. Etezadi-Amoli, Design, implementation, and simulation of a PLC based speed controller using fuzzy logic, *IEEE/PES* 2000 Summer Meeting, vol. 4, 2000, pp. 2475-2480.
- [10] T. Kouthon, M. A. Peraldi, and J. D. Decotignie, Distributing PLC control, *Proceedings of the 1995 IEEE IECON 21st International Conference on*, vol. 2, November 1995, pp. 1614-1619.
- [11] L. Chen and Y. Wang, Design and implementation of a Web-based distributed control system, *Proceedings of the 2002 IEEE Canadian Conference on Electrical and Computer Engineering*, vol. 2, 2002, pp. 681-686.
- [12] B. S. Borowy and Z. M. Salameh, Optimum photovoltaic array size for a hybird wind/PV system, *IEEE/PES 1994 Winter Meeting*, Paper 94 WM 120-6 EC.
- [13] L. Wang, A comparative study of damping schemes on damping generator oscillations, *IEEE Transactions on Power Systems*, vol. 8, no. 2, 1993, pp. 613-619.
- [14] Y. Y. Hsu and L. Wang, Damping of a parallel ac-dc power system using PID power system stabilizers and rectifier current regulators, *IEEE Transactions on Energy Conversion*, vol. 3, no. 3, 1988, pp. 540-549.
- [15] Y. Y. Hsu and L. Wang, Modal control design of an HVDC system for the damping of

subsynchronous oscillations, *IEE Proceedings, Part C*, vol. 136, no. 2, 1989, pp. 76-86.

- [16] L. Wang, J.-H. Chang, W.-M Lin, C.-X. Yu, K.-H. Liu, Real-Time Remote Monitoring and Control of a Hybrid Generation/Energy Storage System Using Internet and Programmable Logic Controller, *Proceeding of 27th ROC* symposium on Electrical Power Engineering, 2006, pp. PB3.6.
- [17] L. Wang, K.-H. Liu, Transient performance and stability analysis of a hybrid grid-connected wind/PV system, 2004 IEEE PES Power Systems Conference and Exposition, Vol. 2, 2004, pp. 795-801.
- [18] L. Wang and K.-H. Liu, Implementation of a web-based real-time monitoring and control system for a hybrid wind-PV-battery renewable energy system, *Proceeding of International Conference on Intelligent System Applications* to Power (ISAP 2007), 2007, pp. 182-187.
- [19] Ned Mohan, Tore M. Undeland, William P. Robbins, *Power Electronic*, Second Edition, John Wiley & Sons, Inc., New York, 1989.
- [20] Gilbert M. Masters, *Renewable and Efficient Electric Power Systems*, John Wiley & Sons, New Jersey, 2004.
- [21] DELTA, *DVP-PLC-Program OPERATION MANUAL*, February 2010.
- [22] DELTA, *DVP-Screen-Editor OPERATION MANUAL*, March 2007.
- [23] Stephen J. Chapman, *MATLAB Programming* for Engineers 3e, Thomson Inc, 2005.
- [24] J. A. Gow, and C. D. Manning, Development of a Model for Photovoltaic Arrays Suitable for Use in Simulation Studies of Solar Energy Conversion Systems, *Proceeding of International Conference on Power Electronics and Variable Speed Drives*, No. 429, Sep.1996, pp. 69-74.
- [25] Cruz Martins, D. Demonti, R. Barbi, and I., Usage of The Solar Energy From the Photovoltaic Panels for the Generation of Electrical Energy, *Telecommunication Energy Conference*, June 1999, pp. 6-9.
- [26] S. Suresh Babu and S. Palanichamy, PC Based Controller for Utility Interconnected Photovoltaic Power Conversion Systems, Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, Vol.1, Jan. 1996, pp. 101-106.
- [27] U. Herrmann and H. G. Langer, Low Cost DC to AC Converter for Photovoltaic Power Conversion in Residential Applications,

Proceedings of IEEE PESC '93, June 1993, pp. 588-594.

- [28] S. J. Chiang, K. T. Chang, and C. Y. Yen, Residential Photovoltaic Energy Storage System, *IEEE Trans. on Industrial Electronics*, Vo1.45, No. 3, June 1998, pp.385-394.
- [29] R. J. Hacker, D. K. Munro, and J. M. Thomycroft, Small Grid-Connected Solar Photovoltaic Generators in the UK, *International Conference on Renewable Energy-clean Power 2001*, 1993, pp. 61-66.
- [30] Allen M. Barnett, Solar Electric Power for a Batter Tomorrow, *Conference Record of IEEE Photovoltaic Specialists Conference*, May 1996,pp.1-8.
- [31] Choi Mong Ping and Andrew Tan, Photovoltaics Demonstration Projects, *Proceedings of IEEE EMPD '98*, Vol. 2, 1998, pp.637–643.
- [32] E. J. Byres, Designing secure networks for process control, *IEEE Industry Applications Magazine*, vol. 6, no. 1, September/October 2000, pp. 33-39.
- [33] R. Kiessling, A battery model for monitoring of and corrective action on lead-acid EV batteries, *Proceedings of the Ninth Annual Battery Conference on Applications and Advances*, January 1994, pp. 191-193.
- [34] T. Shimizu, M. Hirakata, T. Kamezawa, and H. Watanabe, Generation control circuit for photovoltaic modules, *IEEE Trans. On Power Electronics*, Vol. 16, Issue 3, May 2001, pp. 293-300.

Kuo-Hua Liu