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REALISTIC PV PERFORMANCE VALUES OBTAINED BY A NUMBER OF GRID-CONNECTED SYSTEMS IN JAPAN

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ABSTRACT

The authors have been analyzing performance data observed at a number of PV systems, which were constructed by NEDO's "Field Test Project". Although monitored data are taken by a quite ordinary procedure with 4 measured points, Pmax mismatch factor and shading factor can be identified additionally according to the Sophisticated Verification (SV) method developed by the authors. While further modification is still ongoing, array facing any orientation became acceptable by the present version.

The method is summarized as follows:

- System performance ratio K by ordinary formula.
- Power conditioner efficiency K_C by definition.
- Temperature effect K_{PT} on efficiency decrease by ordinary formula, but including array temperature estimation from ambient temperature (due to specification of the Field Test.)
- Maximum irradiance and array output values extracted from each hourly zone during 1 month are fitted by theoretical clear-day pattern.
- Separation of shading effect K_{HS} by observing dips on the extracted maximum pattern.
- Identification of matching factor K_{PM} on array output by removing the shading results.

As a realistic example, SV method is applied to data taken from 104 systems in the Japanese Field Test Project. The mean system performance ratio K in FY'97 was 71.6 % (104 systems).

1. INTRODUCTION

The evaluation of PV systems seems to be very important in order to attain the diffusion of more reliable PV technologies for the future. Not all but some of already installed systems carries monitoring equipments and their data may be obtainable. In Japan all the 180 systems in the Field Test Project provide monitoring devices. 100 systems of around 20,000 roof-top systems are observed by telemetering. Although the conversion efficiency of a photovoltaic module can clearly measured according to standard in-door test procedures, it dose not mean actual operational ability under outdoor conditions. Meteorological conditions vary from place to place. At least, irradiation and ambient temperature have to be known when one wants to evaluate output energy to be generated by a PV system at a certain site. In addition, conversion efficiency may be reduced to a certain level because of various site conditions and system specifications. In fact this might be a troublesome problem. To ease these circumstances, the authors propose advanced approaches to verify additional realistic parameters from ordinary operational data. The method is called SV (Sophisticated Verification) method. Several modifications have been added to the originally proposed procedures (K.Kurokawa, et al., 1997 and 1998) so that shading effect can be effectively identified for an array having an arbitrary orientation angle. Actual field examples are also given for better understanding of system performances.

2. PRINCIPLE OF SHADING IDENTIFICATION BY SV METHOD

A PV system is monitored by a simple data acquisition system when necessary. Typical kinds of data are hourly in-plane irradiation, PV array temperature, array output power, power conditioner output and power from utility. These data can be utilized to obtain system parameters such as system performance ratio K, cell temperature factor K_{PT}, power conditioner circuit factor K_C by a simple calculation normally other useful parameters can be identified in addition, *i.e.*, shading factor K_{HS}, load mismatching factor K_{PM} and other array factor K_{PO}. The identification of these additional parameters has been quite difficult so far. So is it even by a specially planned monitoring method.

At first the principle of shading effect detection is identified by 2 step processes as follows:

(i) Irradiance pattern on a specific solar day representing a given month is calculated for each hour by a theoretical model considering array orientation and inclination angles, hourly monitored data for a certain site are plotted keeping hourly relation. It makes a kind of scattered plot. Looking at a maximum value for each hour as a fine-day pattern for the month, the scale of the given theoretical day pattern is adjusted to fit them as an envelope.

(ii) Supposing that the influence of a shadow doesn't change during the same month so much, it observed on the extracted maximum values can be as a dip compared with the fit fine-day curve.

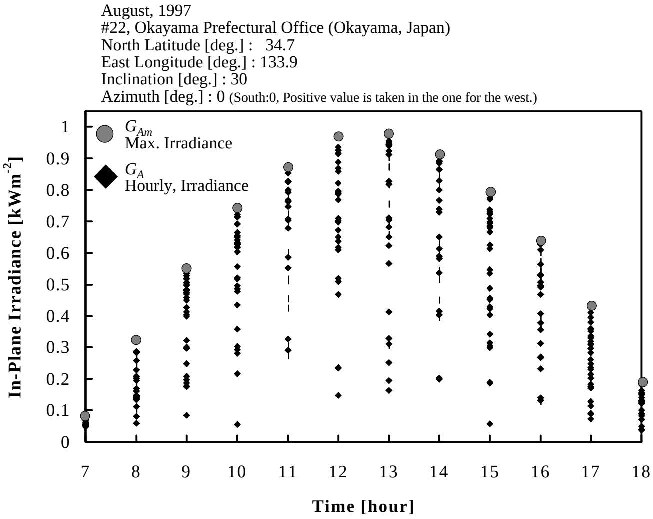

Fig.1 An example of extraction of clear-day pattern

For example, **Fig.1** shows all the hourly irradiance data for a specific month. Each maximum point is taken from each time zone as an envelope of clear-day, which is indicated by a solid circle. This envelope is fit by theoretical irradiance pattern: $G_{Ath}=t^{1/\cos Z}\, G_0 \cos Z + G_d$ in the case of a south-facing array. In this equation, t is transmittance; Z denotes azimuth angle; G_0 corresponds to solar constant; G_d is a diffused component of irradiance. The diffused component on a clear-sky day is estimated 20 % of global irradiance according to a known model. If it is assumed that a shadow on an array does not vary every day in a same month, a maximum value extracted for shaded time zone can not exceed the shaded level of a clear day in this month. Therefore, a level of dip from a theoretical clear curve can be easily observed. Quite the same procedure can also be applied to hourly array output power scatted plotting. If the shading is observed both on irradiance curve and array output curve for a same time zone, this is named “full shading”. If the shading is seen only on the array output curve, it is treated as “partial shading”. It means that a shadow exists only on a radiometer, but not on an array. On the contrary, the case of a shadow only on a radiometer is considered as “quasi-shading”. This is not a shadow on a PV array and monitored irradiance data have to be corrected by removing detected shading effect. This procedure looks a little complicated, but the effective identification of shading effect on PV system performance becomes possible. There seems to be few methods to detect the shading except for this approach at the moment.

Figure 2 gives a typical example of the shading effect that was observed in July 1997 by Kotohira Water Treatment Plant. This system faces 30° west from the south. As a preparation, a top curve E_{ASmax} is calculated by using a clear-day irradiance and array rated output (P_{AS}). E_{Ath} is estimated by applying direct/diffuse separation (Erbs, et al., 1982) to theoretical global, horizontal irradiance by Perez. Then, the scale of curve E_{ASmax} is adjusted so as to fit the array output maximum values for each hourly period. A shading factor (K_{HS}) detected in array output maximum values E_{Am} for each hourly period. As an envelope, this fitting is shown as mE_{ASmax}. Apparently, the effect of shading can be recognized from 15:00 to 18:00 as shown in the graph. In this case, the difference in the point E_{Am} and the point E_{Ath} above the curve E_{ASmax} is caused by the influence of shading. If a diffused component of clear-day irradiance is assumed 20 %, a shading factor can be calculated by "$K_{HS} = (E_{Am}-0.2E_{Ath}) / 0.8E_{Ath}$". It is considered that no shading takes place for the diffused component. Estimation of value m is explained to find a maximum value of m by an iterative algorithm so that any extracted maximum values, E_{Am} do not exceed an estimated curve at any points.

The vertical axis of **Fig.2** corresponds to hourly array output energy at standard cell temperature 25 °C.

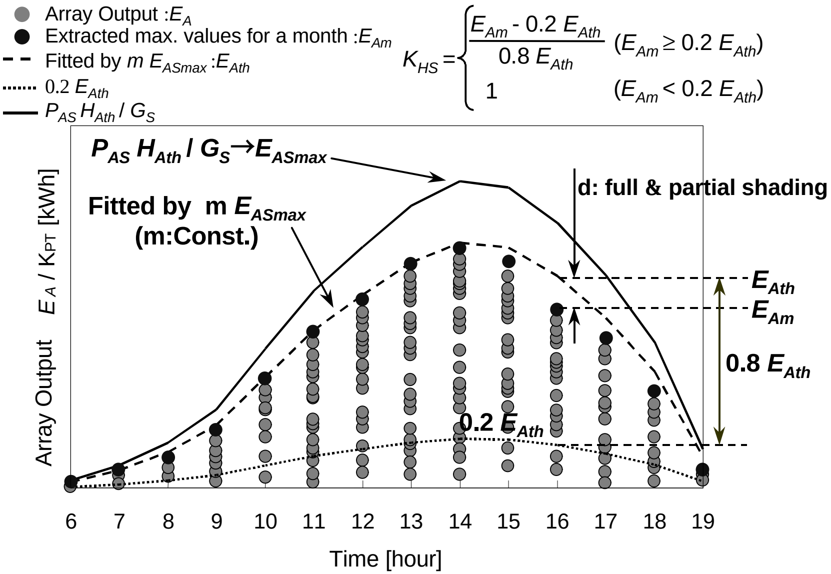

Fig.2 Fitting of clear-day power pattern and separation of shading

The hourly shading factor is shown in **Fig.3**. This is demonstrating the change of the shading factor in course of time on June 30, 1997 by the Kotohira Plant. The previous **Fig.2** corresponds to the same day. Although shading factor was 1 from 6:00 to 11:00, it varied as time passed by. This shows the validity of the shading evaluation by the SV method.

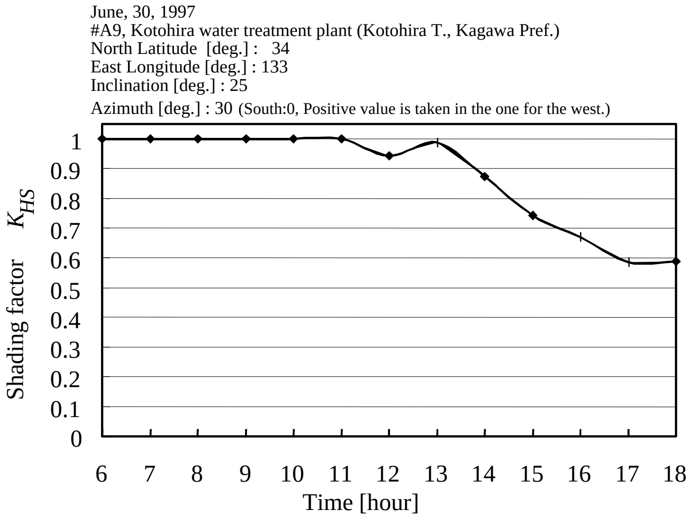

Fig.3 Shading Factor – Time [1^3 K_{HS} ^{3}0]

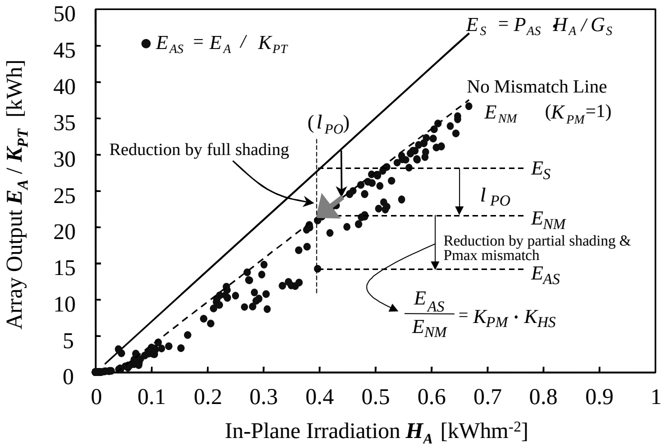

Fig.4 Identification of other array factor K_{PO} and load mismatching factor K_{PM}

3. Pmax MISMATCH IDENTIFICATION

A scattered graph as shown in **Fig.4** also gives very important information. An upper straight line corresponds to ideal energy production by array with its capacity P_{AS} under irradiation H_A. Scattered dots are all the hourly data divided by temperature correction factor K_{PT}. A lower straight line is drawn as the upper envelope of scattered points. This means the most efficient performance in actual operation during a month and no mismatch is assumed along this line $\therefore$(K_{PM}=1). Practically the lower line can be drawn by the following procedure. With respect to all the hourly data, the first straight line is drawn by the regression. After that, the data that are located above the first line are utilized for the second regression. The similar processing is repeated three times to get an envelope line in the **Fig.4**.

It means K_{PM}<1 and/or partial shading when the scattered data are located below this line. For grid-connected inverters with K_{PM}<1, it may be considered that MPPT does not work well or that inverters suppress their ability due to some controlling necessity.

According to shading analysis written previously, if shading effect is observed, shading factor is estimated so that direct, normal sunlight is reduced in proportion to the shading ratio which is identified by the procedure as shown in **Fig.4**. Then, the remaining part of E_{NM}-E_{AS} is thought to be Pmax mismatch component. The difference l_{PO} between the upper and lower straight lines given by E_S-E_{NM} may consist of other array losses such as soiling on module surface, incident-angle-dependent optical losses, array circuit unbalances losses, etc.. Some data indicated that the incident-angle-dependent losses are playing main role.

4. STATISTCAL RESULTS OF 104 PV SYSTEMS BY SV METHOD

Under the Government Basic Guideline for New Energy Introduction, NEDO (New Energy and Industrial Technology Development Organization) has installed 180 PV systems of the total capacity of 4,960kW over Japan since FY1992. Those systems have been being monitored by ordinary, simple data acquisition systems. To demonstrate the applicability of the new SV method to actually monitored data, 104 systems are chosen as a part of the Field Test (FT) Project.

The average value of in-plane irradiation H_A was estimated 1343 kWhm^{-2}/y for 104 sites in FY 1997. This is in the same range as the Japanese average of 1300-1400 kWhm^{-2}/y. Though the irradiation of 4 sites were below 1000 kWhm^{-2}/y, it may occur due to shaded site conditions and some faults in monitoring systems. The average of system yield Y_P of 1007 h/y is the same level as generally spoken in Japan. The average of system performance ratio K was measured as 71.6 % in FY 1997 (104 systems). 75.0 % in FY1996 (71 systems). The peak distribution of K is observed in the class of 70-80 % in each year. **Figures.5 and 6** show the histograms of basic system parameters such as inverter losses l_C and efficiency decrease by temperature l_{PT} on the annual basis for 104 sites. **Fig.7-9** give additional 3 results by SV method: *i.e.*, shading losses l_{HS}, load mismatch losses l_{PM} and other array losses l_{PO}. After all, "$K+l_{HS}+l_{PO}+l_{PT}+l_{PM}+l_C$" becomes 100 %. As shown in **Fig.5**, the inverter losses of 6.8 % is considered excellent. At least, inverter efficiency can be calculated very definitely because both the input and output energy values are monitored directly by Field Test specification. In the **Fig.6**, the array efficiency decrease by temperature of 2.0 % is believed reasonable for whole the year. So-called representative array temperature throughout year is said to range from 15 to 20 °C up over annual average ambient temperature. Roughly speaking, the annual average temperature is around 10 °C over Japan. The evaluated results are well explained by this condition. 19 systems indicated the shading losses of 6 to 10 % and 5 systems of 10 to 14 % as shown in the **Fig.7**. Other 80 systems gave relatively low shading effects. The average was 4.7 % of shading factor. It is possible to reduce this loss if siting conditions are carefully checked in advance. The load mismatch losses are demonstrated in **Fig.8**. The average of 4.7 % is considered so significant. 23 % of all systems are showing worse than 6 % and nearly 3 % are operating with 10 % losses or worse.

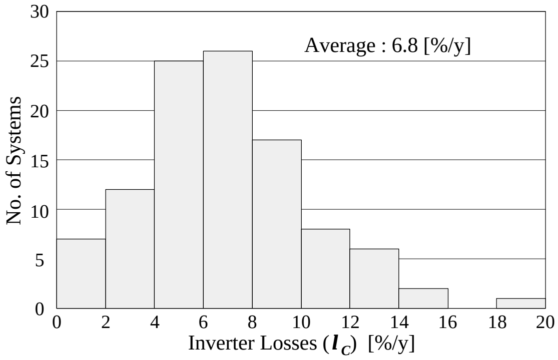

Fig.5 Inverter losses of various systems in FT

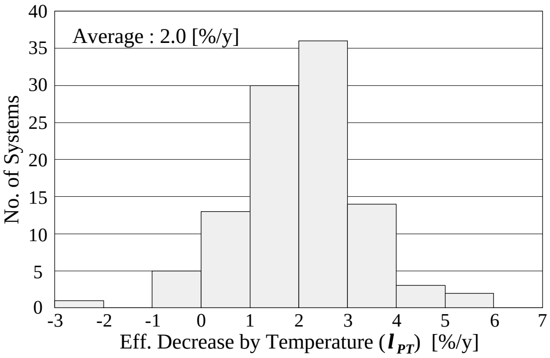

Fig.6 Efficiency decrease by temperature of various systems in FT Project

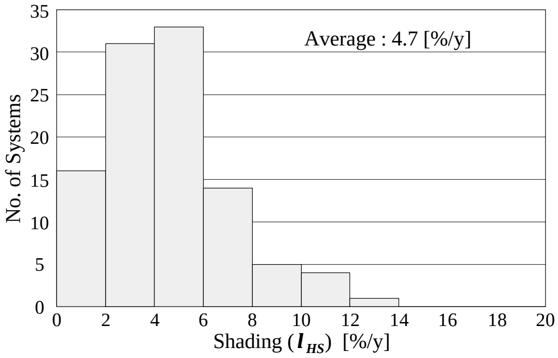

Fig.7 Shading losses of various system in FT

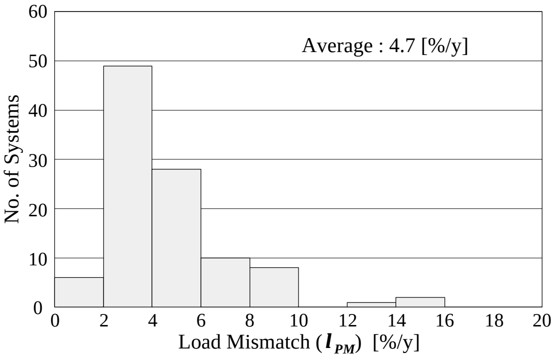

Fig.8 Load mismatch of various systems in FT

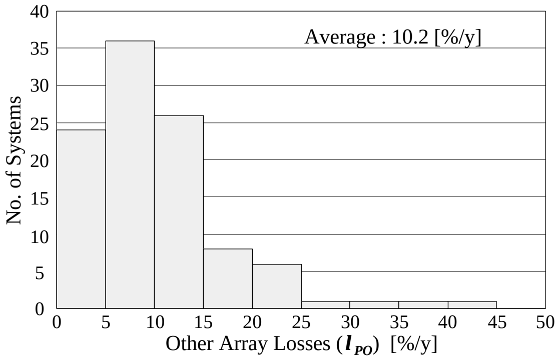

Fig.9 Other array losses of various systems in FT Project

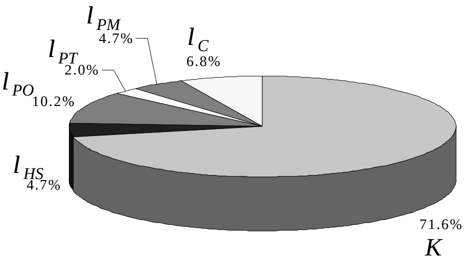

Fig.10 Average loss parameters in the FT Project FY1997 Data

The average of other array losses becomes 10.2 % in the **Fig.9**. Although l_{PO} includes soiling on module surface, incident-angle-dependent reflection losses, array circuit unbalances and losses, in principle, the incident-angle-dependent losses are believed to be major parameter by the other work of authors (K.Kurokawa, et al, 1999). The value, 10.2 % is the most significant figure in 1997 data. It was estimated in 1996 for 71 systems. The value is 6.9 %. This may be caused by degradation of PV array subsystems or some failures in monitoring equipments, most likely due to radiometer troubles. It is felt that the reliability of raw data has to be checked very urgently.

Figure.10 gives the quick summary of the average of all the parameters, which have been analyzed by the new SV method for 104 systems in the Japanese Field Test Project.

5. CONCLUSIONS

By SV (Sophisticated Verification) method the authors presented an actual evaluation example in the Field Test Project. The method is based on a little clever principle in order to utilize very valuable monitored data in actual systems as far as possible. The original version proposed in 1997 has been being modified. This time the procedure has been improved for accepting any orientation angles and some other items. This seems to give very reliable results of shading effect and Pmax mismatch by using very ordinary data monitored in actual PV systems. According to the SV method, very useful information is easily obtainable to improve the performance of PV systems on the market.

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