An evaluation method of PV systems

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Abstract

Data evaluation methods have wide adaptations, such as feedbacks to PV system operation management and design. The authors have already developed sophisticated verification method (SV method) of PV systems, which is a simple evaluation method to identify six kinds of system loss rates using basic information and simple four measurable data. This time, the authors introduced quality diagnosis to our previous model for compensating the measurement errors in field data, and improved the algorithm of the model. Consequently, validity of the evaluation result became better than the previous model. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Japan Quality Assurance Organization (JQA) has arranged operational data from hundreds of PV systems, which were partially funded by New Energy and Industrial Technology Development Organization (NEDO) under the “Field Test (FT) Program”. Data evaluation methods have wide adaptations, such as feedbacks to PV system employment management and design. In this study, sophisticated verification method (SV method) of PV systems has been developed as a simple evaluation method. This method estimates loss factors of PV systems by field operational data. Outlines and analysis result of the SV method have already been
presented in some papers by the authors (e.g. [1–6]). In this paper, improved and extended algorithms of the SV method in order to produce more reliable and robust estimates are described.

2. Outline of the SV method

The SV method classifies loss factors of PV system operation into six kinds of system losses [shading effect, losses due to incident angle, load mismatch, efficiency decrease by temperature, inverter losses and other losses] using system specifications, such as latitude (°), longitude (°), inclination angle (°), azimuth (°), system rating: \( P_{\text{AS}} \) (kW) and temperature coefficient: \( \alpha_{P_{\text{max}}} \) (W/°C), and measured operational data (inclined-plane irradiation: \( H_{\text{A}} \) (kWh/m²), array output: \( E_{\text{A}} \) (kWh), system output: \( E_{\text{P}} \) (kWh) and module temperature: \( T_{\text{C}} \) (°C)]. Before SV method analysis, diagnosis

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**Nomenclature**

- \( P_{\text{AS}} \): system rating (kW)
- \( G_{\text{S}} \): irradiance on STC [=1.0 (kW/m²)] (kW/m²)
- \( \alpha_{P_{\text{max}}} \): temperature coefficient (W/°C)
- \( H_{\text{A}} \): inclined-plane irradiation (kWh/m²)
- \( E_{\text{A}} \): array output (kWh)
- \( E_{\text{P}} \): system output (kWh)
- \( T_{\text{C}} \): module temperature (°C)
- \( E_{\text{AT}} \): array output converts into cell temperature on STC [=25(°C)] (kWh)
- \( E_{\text{NM}} \): array output on no mismatch line (kWh)
- \( E_{\text{II}} \): array output on independent incident angle line (kWh)
- \( E_{\text{AS}} \): ideal energy production (kWh)
- \( L_{\text{HS}} \): shading losses (kWh)
- \( L_{\text{PI}} \): incident-angle-dependent losses (kWh)
- \( L_{\text{PM}} \): load mismatch losses (kWh)
- \( L_{\text{PT}} \): efficiency decrease by temperature (kWh)
- \( L_{\text{C}} \): inverter losses (kWh)
- \( L_{\text{PO}} \): other losses (kWh)
- \( R_{\text{HS}} \): shading ratio (dimensionless number)
- \( R_{\text{PI}} \): incident-angle-dependent ratio (dimensionless number)
- \( R_{\text{g}} \): diffused component (dimensionless number)
- \( \theta \): incident angle (°)
- \( m_{\text{NM}} \): variable for making “no mismatch line” (dimensionless number)
- \( m_{\text{II}} \): variable for making “independence incident angle line” (dimensionless number)
- \( m_{\text{PI}} \): variable for making “incident-angle-dependent rate curve” (dimensionless number)
of quality of irradiation data is carried out, and the outlying observations and missing data are compensated by external weather observations.

3. The SV method analysis

3.1. Principle of loss rate definitions on monthly basis

This method adopts the model by appropriate assumption based on experience. It is the essence of the SV method to make each rate of losses for a month using each model and the measured data for every site. The principle of analysis of the SV method is shown in Fig. 1. The principle of shading rate and incident-angle-dependent rate definition monthly are described as follows. Firstly, some monthly basis are made by the measured data. Secondly, principles of some loss rates are defined using the measured monthly basis.

3.2. Making no mismatch line

A scattered graph as shown in Fig. 2 also gives very important information. An upper straight line corresponds to ideal energy production: \( E_{AS} \). Scattered dots are all the hourly data \( E_{AT} \) [it converts into cell temperature: 25(°C) of standard test condition]. A lower straight line is drawn as the upper envelope of scattered points by changing \( m_{NM} \) in Eq. (1). The line is called “no mismatch line”: \( E_{NM} \) means the most efficient performance and no shading, no mismatch and not due to incident-angle dependence.

\[
E_{NM} = m_{NM} P_{AS} \frac{H_A}{G_S}
\]  

\( E_{NM} \) = no mismatch line
\( E_{AS} \) = Maximum array output
\( E_{AT} \) = Ideal energy production
\( E_{NM} \) is the most efficient performance.

Fig. 1. Principle of analysis of the SV method.
3.3. Making maximum array output estimates

In order to apply for the principle of shading rate, maximum array output curve: $E_{A_{\text{max}}}$ is made, which is shown by the measured curve in Fig. 3. It has only extracted $E_{A_{\text{AT}}}$ of the maximum data for every hour, which contain shading effects.

3.4. Theoretical array output estimates

When shading effects are identified, The measured curve is compared to the theoretical curve that has no effect on shading. Theoretical array output curve is obtained as follows. $E_{\text{NM}}$ calculated from “no mismatch line” using $H_A$ corresponds
to \( E_{A \text{ max}} \) each hour. And the envelope is adjusted to fit as it may pass along the second \( E_{A \text{ max}} \). This is shown in the theoretical curve in Fig. 3.

3.5. Principle of shading rate definition for a month

The principle of shading rate definition for a month has the following assumption. The shading should be the shadow from obstacles such as building, etc. There needs to be a day with fine weather in a month one day at least. There is at least one datum that has no losses of the shading, load mismatch, and incidence-angle-dependent among the data for a month. Shading effects are identified for the above assumption using the measured curve and the following procedure. The gap between \( E_{A \text{ max}} \) and \( E_{A \text{ th}} \) for every hour is assumed to be shading effect interrupting a part for direct irradiance. Apparently, the effect of shading can be recognized from 6:00 to 11:00 as shown in Fig. 3. If the diffusion component is assumed 20% that is on a standard fine day because \( E_{A \text{ max}} \) is close to a fine weather day, Eq. (2) can calculate the shading rate. It is considered that no shading takes place for the diffused component:

\[
R_{\text{HS}} = \frac{(E_{A \text{ max}} - 0.2E_{A \text{ th}})}{0.8E_{A \text{ th}}}. \tag{2}
\]

3.6. Principle of incident-angle-dependent rate definition for a month

It is known that \( E_{A \text{ T}} \) and \( H_{A} \) are not proportionally related due to the incidence angle but their curves fall for a while from the straight line relation in a small range of \( H_{A} \). Therefore, a lower curve is drawn by changing \( m_{II} \) in Eq. (3). The curve is called “independence incident angle line”: \( E_{II} \) means almost not being due to incidence angle. (refer to Fig. 3).

\[
E_{II} = (1 + m_{II})H_{A} - m_{II}\{1 - \exp(-8H_{A})\}. \tag{3}
\]

\( E_{II} \), \( E_{NM} \) and the incident angle corresponding to hourly \( h_{A} \) is determined, and the maximum ratio of \( E_{II} \) and \( E_{NM} \) is extracted for every incident angle The curve is adjusted to fit scattered points by changing \( m_{PI} \) in Eq. (4). The envelope shows the incident-angle-dependent rate of loss by for every incident angle: \( R_{PI} \) (refer to Fig. 4):

\[
R_{PI} = m_{PI}\left(\frac{1}{\cos \theta} - 1\right). \tag{4}
\]

3.7. Principle of losses identification on hourly basis

Efficiency decrease by temperature and inverter losses and other losses hourly are simply calculated by Eqs. (8) and (9). Other hourly losses are identified by Eqs. (5)–(7) and 10 are defined by each loss rates and a diffused component: \( r_{g} \).
3.8. Hourly shading losses identification

Losses by shading are identified from the following using the fact that $r_{HS}$ and $r_g$ for each hour are only a part of direct irradiation:

$$l_{HS} = \left\{ (1 - r_g) h_A P_{AS}\right\} (1 - r_{HS}).$$ (5)

3.9. Hourly incidence-angle-dependent losses identification

Incident-angle-dependent losses are identified from the following equation using hourly $r_{PI}$ and $l_{HS}$ in consideration of the fact that they are only a part of the direct irradiation containing the shading effect:

$$l_{PI} = \left\{ (1 - r_g) h_A P_{AS} - l_{HS}\right\} (1 - r_{PI}).$$ (6)

3.10. Hourly load mismatch losses identification

It is assumed that the difference of $e_{NM}$ and $e_{AT}$ corresponding to $h_A$ contain $l_{HS}$, $l_{PI}$ and load mismatch losses: $l_{PM}$. Losses by load mismatch are identified from the following Eq. (7) using each loss:

$$l_{PM} = (e_{NM} - l_{HS} - l_{PI}) - e_{AT}.$$ (7)

3.11. Calculation of efficiency decrease by temperature

Efficiency decrease by temperature: $l_{PT}$ are identified from the following equation using temperature coefficient: $a_{P_{max}}$ peculiar to a module:

$$l_{PT} = \frac{a_{P_{max}}(25 - t_C)}{1 + a_{P_{max}}(t_C - 25)} e_A.$$ (8)
3.12. Calculation of losses by inverter

Losses by inverter efficiency are calculated from the following equation according to the difference of $e_A$ and $e_P$:

$$l_C = e_A - e_P.$$  \(9\)

3.13. Other losses identification

Other losses are the undissociating factors that may consist of array circuit losses, soiling on module surface and system rating is more insufficient than a noted board, etc. These are the differences between $e_{AS}$ and $e_{NM}$ corresponding to $h_A$. It can be identified from the following equation:

$$l_{PO} = e_{AS} - e_{NM}.$$  \(10\)

4. Analysis results

4.1. Compensation factor and the loss rate

The SV method was evaluated by losses: $l_X$, compensation factors: $k_X$, and loss ratios: $\lambda_X$. Compensation factors are coefficient based on the parameter analyzing method [8], and an output ratio to the input in each loss process. Loss ratios are defined as the ratio of the rate for which each loss occurs to the system input. The relation between $l_X$, $k_X$, and $\lambda_X$ is shown below

$$k_X = \frac{e_X^{\text{out}}}{e_X^{\text{in}}}.$$  \(11\)

$$\lambda_X = \frac{l_X}{P_{AS} h_A/G_s}.$$  \(12\)

4.2. Comparison with fisheye photograph analysis

Shading losses analysis using fisheye photographs have been also developed by another group in the author’s organizations in order to identify with the shading factor [9]. The comparison with the SV method and the fisheye photograph analysis analyzed the data from a 70 kW PV system in AIST Tsukuba for two years. This result is shown in Fig. 5. There are differences in the range of values between SV method’s estimation and fisheye photograph analysis’s estimation, but the trend of the time series is almost the same. The difference of the range was likely caused by the difference in treatment diffuse irradiation.
4.3. An evaluation result for NEDO FT systems

As a part of FT, NEDO has installed around 260 PV systems over Japan since FY1992. The average of parameters was estimated by the SV method for four fiscal years FY1995 to FY1999, as shown in Fig. 6. To validate the data out of the actually monitored total of 525 sites only 421 sites are chosen. The major loss of PV systems is clarified by Field Test project, which is loss by load mismatch and others.

5. Conclusions

The SV method developed at this study has established the fundamental model. The measurement errors in field data have been able to be compensated by introducing quality diagnosis, and the algorithm of this method had been improved; therefore, evaluation results have become better than the previous model, and establish the evaluation method of PV systems. According to the SV method, very
useful information is easily obtainable to improve the performance of PV systems in
the market, and evaluation result is used to improve system reliability.

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References

Ohshiro, Tamon Matsuo, Toshio Katagiri, Extended performance analysis of 70 systems in Japanese
Otani, Kazunori Fukusawa, Sophisticated verification of simple monitored data for Japanese Field
Test Program, WCPEC-2nd, Second World Conference on Photovoltaic Energy Conversion, Vienna,
[3] Kosuke Kurokawa, Realistic values of various parameters for PV system design, World Renewable
clear-day pattern obtained from hourly maximum irradiance data, PVSEC-11th, 11th International
residential PV systems and their monitoring by citizen-oriented efforts in Japan, 16th European
[6] Kosuke Kurokawa, Realistic PV performance values obtained by a number of grid-connected systems
[7] P. Schaub, A. Mermoud, O. Guisan, evaluation of the different losses involved in two photovoltaic
Amsterdam, 1994.
[8] Motonobu Yukawa, Kosuke Kurokawa, Research and development of evaluation technology of
shading loss of photovoltaic systems, EuroSun98, The Second ISES-Europe Solar Congress, Portoroz,