SOPHISTICATED VERIFICATION OF SIMPLE MONITORED DATA FOR JAPANESE FIELD TEST PROGRAM

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ABSTRACT: A new method is proposed to verify detailed system parameters from ordinary, monitored data. PV system performance data are normally taken by data acquisition system for the evaluation of long-term energy performance. By using monitored data, calculation is made to know major system parameters such as input radiant energy, output electrical energy, system yield (equivalent operated hours), system performance ratio and so on. The authors have developed sophisticated verification procedures (SV method), where system performance ratio $\boldsymbol{K}$, power conditioner efficiency $\boldsymbol{K_C}$, array temperature factor $\boldsymbol{K_{PT}}$, shading factor $\boldsymbol{K_{HS}}$, load matching factor $\boldsymbol{K_{PM}}$ and other array parameter $\boldsymbol{K_{PO}}$ can be identified explicitly by only 4 monitored points with other externally available information. Especially, time series data verification process can produce more realistic results of shading and mismatch losses respectively. As a realistic example, SV method is applied to data taken from 71 systems in the Japanese Field Test Project. It is understood by this examination that there may be some problems in load matching factor commonly because of the lack of well developed MPPT function in power conditioning. Significant shading effects are also often observed.
Keyword: Monitoring – 1: Performance –2: Evaluation –3:

1. INTRODUCTION

Although the conversion efficiency of a photovoltaic cell can clearly measured according to standard test procedures, it does not mean 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 have been troublesome problems. The authors clarify theoretical background to define system parameters and propose a new method to verify various realistic parameters from ordinary operational data. The method is applied to data from the Japanese Field Test Program. Field Test systems have been evaluated so far with the ordinary method by the same authors[1],[2]. From now, the new method brings additional knowledge to the Program helpfully.

2. PARAMETER DEFINTIONS

Table 1 gives fundamental equations necessary for system sizing and evaluation. The first equation (1) shows energy balance between generated energy and consumed one. The right-hand side is given by incident solar energy

Table 1 Fundamental Equations for System Sizing and Evaluation

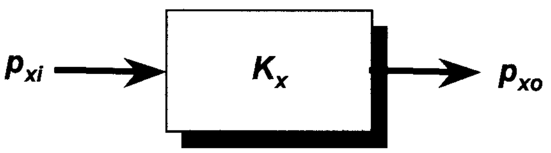
Fundamental Equations	Parameter Definitions
<Energy balance> $H_A \cdot A \cdot \eta_{PS} \cdot K = E_L \cdot D_P \cdot R$ .....(1)	H_A: in-plane irradiation ($kWhm^{-2}$)
<PV efficiency definition> $\eta_{PS} = P_{AS} / (G_S \cdot A)$ .....(2)	A: array area (m^2)
<Sizing> $P_{AS} = \dfrac{E_L \cdot D_P \cdot R}{(H_A / G_S) \cdot K}$ ....(3)	η_{PS}: PV efficiency at STC
<Generated electricity> $E_P = P_{AS} \cdot (H_A / G_S) \cdot K$ ....(4)	K: performance ratio
$= P_{AS} \cdot Y_H \cdot K = P_{AS} \cdot Y_P$ ....(5)	E_L: load energy consumption (kWh)
<Performance Evaluation> $Y_H = H_A / G_S$ ....(6)	D_P: solar energy dependence
$Y_P = E_P / P_{AS}$ ...(7)	R: design redundancy
$K = \dfrac{E_P}{P_{AS} \cdot (H_A / G_S)} = \dfrac{Y_P}{Y_H}$ ...(8)	P_{AS}: array output at STC (kW)
	G_S: reference irradiance ($=1kWm^{-2}$)
	E_P: system generated electricity (kWh)
	Y_H: equivalent sunshine hours (h)
	Y_P: system yield (h)

$H_A \cdot A$, photovoltaic conversion efficiency η_{PS} at the standard test condition (STC) and other efficiency K found in an actual PV system (normally K<1). The left-hand side is evaluated by considering load energy consumption E_L, dependence D_P of a PV system in the presence of other back-up energy and redundancies R for future load increase, safety margin, etc..

Applying Conversion efficiency η_{PS} (2) to (1), PV array output power P_{AS} at STC is calculated by (3). This becomes quite helpful when PV array size is specified according to a given load consumption. Energy E_p generated by a PV system is evaluated by (4) for a specified array output capacity P_{AS}. Sometimes, equivalent sunshine hours Y_H and system yield Y_P, which are respectively defined by (7) and (8), are used to give E_p as shown in (5). When a PV system is monitored, system performance ratio is evaluated by (9), which is induced from (4).

System performance ratio K is the most convenient value since it is normalized by site irradiation and system size. However, it is not a single parameter but consists of various parameters as follows [3]:

- K_H: irradiation modification factor - caused by shadow, soiling,
- K_{PH}: incident angle dependent factor - due to module glass surface reflection,
- K_{PT}: cell temperature factor - because of negative temperature coefficient of P_{max},
- K_{PA}: array circuit factor - consisting of series-connected module mismatch and wiring resistive losses,
- K_{PM}: load matching factor - caused by mismatch operation apart from P_{max} point,
- K_B: battery circuit factor - including battery and its peripheral losses,
- K_C: power conditioner circuit factor - including power conditioner and its peripheral losses.



$$K_x = \frac{E_{xo}}{E_{xi}} = \frac{\int_\tau p_{xo}\, d\tau}{\int_\tau p_{xi}\, d\tau} \neq \frac{p_{xo}}{p_{xi}}$$

Figure 1: General definition of system parameters

The parameters listed above are not all the parameters which can be considered theoretically but the major parameters which apparently affect system performance ratio K in actual PV systems. When these parameters are evaluated, it is notified that they are calculated as energy ratio, not as power ratio. If the input and output powers of a given component X are denoted p_{xi} and p_{xo} ,. parameter K_x is defined by the ratio of 2 integrals as indicated in Fig.1.

3. SV EVALUATION METHOD OF MONITORED DATA AND ITS PRINCIPLE

A PV system is monitored by a simple data acquisition system when necessary. Typical kinds of data are hourly in-plane irradiance, PV array temperature, array output power, power conditioner output and power from utility for a utility connected system. By using these data, several energy values are calculated on monthly basis or annual basis, *i.e.*, in-plane irradiation, array output energy, PV system output energy, energies from and to utility separately. In addition, these energy data can be utilized to obtain system parameters such as system performance ratio K, array performance ratio $K_A(=K_P+K_H)$, cell temperature factor K_{PT} and power conditioner circuit factor K_C.

At this time the evaluation of other detailed parameters has become possible by SV (Sophisticated Verification) procedure. In contrast with this, the ordinary procedure described above is named OV (Ordinary Verification) procedure in this article. According to SV method, shading factor K_{HS}, load matching factor K_{PM}, other array factor K_{PO} can be estimated additionally. K_{HS} is a part of K_H. K_{PO} includes incident angle dependent factor K_{PH} and array circuit factor K_{PA} as well as losses induced by soiling on module surface. 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 described here. Proposed procedures are 2 step processes as follows:

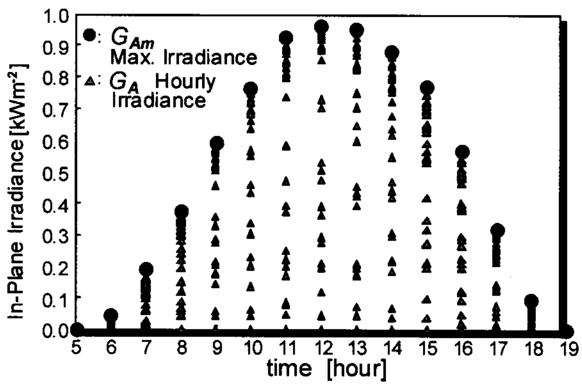


Figure 2: An example of extraction of clear-day pattern

(i) A daily irradiance profile on a clear day is formulated for a specific month by utilizing hourly irradiation data for the month.

(ii) Assuming that shading effect does not vary so much during a same month, the formulated pattern includes shadows on a clear day apparently.

For example, Fig.2 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 fitted by theoretical irradiance pattern : $G_{Ath} = \tau^{1/\cos Z} G_0 \cos Z + G_d$, as shown in Fig.3. In this equation, τ 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 in Japan.

If shading is assumed to exist every day almost in the same way during the month, maximum values for a specific hour cannot exceed a shaded level of a clear day. Therefore, a certain level of dip from the theoretical clear day curve can be easily observed on the envelope. This is also illustrated in Fig.3. This shadow observed on irradiance curve is named "full shading". Coincidentally,

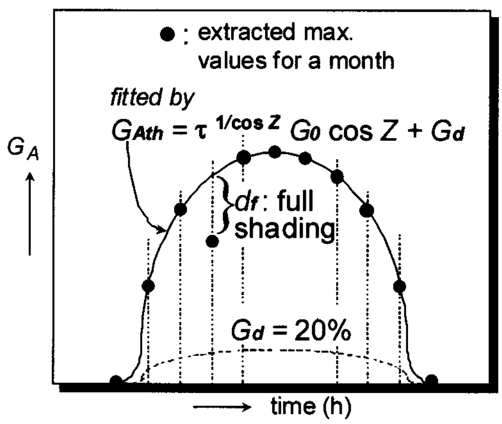


Figure 3: fitting of clear-day pattern and separation of shading

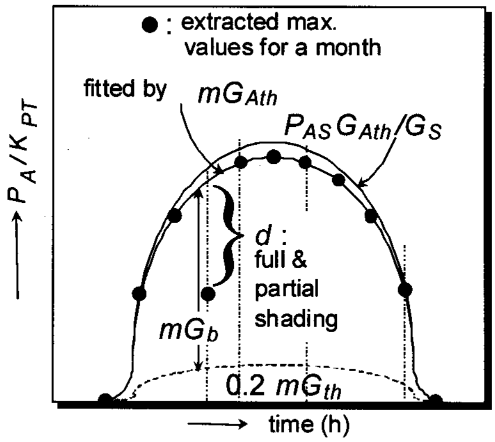


Figure 4: fitting of clear-day power pattern and separation of shading

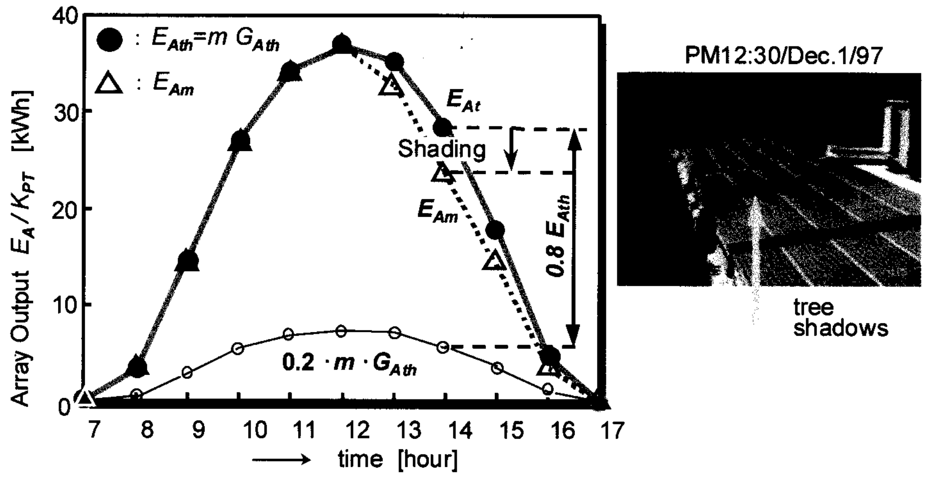


Figure 5: A typical example of identification of shading effect

the same kind of clear-day curve including shadow can also be formed by using array output power data. The clear-sky power pattern may contain "partial shading", which means that shadow exists on a part of PV array surface, but not on a radiometer. When the both surfaces are shaded, this becomes full shading. If only a radiometer is shaded, this is false and not a shading problem for PV systems. The power data may also be additionally affected by so-called mismatch effect. It is naturally omitted by the extraction of hourly maximum values because the mismatch hardly occurs on a clear day.

Figure 5 gives a typical example of the shading effect which was observed in December 1997 by 70kW Tsukuba AIST Guest House system. A dotted line with triangular points is formed by hourly maximum values of array output energy during this month. A solid line denoted by solid circular points is analogous to the clear-day pattern fitted by the theoretical irradiance as an envelope for triangular points. From 13:00 to 16:00, shading effect is apparently identified as shown in the graph.

A scattered graph as shown in Fig.6 also gives very important information. Horizontal axis shows all the data of hourly in-plane irradiation during the same month. Vertical axis corresponds to hourly array output energy at standard cell temperature 25°C. 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 actually most efficient performance and no mismatch is assumed along this line, *i.e.*, $K_{PM} \approx 0$.

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 which are located above the first line are utilized for the second regression. Similar processing are repeated for three times to obtain the envelope line in Fig.6. When data are located below this line, it means $K_{PM} \neq 0$ and/or partial shading. For grid-connected inverters with $K_{PM} \neq 0$, it is considered that MPPT does not work well.

According to shading analysis written previously, if shading effect is observed, shading factor K_{HS} 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.6. Then, the remaining part of E_{NM} -E_{AS} is considered to be Pmax mismatch component. The difference λ_{PO} between both the upper and lower straight lines such as E_S -E_{NM} is supposed to consist of the following other array losses: soiling on module surface, incident-angle-dependent reflection losses, array circuit losses and mismatch, etc.. Some data indicated that the

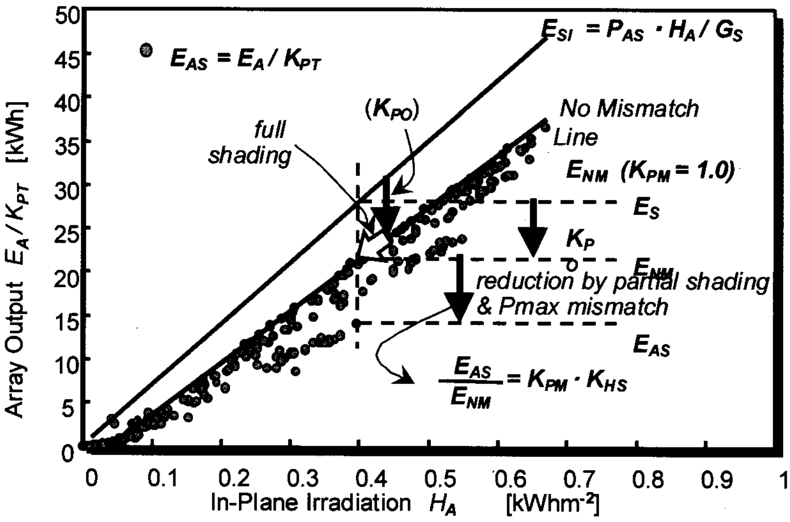


Figure 6: Identification of other array factor K_{PO} and load matching factor K_{PM}

incident-angle-dependent reflection losses are playing main role.

4. FIELD TEST EVALUATION BY SV METHOD

Under the Japanese Government Basic Guidelines for the new energy introduction, NEDO (New Energy Development and Industrial Technology Organization) has installed 180 PV sites having the total capacity of 4,960kW over Japan since FY1992. Those systems have been being monitored by ordinary, simple data acquisition systems. The authors made a first attempt of more detailed system parameter separation by using such limited points of data, as reported by [1] and [2]. Moreover, a new method of sophisticated verification procedures have been developed recently.

To demonstrate the applicability of the new SV method to actually monitored data, 71 systems shown in Fig.7 are chosen as a part of the Field Test Program. Overall procedures to verify the data are illustrated in Fig.8. While monitoring specification is quite ordinary and simple, obtainable results are so precise and would become very helpful to give guidelines for improving system performances. Figures 9-13 show the histograms of basic system parameters such as in-plane irradiation, system yield, system performance ratio, inverter losses and efficiency decrease by temperature on the annual basis for 71 systems. The ordinary verification method gives these 5 parameters only. Figs. 14-16 are extra 3 results by SV method: *i.e.*, shading losses, load mismatch losses and other array losses.

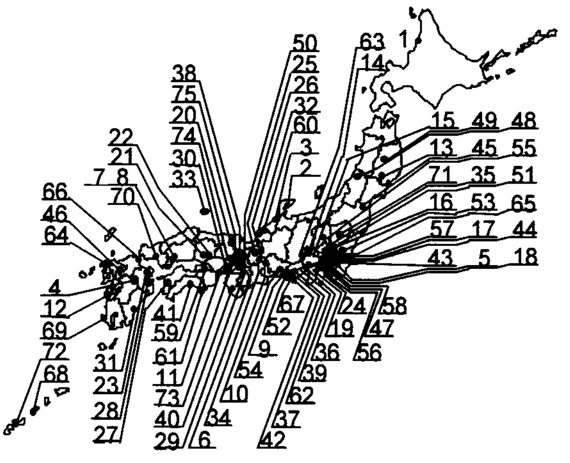


Figure 7: Location of Field Test sites

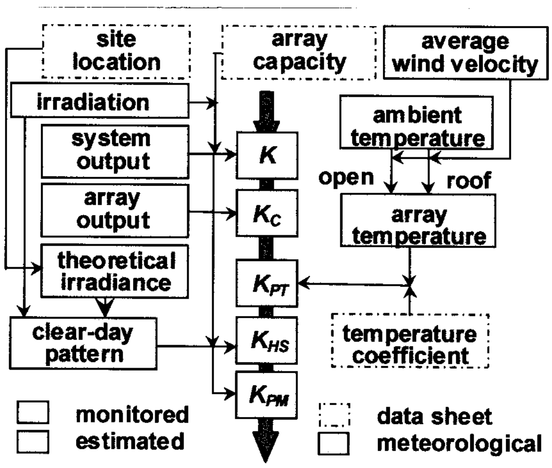


Figure 8: Overall SV procedures in Field Test Projects

The average value of in-plane irradiation was estimated 1173 kWhm^{-2}/y for 71 sites in FY1996 as shown in Fig.9. This is lower than the Japanese average of 1300-1400 kWhm^{-2}/year, which are widely believed. Irradiation classes below 1000 kWhm^{-2}/y may occur due to shaded site conditions and some faults in monitoring systems. The average system yield of 915 h/year in Fig.10 was also relatively low although it is much higher than values reported for the German 1000 roof project. The average system performance ratio of 75 % in Fig.11 is not high or not low. Since the ratio is the most independent parameter regardless of irradiation level and system size, its deviation looks smaller than other major parameters.

As shown in Fig.12, the inverter losses of 6.9% is considered excellent. At least, inverter efficiency can be

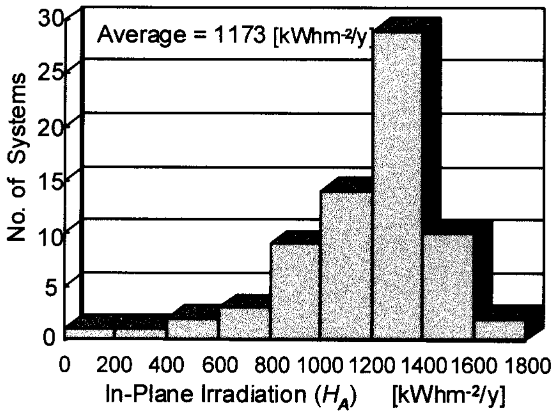


Figure 9: In-plane irradiation at the sites of Field Test Project

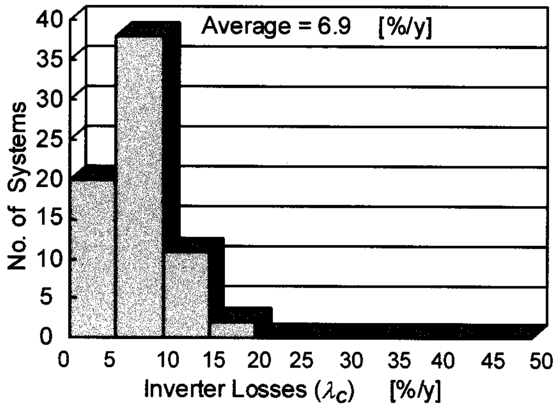


Figure 12: Inverter losses of various systems in Field Test Project

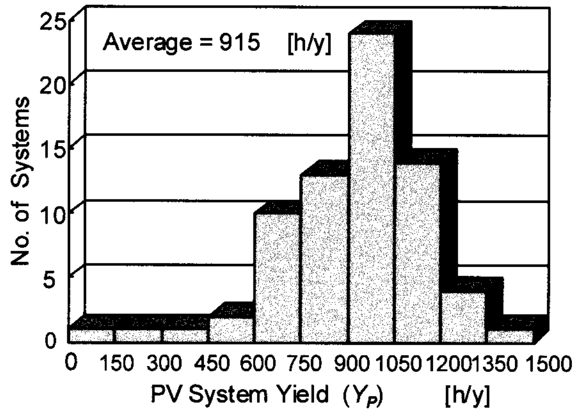


Figure 10: System yield of various systems in Field Test Project

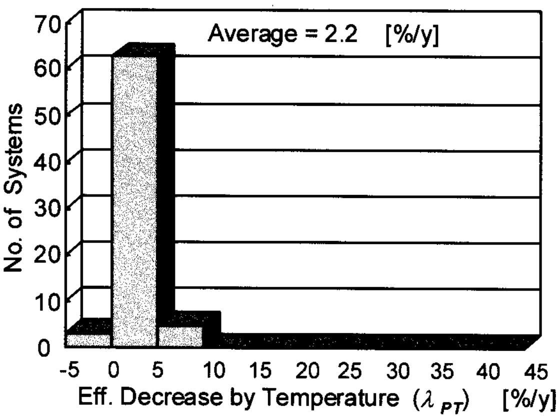


Figure 13: Efficiency decrease by temperature of various systems in Field Test Project

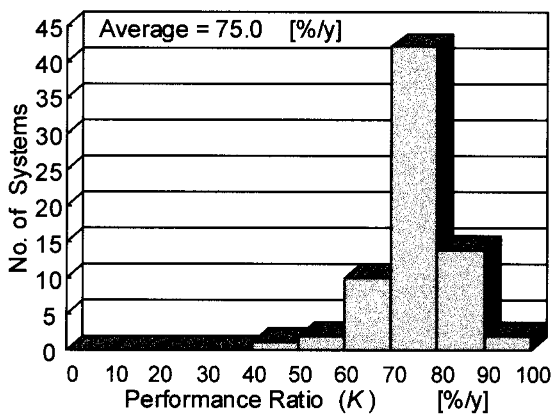


Figure 11: System performance ratio of various systems in Field Test Project

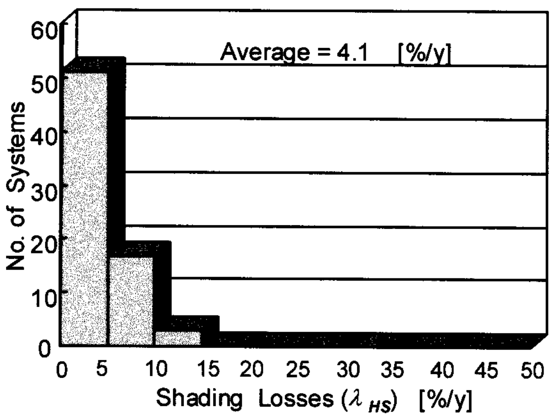


Figure 14: Shading losses of various systems in Field Test Project

calculated very definitely because the both input and output energy values are monitored directly in general. In Fig.13, the array efficiency decrease by temperature of 2.2% is believed very reasonable. So-called representative array temperature through 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.

7 systems indicated the shading losses of 5 to 10% and 3 systems of 10 to 15% as shown in Fig.14. Other 51 systems gave relatively low shading effects. The average was 4.1%. It is possible to reduce this loss, but siting conditions have to be carefully checked in advance. Too much attention to this item may reduce a chance of introducing a large number of PV systems into civilized zones. The load mismatch losses are demonstrated in Fig.15. The average of 5.1% is considered so significant.

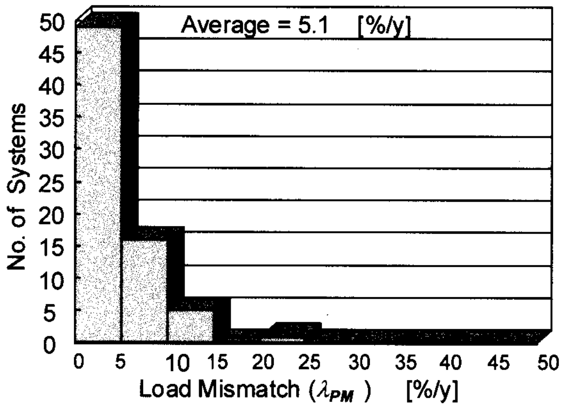


Figure 15: Load mismatch of various systems in Field Test Project

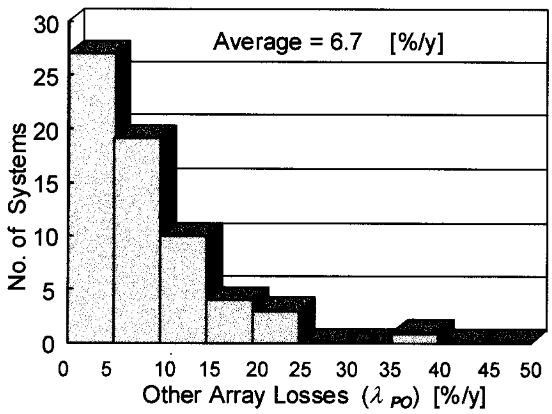


Figure 16: Other array losses of various systems in Field Test Project

30% of all systems are showing worse than 5% and nearly 10% are operating with 10% losses or worse. The worst case was 20% more. It is thought that MPPT has to be improved very much. The average of other array losses became 6.7% in Fig.16. Although this is caused by soiling on module surface, incident-angle-dependent reflection losses, array circuit losses and mismatch, etc., in principle, the incident-angle-dependent losses are believed to be major parameter by the other work of the authors. 6.7% is not so negligible, but the incident-angle-dependent

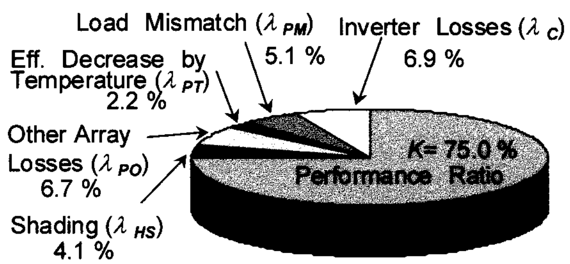


Figure 17: Various loss parameters in the Field Test Project / FY1996 Data

reflection losses cannot be easily reduced. This statistics is also showing large deviation. This may be caused by low inclination arrays or some of other reasons listed above.

Figure 17 gives the quick summary of the averages of all the parameters which have been analyzed by the new SV procedures for 71 systems in the Japanese Field Test Program.

5. CONCLUSIONS

The authors proposed a new PV system evaluation method by sophisticated verification procedure. This is applied to the Field Test operational data as actual examples. The works are summarized as follows:

- developed a new method called "SV Method" (sophisticated verification procedures) to verify detailed system parameters from ordinary, monitored data,
- normal items including system performance ratio $\boldsymbol{K}$, power conditioner efficiency $\boldsymbol{K}_{C}$, temperature factor $\boldsymbol{K}_{PT}$,
- new items such as shading factor $\boldsymbol{K}_{HS}$, load matching factor $\boldsymbol{K}_{PM}$ and other array parameter $\boldsymbol{K}_{PO}$, where time series data verification process can produce more realistic results of shading and mismatch losses respectively, especially,
- as a realistic example, evaluation results for 71 systems in the Japanese Field Test Project by SV method.

This study is very much concerned with the activities of both the Field Test Program and the New Sunshine Program conducted by the New Energy and Industrial Technology Development Organization (NEDO). Under the contract of NEDO, monitored data are collected by the Japan Quality Assurance Organization (JQA). Theoretical background has been discussed with researchers in Electrotechnical Laboratory. Authors in Tokyo University of Agriculture and Technology (TUAT) are financially supported by the Photovoltaic Power Generation Technology Research Association (PVTEC). They wish to thank many people for their hearty support.

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