Dynamic Characteristics and Graphic Monitoring Design of Photovoltaic Energy Conversion System

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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 PLC-based 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.
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 paper. The framework includes data area, foreground program, background program, and application program.

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.
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 n-type 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 \( i \) is the current of solar energy, junction diode, equivalent series resistance inside material \( r_s \), and parallel resistance \( r_p \), and \( v_b \) and \( v_a \) are the output current and voltage of solar cell, respectively.

Fig. 4 Photo of hardware framework for decision-making control.

Fig. 5 Photo of the arrangement of the studied complete system.
The mathematical equation of output current of solar cell is

\[ I_{p\text{v}} = I_{ph} - I_{sat} \left( e^{\frac{qV_{pv}}{AKT_{pv}}} - 1 \right) \]  

(1)

where, \( q \) denotes the electronic charge, \( q = 1.602 \times 10^{-19} \text{C} \), \( K_b \) is Boltzmann's constant, \( K_b = 1.38 \times 10^{-23} \text{J/K} \), \( T \) 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

\[ I_{sat} = I_{rr} \left( \frac{T}{T_r} \right)^3 \left( \frac{T}{T_r} \right) e^{\frac{qE_g}{AK} \left( \frac{T}{T_r} - 1 \right)} \]  

(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

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

(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)

\[ P_{pv} = I_{pv}V_{pv} = I_{ph}V_{pv} - I_{sat}V_{pv} \left( e^{\frac{qV_{pv}}{AKT_{pv}}} - 1 \right) \]  

(4)

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)–(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]:

\[ V_i = V_{ql} \cos \gamma_i - \frac{\pi}{6} X_c I_i \]  

(5)

where, \( V_{ql} \) is the voltage of the AC side of a inverter, and \( \gamma_i \) is the extinction angle of the inverter.
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.

\[ L_R \dot{I}_R = V_R - R_R I_R - E_D \]  \hspace{1cm} (6)

\[ C_D \dot{E}_D = I_R - I_L \]  \hspace{1cm} (7)

\[ L_R \dot{I}_L = E_D - R_L I_L - V_L \]  \hspace{1cm} (8)

\[ C_I \dot{V}_L = I_L - I_L \]  \hspace{1cm} (9)

\[ L_L \dot{I}_L = V_L - R_L I_L \]  \hspace{1cm} (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.

\[ L_R \dot{I}_R = \dot{V}_R - R_R \dot{I}_R - \hat{E}_D \]  \hspace{1cm} (11)

\[ C_D \dot{E}_D = \dot{I}_R - \dot{I}_I \]  \hspace{1cm} (12)

\[ \dot{E}_D = -(R_R - \pi X) \dot{I}_I - V_{I0} \cos \hat{\gamma}_I - \cos \gamma_0 \hat{V}_L \]  \hspace{1cm} (13)

\[ C_I \dot{V}_L = \dot{I}_I - \dot{I}_L \]  \hspace{1cm} (14)

\[ L_L \dot{I}_L = \hat{V}_L - R_L \hat{I}_L \]  \hspace{1cm} (15)

Eqs. (11)–(15) are the equations after system linearization, the state vector \( X = [\dot{I}_R, \dot{E}_D, \dot{I}_I, \dot{I}_L, \dot{V}_L]^T \).

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, real-time power of photovoltaic energy can be known, as shown in Fig. 11.
### Table 2 Operating point analysis when solar cell short-circuit current $I_{SC(p.u.)}$ changes

<table>
<thead>
<tr>
<th>$I_{SC}$</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_R$</td>
<td>0.168</td>
<td>0.174</td>
<td>0.182</td>
</tr>
<tr>
<td>$E_D$</td>
<td>1.123</td>
<td>1.138</td>
<td>1.141</td>
</tr>
<tr>
<td>$I_I$</td>
<td>0.161</td>
<td>0.163</td>
<td>0.164</td>
</tr>
<tr>
<td>$V_L$</td>
<td>1.091</td>
<td>1.098</td>
<td>1.106</td>
</tr>
<tr>
<td>$I_L$</td>
<td>0.182</td>
<td>0.185</td>
<td>0.189</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>0.831</td>
<td>1.231</td>
<td>1.624</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>0.196</td>
<td>0.198</td>
<td>0.199</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.152</td>
<td>0.146</td>
<td>0.135</td>
</tr>
</tbody>
</table>

### Table 3 Operating point analysis when extinction angle of inverter $\gamma_i$ changes

<table>
<thead>
<tr>
<th>$\gamma_i$</th>
<th>12°</th>
<th>15°</th>
<th>18°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_R$</td>
<td>0.163</td>
<td>0.167</td>
<td>0.171</td>
</tr>
<tr>
<td>$E_D$</td>
<td>1.154</td>
<td>1.143</td>
<td>1.138</td>
</tr>
<tr>
<td>$I_I$</td>
<td>0.161</td>
<td>0.165</td>
<td>0.168</td>
</tr>
<tr>
<td>$V_L$</td>
<td>1.083</td>
<td>1.091</td>
<td>1.211</td>
</tr>
<tr>
<td>$I_L$</td>
<td>0.181</td>
<td>0.184</td>
<td>0.188</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>0.913</td>
<td>1.241</td>
<td>1.589</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>0.197</td>
<td>0.199</td>
<td>0.211</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.177</td>
<td>0.182</td>
<td>0.189</td>
</tr>
</tbody>
</table>

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 $\gamma_i$ 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 $t=0.5$ s, 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. 14 Dynamic response of battery.

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

Fig. 16 Dynamic response of load voltage.

Fig. 17 Dynamic response of load current.
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.

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